A COMPARATIVE STUDY OF GARNETS FROM AFRICAN KIMBERLITES

by

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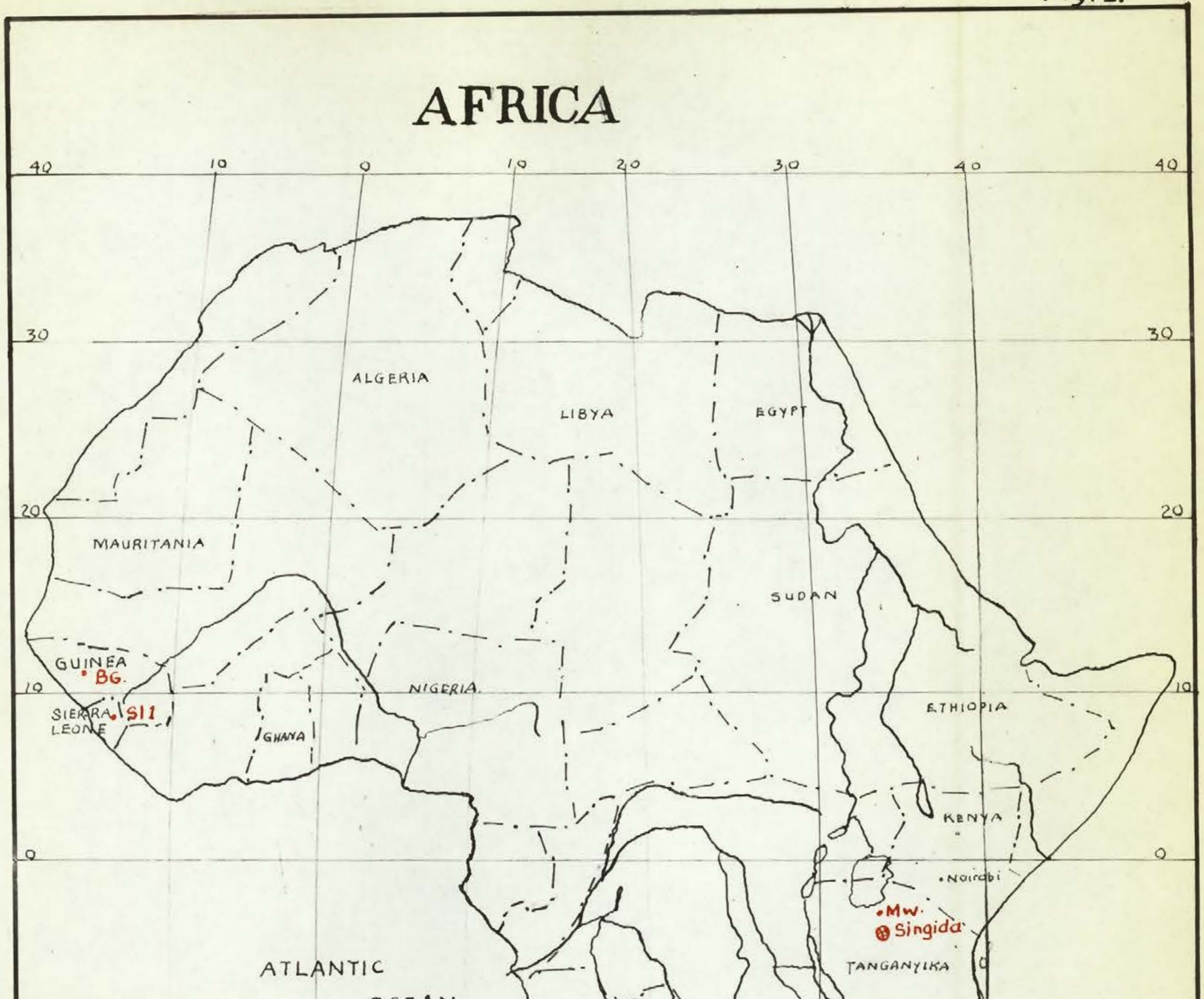
ABSTRACT

Garnets from kimberlite occurrences in the Republic of South Africa, South West Africa, Southern Rhodesia, Tanganyika, Guinea and Sierra Leone were analysed, by physical methods of analysis. The purpose of making the analysis was two-fold: 1. To compare the composition of garnets from diamond-bearing, with those from non diamond-bearing kimberlites. 2. To evaluate the results of analysis by physical methods, by comparing them with the results of chemical analyses.

Analyses by physical methods were made by measuring the refractive indices, the lattice constants and the specific gravities of the garnets and plotting them, along with chemical composition, on a three dimensional tetrahedral diagram (after Winchell, 1958).

No difference was found between the garnets from diamond-bearing and those from non diamond-bearing kimberlites. Analysis by physical methods was found to be almost as good, and in the case of small samples, probably better than chemical analyses.

Fig. 1.


AFRICA
40
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ALGERIA
LIBYA
EGYPT
MAURITANIA
SUDAN
GUINEA
BG.
SIERRA LEONE
SI1
GHANA
NIGERIA.
ETHIOPIA
KENYA
Nairobi
Mw.
Singida
TANGANYIKA
ATLANTIC OCEAN
CONGO
ANGOLA
NORTHERN RHODESIA
MOSAMBIQUE
SOUTHERN RHODESIA
C1.
Bulawayo
South West AFRICA
BECHUANALAND
INDIAN OCEAN
Gibeon
Bersaba
REPUBLIC of
FS.
Kp
Kimberly
JP
Klp.
SOUTH AFRICA
Cape Town
0
500
1000
MILES
10
0
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20
30
40
Kimberlite bodies • Mw or ⊗ Singida

Chapter 1.

INTRODUCTION

1.1 OUTLINE OF THE PURPOSES OF THIS STUDY

The purpose of this study is twofold: (1) to compare the garnets from diamond-bearing and non diamond-bearing kimberlites; any differences which could be detected between the garnets from diamond bearing and non diamond-bearing kimberlites would be exceptionally useful in prospecting for diamonds; and (2) to compare the modal composition of garnets calculated from the percentages of the oxides found by wet chemical analysis, with the modal composition derived from a graph, obtained by plotting physical properties against chemical composition.

1.2 MATERIAL STUDIED

The material used in this study consists of garnet crystals from concentrates derived from kimberlite bodies in Africa (map Fig. 1).

Garnets from the following districts, which might be termed 'kimberlite provinces', were studied:

1. South Africa, Kimberly province,
2. South West Africa, Berseba-Gibson province,
3. Southern Rhodesia, Bulawayo province,
4. Tanganyika, Singida and Shinyanga provinces,
5. Sierra Leone, Sefadu province,
6. Guinea (location unknown).

With the exception of the Basutoland and Katanga provinces, the above list covers most of the known kimberlite provinces of Africa.

1.3 DEFINITIONS

The term kimberlite and more particularly the term pyrope may be used in several contexts. The terms are defined here in order to clarify their usage in this thesis.

(a) Kimberlite

The term was proposed by C. Lewis (1888) for the diamond bearing peridotite from the Kimberly area of South Africa. This rock is a volcanic breccia, but neither an ash nor a tuff; the peculiar brecciated structure being apparently due to successive paroxismal eruptions. In the kimberlite, olivine, with its alteration products serpentine and magnetite, is the most abundant constituent and it is associated with bronzite, chrome-diallage, biotite, perovskite, pyrope, ilmenite and other minerals. For more complete modern definitions one must turn to Dawson (1960, p.6) and to Mannard (1962, p.326). Owing to the rather variable composition of the rock normally called kimberlite, a rather generalized description such as proposed by Mannard (1962) is possibly the best. According to Mannard (1962, p.326) "Kimberlite is a serpentinized, mica peridotite of volcanic origin, which invariably contains pyrope".

(b) Pyrope

In the strict sense of the word, the term pyrope is applied to the end member or molecule of the garnet series, having a composition

$Mg_3 Al_2 (SiO_4)_3$. The term pyrope, however, has come to be used loosely to refer to any member of the garnet series in which, compositionally, the pyrope end member predominates. Unless otherwise stated, the term pyrope is used in the latter sense throughout this thesis. The term pyralspite is sometimes used in place of the term pyrope, but this is incorrect usage. Winchell and Winchell (1956, p.483) apply the term pyralspite to a series consisting of pyrope, almandite and spessartite. As pyrope garnets also contain small amounts of the grossularite, andradite and uvarovite molecules, the term pyralspite is clearly not applicable to them.

1.4 ACKNOWLEDGMENTS

Thanks are due primarily to Dr. E. Gerryts, formerly with Anglo American Corporation of South Africa Ltd. for encouraging the author to undertake this thesis and for donating many of the samples.

Thanks are also due to: Dr. G. Mannard who donated the samples from the Singida area of Tanganyika; Dr. J. S. Stevenson, under whose direction this thesis was written; Dr. A. Frueh for assistance with the X-ray studies; Dr. Jellema for assistance in setting up the procedure for the spectroscopic analysis; Miss H. Ulk for the chemical analyses of two garnets.

I wish also to express my thanks to the other members of the geology department at McGill University, both staff and students, who have contributed invaluable services at various times.

Chapter 2.

PETROLOGY AND GEOLOGY OF THE KIMBERLITES

2.1 INTRODUCTION:

This section is devoted to short descriptions of the petrology and geology of the kimberlite bodies from which the garnets are derived, in order to provide a background against which to view the results of the garnet analyses.

Numerous thin sections cut from African kimberlites were examined by the author. The rocks from which the sections were made are highly altered, serpentinized and chloritized and contain numerous xenoliths. These highly altered and brecciated rocks are typical of the upper portions of kimberlite pipes, but are too altered to be representative of the parent kimberlite magma, from which the garnets are derived, and so they will not be described in this thesis. Instead, descriptions have been taken from other sources.

2.2 MWADUI KIMBERLITE:

The Mwadui diamond mine is in the Shinyanga district of Tanganyika (longitude 30° 30' east, latitude 3° 30' south). The mine is approximately sixty miles south of Lake Victoria. The diamond mine at Mwadui differs from most others in that the diamonds are recovered from gravels which overlie a crater, about 4000 feet in diameter, filled with tuffaceous rocks. Tremblay (1956, p.16a) Thirty intrusives similar to that at Mwadui lie within a radius of fifteen miles from it.

A general geological map of the Mwadui area is shown in Fig. 2, p.6. The kimberlite pipes have bored their way up through the Basement Complex, which underlies the area. The Archaean rocks of the Basement include: granites, gneisses, greenschists and some quartzites. "No Triassic rocks could possibly overlie the Basement Complex at the time of the kimberlite extrusion." Tremblay (1956, p.14)

The rocks of the crater consist of a variety of tuffs with some tuffaceous marls and clays and are described in detail by Tremblay (1956, p.49-83). No kimberlite occurs within the crater. Heavy minerals from the Mwadui mine are discussed by Tremblay (1956, p.101). Diamond, garnet and ilmenite occur in the diamond concentrates. The presence of these minerals indicates that the tuffs of the crater must be the upper portion of a kimberlite volcano, because in this district, pyrope, diamond and ilmenite are not found outside the crater rocks.

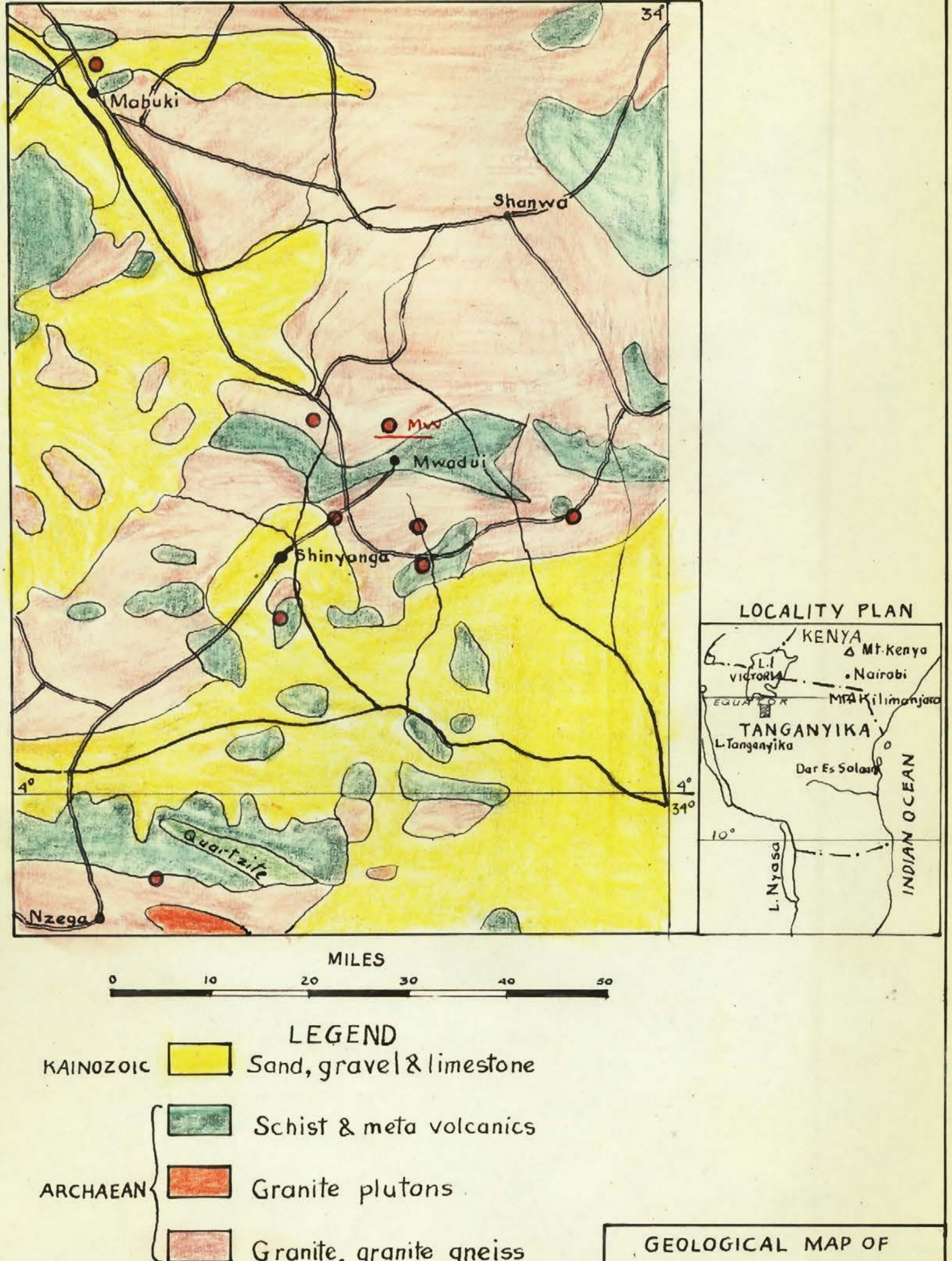
The presence of the crater series of rocks at Mwadui is in marked contrast to the kimberlites of South Africa, where only the throat, or pipe-like portion of the volcanos, is preserved.

2.3 KIMBERLITES OF THE SINGIDA REGION OF TANGANYIKA

The garnet samples, obtained from kimberlites in the Singida district, are numbers:

3, 4, 5, 6, 8, 11, KS-13, 16, 24-2, 24-3, 24-5, 26-2, 26-3, 27-2, 27-3, 30-2, 30, 30-1, 32-0, 46, 9-R, 9-V, 32-V, 12.

Fig.2.



LEGEND

KAINOZOIC 🟨 Sand, gravel & limestone

ARCHAEAN
- 🟩 Schist & meta volcanics
- 🟧 Granite plutons
- 🟥 Granite, granite gneiss

● Kimberlite occurrences
Mwadui kimberlite body is underlined
▭ Geological contact
Roads ═
Rivers ~
Towns •

GEOLOGICAL MAP OF
SHINYANGA DISTRICT
TANGANYIKA

Compiled from Geological Map of Tanganyika (Tanganyika Geological Survey 1959)
by P. Grattan-Bellew. March 1963

As all the kimberlites in the Singida district are more or less similar, a general description will be given here. The description is after Mannard (1962, p.18-346).

The kimberlite bodies are in the administrative districts of Singida and Iramba in Tanganyika; the area is bounded by latitudes 4° 00' and 5° 15' south, and by longitudes 34° 00' and 34° 15' east.

The Singida district is underlain by granites, gneisses, metavolcanics and greenschists of the Basement (map Fig.3). The Basement rocks are cut by dolerite dykes of an unknown age and by kimberlite pipes and dykes (Mannard, 1962, p.18). The surface area of the pipes varies from 920 to 2500 square yards. In this respect, they are similar to the kimberlite pipes of South Africa, Basutoland (Dawson, 1960) and the Congo (Verhoogen, 1938).

The outcrop and sub-outcrop of the Singida pipes varies from round to oval to elongate. "The internal structures of the Singida kimberlite pipes confirms the often disputed conclusion of Wagner (1914, p.5) that kimberlite pipes are eroded funnel shaped volcanic necks of the Maar type." Mannard (1962, p.268)

With the exception of the Mamungo pipe, No.16, the pipes in the Singida district fall into the basaltic category (Mannard, 1962, p.346).

The petrology of the basaltic kimberlites of Singida is essentially similar to that of Jagersfontein and Kimberly mines, but, owing to the fact that the exposed portion of the craters is, in most cases, filled with tuff, fresh kimberlite is not common. As a result, the petrology of the rocks which form the exposed portions of the pipes varies considerably. The petrology of the crater rocks has been dealt with exhaustively by Mannard (1962, p.18-346).

Conclusions:

The kimberlite bodies of the Singida district are at a stage of erosion similar to that of the Mwadui kimberlite crater. The crater-like form and the shattered condition of the rocks comprising the kimberlite pipes leaves no doubt that the kimberlites were formed by explosive eruption. (Mannard, 1962, p.270)

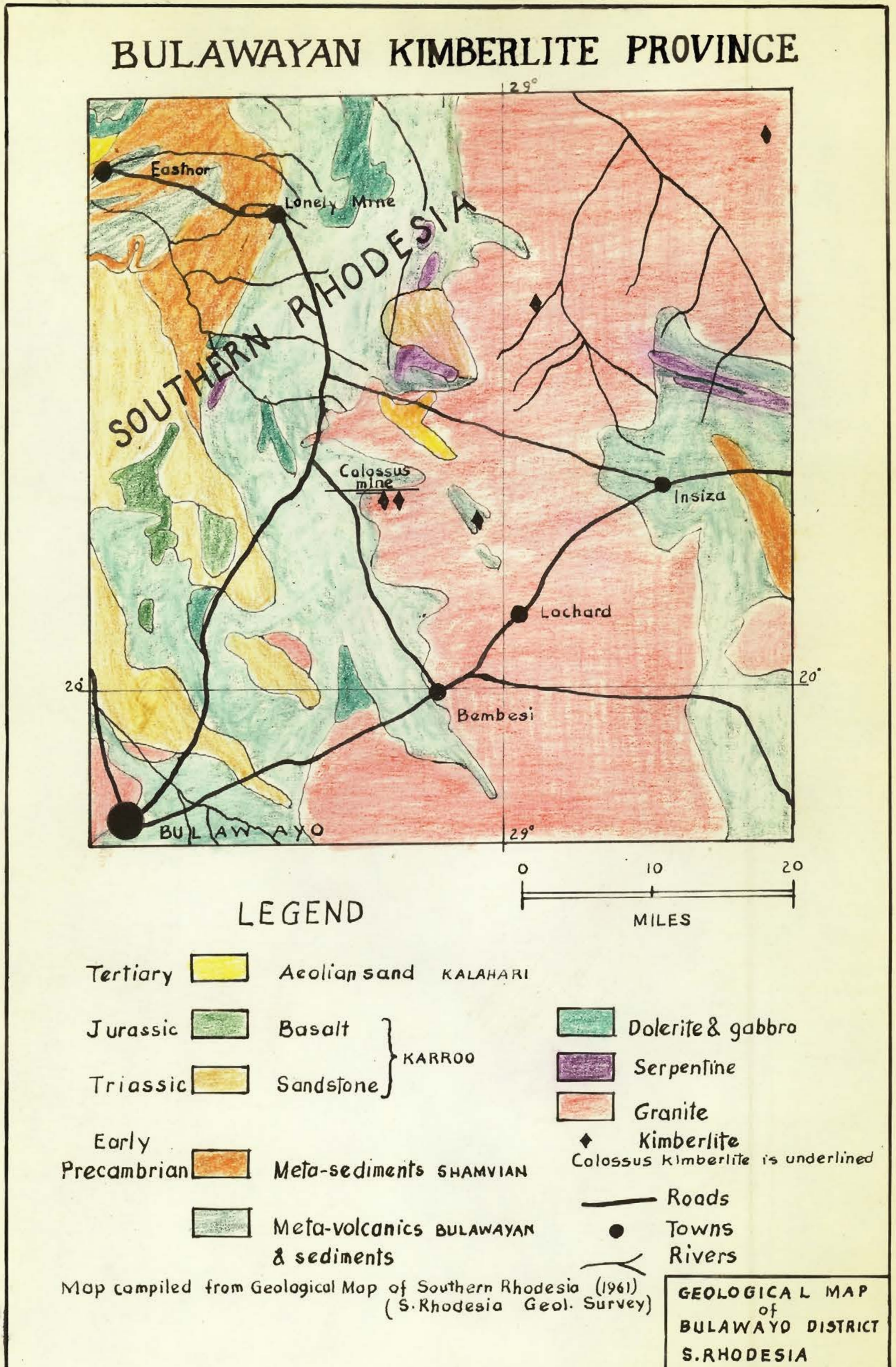
2.4 COLOSSUS KIMBERLITE OF SOUTHERN RHODESIA

The Colossus mine is about 30 miles northeast of Bulawayo. The approximate latitude is 19° 50' south, the longitude is 28° 55' east (see map Fig.4).

Three kimberlite bodies occur in the area near Lochard. Two more kimberlites occur further north. The area in which the two groups of kimberlites occur might be termed The Bulawayan Kimberlite Province. The area is underlain, for the most part, by granite and granite gneiss of varying age, but mostly Pre-Cambrian. Some Pre-Cambrian meta-volcanics and interbedded sediments (schists, etc.) of the Bulawayan and Sebakwian systems also occur.

The kimberlite bodies of the Bulawayan Province are composed of micaceous kimberlite (Wagner, 1914, p.114). The kimberlite is composed of large porphyritic crystals of olivine, phlogopite, ilmenite, pyrope and diopside, set in a holocrystalline groundmass of phlogopite,

Fig. 4.


BULAWAYAN KIMBERLITE PROVINCE
29°
Eastnor
Lonely Mine
SOUTHERN RHODESIA
Colossus mine
Insiza
Lochard
20°
20°
Bembesi
BULAWAYO
29°
0
10
20
MILES
LEGEND
Tertiary
Aeolian sand KALAHARI
Jurassic
Basalt
Triassic
Sandstone
KARROO
Early Precambrian
Meta-sediments SHAMVIAN
Meta-volcanics BULAWAYAN & sediments
Dolerite & gabbro
Serpentine
Granite
Kimberlite
Colossus kimberlite is underlined
Roads
Towns
Rivers
Map compiled from Geological Map of Southern Rhodesia (1961) (S. Rhodesia Geol. Survey)
GEOLOGICAL MAP of BULAWAYO DISTRICT S. RHODESIA
P.E.G-B March 1963

olivine, apatite and perovskite. As is usual in kimberlites, the olivines have been almost completely replaced by pseudomorphs of serpentine (bastite). The rock is practically free from carbonate; this is a rather unusual feature in kimberlites.

2.5 SIERRA LEONE KIMBERLITES (sample number SL1)

The kimberlite bodies are located about one and one half miles south of the administrative post of Sefadu, latitude 8° 38' north, longitude 10° 59' west.

The kimberlite bodies in Sierra Leone occur as a series of dykes. These dykes are unusual in that they are highly diamondiferous. Kimberlite dykes are also found in the Winberg district of South Africa about 100 miles east of Kimberly. In the Winberg district the swarm of kimberlite dykes is almost 40 miles long (Wagner, 1914, p.43). With the exception of a few dykes in the Barkley west area of South Africa, most of the dykes have too low a diamond content to be of ore grade.

The rocks which underlie the area are part of the Basement Series. Granites, some foliated, are the dominant rocks, but, in addition, there are bands of quartzite, schist and banded ironstone. A few dolerite dykes occur and, in one instance, a dolerite dyke is cut and displaced by a kimberlite dyke (Grantham & Allen, 1960, p.7). Apart from the fact that the kimberlite dykes are younger than the dolerite dykes, there is no evidence for their age.

The kimberlite dykes are arranged en echelon in a zone 12 miles long and 2 miles wide, that trends in a northeast direction.

The following is a much abbreviated description of the petrography of the Sierra Leone kimberlite dykes after Grantham & Allen (1960, p.8-15). The rock is classed as a basaltic kimberlite; analysis shows it to be similar in composition to kimberlite from Jagersfontein. The fresh unaltered material in the dykes is a hard blue-green porphyritic rock with prominent euhedral pseudomorphs of serpentine after olivine, large fragments of black ilmenite and sporadic grains of garnet. Some of the serpentines contain much exsolved magnetite. Pale euhedral phlogopite crystals range in size from a few millemetres to 0.5 mm in diameter, but a few crystals are several millemetres in length. The phlogopite crystals frequently show alteration to chlorite. Small octahedra of magnetite are common, and in conjunction with magnetite liberated in the formation of serpentine, impart a definite magnetism to the kimberlites. Corroded pieces of ilmenite up to several millemetres in diameter occur. The margins of the ilmenites are altered to perovskite. Radiating, slender apatite crystals occur in the groundmass, along with small grains of ilmenite. As in most other kimberlites, carbonate occupies the interstices between other minerals. Isolated grains of garnet have broad kelyphitic rinds.

2.6 KIMBERLITES OF THE KIMBERLY PROVINCE:

Kimberly is in the Republic of South Africa, almost in the centre of the southern portion of the African continent, latitude 28° 40' south, longitude 24° 45' east.

A large group of kimberlite pipes occurs around the town of Kimberly. The following is a list of the larger mines: Kimberly mine, Belgravia, Bultfontein, Wesselton, DuToit's pan, DeBeers, St. Augustines, Taylor's Kopje, and Kamfersdam. (see map Fig.5)

Most of the rocks in the Kimberly district belong to the Dwyka Series, of the Upper Carboniferous age. The rocks consist of shales and tillite. The Dwyka series is underlain by the Ventersdorp lavas which are of Pre-Cambrian age. In the Kimberly Mine, about 350 feet of Dwyka shales occur above the amygdaloidal diabase of the Ventersdorp series. Blocks of Permian or Triassic Beauford sandstone were found as inclusions in the kimberlite of Wesselton mine. Fragments of amygdaloidal basalt which have been identified with the Stormberg series of the Triassic,have been found in the pipes between Jagersfontein, Postmasterberg and Prieska. The above observations establish the age of the kimberlites as post Stormberg, i.e. post Jurassic (Du Toit, 1956, p.417). The probable age of the Kimberly kimberlites is late Cretaceous (Du Toit, 1956, p.429).

Kimberly Mine

The kimberlite pipe in which the Kimberly mine is excavated was formed by the coalescence of three distinct pipes (Wagner, 1914, p.5). The pipes are arranged along a fissure having an east-northeast trend. On the eastern wall of the mine the fissure is occupied by a narrow dyke of kimberlite.

The kimberlite of the pipes and dykes of the Kimberly district is typical of basaltic kimberlites. The following is a brief description of slide No.131, after Williams (1932, Vol.1, p.254-255). Serpentinized olivine makes up most of the matrix of the rock. Embedded in the fine serpentine matrix are olivine crystals, rounded by resorption and ranging from 15 mm to less than 0.5 mm in diameter. Most of the garnets are altered to black/brown bodies composed of fibrous limonite and represent kelyphitic rinds of altered pyrope garnets. Ilmenite occurs as rounded fragments. Most grains show marginal alteration to perovskite. Calcite in streaks and irregular patches makes up a considerable portion of the rock. The large rounded olivines, pyroxenes and garnets are not indigenous to the kimberlite lava but have been transported from a more deep-seated part of the crust.

2.7 KAMFERSDAM KIMBERLITE

The Kamfersdam mine is about 5½ miles northwest of Kimberly Mine (see map Fig.5). The kimberlite body at Kamfersdam consists of a pipe like structure and a 'harde-bank' dyke. The term 'harde-bank' is applied to a hard unweathered, intractable kimberlite (Du Toit, 1956, p.421). A section cut from the harde-bank dyke reveals pseudomorphs of serpentine after large and small elements of olivine, in a groundmass of serpentine and calcite. Perovskite in cubic crystals and irregular grains is abundant. The rock is practically free from mica (Wagner, 1914, p.88).

2.8 FRANK SMITH KIMBERLITE

The Frank Smith Mine is about 45 miles northwest of Kimberly, longitude 24° 30' east, latitude 28° 15' south (see map Fig.5).

Dwyka shales and tillite are the dominant rock groups in the area. The Dwyka series is underlain by cherts, dolomites and ironstones of the Transvaal system, which are in turn underlain by the Ventersdorp lavas. Both the Transvaal and the Ventersdorp systems are Pre-Cambrian in age.

The kimberlite body at Frank Smith consists of two distinct pipes which are located on a kimberlite dyke having a northeast trend. The two pipes form a dumbell-shaped body about 1500 feet long. In general, the kimberlite is intermediate between the basaltic kimberlite of Kimberly Mine and the micaceous kimberlite of the Lion Hill dyke (Wagner, 1914, p.112).

The following is a brief description of the petrology of the kimberlite from Frank Smith Mine after Wagner (1914, p.111). In the hand specimens are found rounded grains of olivine, flakes of phlogopite, deep red garnets and ilmenite, in a fine matrix. The ilmenite often builds large individuals. Thin sections exhibit the above mentioned minerals interspersed through a panidiomorphic granular groundmass composed of plates of phlogopite, crystals of serpentinized olivine, prisms of apatite, granules of perovskite and iron ore. Both the olivine and perovskite occur in two distinct generations. The groundmass of the rock is strongly impregnated with calcite.

2.9 KLIPFONTEIN KIMBERLITE

The Klipfontein Mine is in the Republic of South Africa, about 50 miles south of Kimberly and 5 miles northwest of Koffiefontein, longitude 25° east, latitude 29° 25' south (see map Fig.5).

Most of the area around Klipfontein is underlain by Permian rocks of the Ecca series. The Ecca series consists of shales and sandstones; they are underlain by Dwyka shales and ventersdorp lavas.

The Klipfontein kimberlite body consists of a blow, or enlargement of the subterranean kimberlite dyke which extends from Koffiefontein to Klipfontein. The following description of the petrology of the Klipfontein kimberlite is after Wagner (1914, p.88-89). The Klipfontein kimberlite is coarsely porphyritic and shows conspicuous phenocrysts of olivine, grains of bronzite, garnet and flakes of phlogopite, in a dense, greenish black matrix. The groundmass of the rock is largely composed of minute pseudomorphs of serpentine after idiomorphic olivines belonging to a second generation. From an analysis of the kimberlite from Klipfontein, Wagner (1914, p.89) concludes that "The rock must originally have consisted almost entirely of olivine." It thus represents an extreme type of basaltic kimberlite, and might perhaps be more correctly described as a porphyritic dunite.

The garnet sample KLP from Klipfontein Mine was analysed by the author (see Table 7, p.53). The analysis indicates that the garnet belongs to the normal kimberlite group XIV (see Table 6, p.52); this suggests that the rock is probably a kimberlite rather than a dunite.

2.10 JAGERSFONTEIN KIMBERLITE

Jagersfontein mine is in the Republic of South Africa about 30 miles southeast of Kimberly, latitude south 29° 43', longitude 25° 32' east (see map Fig.5).

The Beauford shale which is Triassic in age is the dominant rock group in this area. It is underlain by other rocks of the Karroo series which are Upper Carboniferous in age (Wagner, 1914, p.4). The kimberlite pipe has pierced a sill of dolerite having an average thickness of 800 feet.

The kimberlite of Jagersfontein is the normal basaltic type and closely resembles the rock from Kimberly Mine. For a description of the petrology of the Jagersfontein kimberlite, see Wagner (1914, p.89).

NOTE

No information is available on the Olifants Kop kimberlite, and its exact location is unknown. However, it occurs in the Kimberly Kimberlite Province. No geological map is available for Sierra Leone nor for Guinea, and no information is available concerning the kimberlite deposits of the latter country.

Chapter 3

A REVIEW OF THE MINERALOGY, THE ASSOCIATION WITH DIAMONDS AND THE ORIGIN OF PYROPE GARNETS, AND A DESCRIPTION OF THE GARNETS USED IN THIS THESIS.

3.1 OCCURRENCE OF PYROPE GARNET:

Pyrope garnets are commonly found in two rock types, eclogites and kimberlites. Their occurrence in the latter rock is discussed by the author of this thesis. "Garnet is not a primary constituent of kimberlite, but, like the large crystals of olivine, phlogopite and ilmenite, is a transported mineral which crystallized at greater depth. .....In kimberlite the garnets generally appear like buckshot peppered throughout the matrix, their size varying from tiny specks to pellets up to one half inch in diameter. In exceptional cases garnets have been found measuring six to seven inches in diameter." (Williams, 1932, Vol.2, p.368)

3.2 ASSOCIATION OF PYROPE GARNETS WITH DIAMONDS:

Garnets are intimately connected with diamonds in kimberlites and have been used as tracer minerals in diamond prospecting. The association of garnets and diamonds was observed at an early stage in the examination of kimberlites (Sutton, 1907, p.488). By comparing the analyses of pyrope garnets and kimberlite breccia, Zveder (1957, p.22-23) concludes that "The pyropes are paragenetic companions of diamonds".

Inclusions of diamond are found in garnets (Williams, 1932, Vol.2, p.373). Inclusions of garnet are sometimes found in diamonds (personal observation by the author). Laue diagrams of diamonds containing inclusions show individual crystals of pyrope-like garnet having a lattice constant ('a') of 11.471 or 11.491 Å. (Futergendler, 1956, p.586-589). The lattice constants for these garnets are rather lower than the average for pyrope garnets from kimberlites, i.e. 11.45 Å. Orlov (1959, p.103-120) measured the refractive index of some garnet inclusions in diamonds. The refractive indices determined by Orlov are 1.761 - 1.772, these values are higher than the normal for pyrope garnet from kimberlites, i.e. 1.740 - 1.760. A refractive index of 1.761 - 1.772 would put the garnets in the eclogite group (see Fig.7, p.53). From the foregoing discussion, it is clear that there is a definite connection between the occurrence of pyrope garnets and diamonds.

3.3 GARNET GROUP

The garnet group consists of rather complex silicates whose formulae may be summarized as $3A'' \, 2B''' (SiO_4)_3$ in which A'' may be Ca, Mg, Fe'', or Mn'' and B''' may be Al, Fe''', Cr, Ti''' or Mn'''. Finally SiO_4 may be replaced by PO_4 to about 4% P_2O_5 which would account for the presence of P_2O_5 in many garnet analyses. Naturally occurring garnets rarely approach any single end member of the garnet series in composition, but form solid solutions of two or more end members (Winchell & Winchell, 1956, p.483).

TABLE 1

End Member	Composition	n *	G *	a *
Pyrope	$Mg_3 Al_2 (SiO_4)_3$	1.714	3.582	11.459
Almandine	$Fe_3 Al_2 (SiO_4)_3$	1.830	4.318	11.526
Spessartite	$Mn_3 Al_2 (SiO_4)_3$	1.800	4.190	11.621
Grossularite	$Ca_3 Al_2 (SiO_4)_3$	1.734	3.594	11.581
Uvarovite	$Ca_3 Cr_2 (SiO_4)_3$	1.860	3.90	12.00
Andradite	$Ca_3 Fe'''_2 (SiO_4)_3$	1.887	3.859	12.048

Minor Components

Khoharite	$Mg_3 Fe'''_2 (SiO_4)_3$	-	-	-
Skiagite	$Fe''_3 Fe'''_2 (SiO_4)_3$	-	-	-
Calderite	$Mn''_3 Fe'''_2 (SiO_4)_3$	-	-	-
Blythite	$Mn''_3 Mn'''_2 (SiO_4)_3$	-	-	-
Titanium Garnet	$Ca_3 Ti_2 (SiO_4)_3$	-	-	-

* Abbreviations: n - refractive index, G - specific gravity,
a - lattice constant.

Physical properties of the end members of the garnet group (Skinner, 1956, p.428).

With the exception of uvarovite, the values given in Table 1 for refractive index, lattice constant, and specific gravity are those determined by Skinner (1956). The values of refractive index, lattice constant, and specific gravity for uvarovite are taken from Deer Howie Zussman (1962, Vol.1, p.77). The occurrence of khoharite, skiagite, calderite and blythite should be noted. Tröger (1962, p.666) states that "Hitherto mineralogists have treated these minor components with light regard, for example the occurrence of them as the result of calculation of garnet analyses has been dismissed as not real, or of minor importance."

Stability of Pyrope Garnets

The pyrope end member of the garnet series is not stable at atmospheric pressure (Boyd & England, 1958-59, p.83). At temperatures above 1200°C. and pressures of 23 kb., pyrope forms rapidly from a glass mixture of anhydrous crystalline phases. At temperatures below 1100°C. the reaction is sluggish. A pressure of 23 kb. is about the minimum at which pyrope will form.

The information in the above paragraph is derived from the graph of temperature versus pressure for pyrope by Boyd and England (1958-59, Fig.1, p.84). The presence of pyrope in a rock would, therefore, appear to indicate high pressure conditions during its formation.

Origin of Pyrope-rich Garnets in Kimberlites

The origin of pyrope-rich garnets in kimberlites is discussed by

Dawson (1962, p.556) who concludes that the inclusions, including garnet, in kimberlites are cognate, because the inclusions are abundant in kimberlites throughout the world. However, altered fragments of peridotite, garnet and ilmenite have given rise to minerals which are an integral part of kimberlite. It is therefore probably true to say that the answer to the problem of the origin of pyrope garnets in kimberlites will be found in the solution to the origin of kimberlite itself, a problem which is outside the scope of this work.

Alteration of Garnets:

There are two main alteration products of pyrope garnets: (1) kelyphite, (2) chlorite (Winchell and Winchell, 1956, p.409). Kelyphite forms a distinct crust around the grains of garnet. It is usually composed of an intergrowth of fibrous amphibole, feldspar and biotite (Deer, Howie, Zussman, 1961, Vol. 1, p.98). Yoder (1952, p.613, Fig.14) shows the phases stable at 600°C. for the system $MgO-Al_2O_3-SiO_3$ at 1,100 kb. Yoder states that "rock of pyrope composition at 600°C. would consist of pyrope alone or pyrope and clinochlore, or of cordierite and talc, depending upon the amount of H_2O present. These stages represent stages in the development of kelyphite around garnet. Such changes can take place without any changes of temperature or pressure. ....

On the basis of the above views, the conception that kelyphitization is solely a retrograde process is open to question."

3.4 THE EFFECT OF HIGH PRESSURE ASSOCIATED WITH THE FORMATION OF DIAMONDS ON THE COMPOSITION OF PYROPE GARNETS.

At temperatures above 1200°C. and pressures above 25 kb., pyrope forms rapidly from melts of suitable composition (Boyd and England, 1958-59, p.83). Pressures of 23 kb. would be found in the mantle below the continental crust, this depth would presumably correspond to the zone of peridotites or eclogites. The formation of diamonds takes place at much higher pressures, around 70 kb. (Dana-Hurlburt, 1959, p.239). As pyrope is stable at 23 kb. it is unlikely that the higher pressures associated with the formation of diamonds would have any effect on the garnets, so long as they were formed at pressures in excess of 23 kb. The fact that no difference could be found between the garnets from diamond bearing and non diamond-bearing kimberlites, in this study or that of Mannard (1962), tends to support the above hypothesis.

3.5 INCLUSIONS IN PYROPE GARNETS

The author has observed that although most pyrope garnets are free or almost free from inclusions, some are riddled with inclusions. G. I. Smirnov (1959, p.26) states that "some inclusions are idiomorphic chrome spinel grains, with well developed octahedral faces; others are needle like or tabular rutile. Fairly large chrome-diopside inclusions occur in some grains". The occurrence of diamonds as inclusions in garnets has already been referred to.

3.6 COLOUR OF PYROPE GARNETS

Pyrope garnets occur in several shades of red, violet, orange and yellow-brown; some grains are almost colourless. The yellow-brown garnets usually tend to be shattered and to have a rather dull lustre, a feature that may be due to the breakdown of the crystal lattice. If thin grains are examined, most garnets can be fitted into two colour groups: violet and orange red; a lesser number fall between these two groups and have a purple colour.

Several attempts have been made to correlate the colour of pyropes with some physical properties, eg. refractive index, or specific gravity, and also with the presence of such elements as Cr, Ti and Mn, in the analysis of garnets, but the results so far have been inconclusive (Smirnov, 1959, p.25).

3.7 DESCRIPTION OF THE GARNETS STUDIED IN THIS THESIS

A list of garnets studied in this thesis is given in Table 2, p. 26. The main physical properties are also listed in this table. In this section a brief note is made of garnets that have marked kelyphitic rinds or contain numerous inclusions.

1. Olifants Kop (sample OP)*

An orange coloured garnet from this sample contains a rounded inclusion of green diopside (omphacite) 0.5 mm in diameter. Apart from this one inclusion the grains are relatively free from them.

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* OP refers to the author's labelling of the sample from the Olifants Kop kimberlite.

2. Klipfontein (sample Klp)

In addition to the orange coloured grains of garnet, this sample contains one rather shattered grain of violet coloured garnet. Some of the grains contain numerous angular inclusions of omphacite, up to 0.4 mm in length.

3. Jagersfontein (sample JP)

The grains of garnet in this sample are rather shattered and have a pale yellowish-brown colour. Many of the garnets have marked kelyphitic rinds.

4. Colossus (sample Cl)

Many of the garnets are well rounded and are surrounded by kelyphitic rinds. In addition to the orange grains, one or two violet coloured grains occur.

5. Mwadui (sample MW)

The garnets from this sample are angular and are free from inclusions or kelyphitic rinds. They are, on average, of a somewhat deeper reddish-orange colour than most other pyropes from kimberlites.

6. Darja Pipe No.5

The garnets from this pipe are violet-purple, or orange in colour. The orange coloured grains contain numerous small inclusions; some are rounded and black in colour (probably spinel), others are brown needle-like and are probably rutile. The violet coloured garnets also contain some black inclusions.

7. Itagata Pipe No.26-2

The garnets from this pipe are a pale yellow-orange colour and contain numerous small inclusions; they are lath-shaped and are probably rutile.

8. Kolongo Pipe No.13

The orange coloured samples of garnet from this pipe contain numerous long needle-like inclusions which are probably rutile.

TABLE 2

TABLE OF GARNETS

Name of Pipe or Locality	Sample Number	Reference Number on Graph Fig. 8	Colour	a.	n.	G.
Olifantskop	OP-V	1	violet	11.529	1.7415	3.68 ± .02
	OP-2-0	2	orange	11.520	1.746	3.69 ± .02
Berseba Reserve	BR-V	7	violet	11.528	1.749	3.72 ± .02
	BR ex 2-0	10	orange	11.533	1.751	3.73 ± .02
Lichtenfels	L2A	17	orange	11.539	1.748	3.70 ± .02
Klipfontein	Klp	14	orange	11.536	1.7435	3.71 ± .02
Kamfersdam	Kaf-0	22	orange	11.534	1.747	3.70 ± .02
	Kaf-V	23	violet	11.522	1.7375	3.66 ± .02
Jagersfontein	JP	25	orange	11.532	1.747	3.70 ± .02
Lichtenfels	LB-v	18	violet	11.557	1.750	3.68 ± .02
	LB-2	19	orange	11.542	1.7455	3.71 ± .02
Bellsbank	BBK-0	15	orange	11.532	1.757	3.77 ± .02
Frank Smith	FS-0	14	orange	11.537	1.753	3.739 ± .02

TABLE 2 (cont'd)

Name of Pipe or Locality	Sample Number	Reference Number on Graph Fig. 8	Colour	a.	n.	G.
Colossus	C-I	28	orange	11.544	1.755	3.73 ± .02
Kimberly Pool	KP	29	orange	11.518	1.750	3.70 ± .02
Sierra Leone	SL1	31	orange	11.541	1.7515	3.72 ± .03
Lichtenfels 7	L7	20	orange	11.524	1.7415	3.67 ± .02
Mwadui	MW	33	orange	11.539	1.7485	3.71 ± .02
Guinea Banonkoro	GB	21	orange	11.546	1.763	3.82 ± .02
Mamumgo	16-0	16-0	orange	11.539	1.752	3.67 ± .03
	16-V	16-V	violet	11.540	1.744	3.70 ± .02
Mpuru Pipe No.1	24-2	24-2	orange	11.603	1.7675	3.85 ± .02
	24-3	24-3	orange	11.567	1.7635	3.80 ± .02
	24-5	24-5	orange	11.641	1.764	3.83 ± .02
Itagata Pipes	26-2	26-2	orange	11.554	1.7605	3.82 ± .03
	26-3	26-3	orange	11.545	1.754	3.71 ± .03
	27-2	27-2	orange	11.542	1.7505	3.67 ± .02
	27-3	27-3	orange	11.542	1.748	3.70 ± .02

TABLE 2 (cont'd)

Name of Pipe or Locality	Sample Number	Reference Number on Graph Fig. 8	Colour	a.	n.	G.
Tambola Pipe	30-2	30-2	orange	11.602	1.767	3.70 ± .03
	30	30	orange	11.562	1.7415	3.70 ± .02
	30-1	30-1	orange	11.556	1.758	3.73 ± .02
Kimbelekese	32-0	32-0	orange	11.545	1.7515	3.74 ± .02
	32-V	32-V	violet	11.515	1.7380	3.70 ± .02
Mingui	MG	34	orange	11.532	1.755	3.80 ± .02
Gonambogo	3	3	orange	11.535	1.753	3.70 ± .02
Magoba	4	4	orange	11.542	1.745	3.67 ± .02
Daraja	5-V	5-V	violet	11.541	1.7465	3.72 ± .02
	5-0	5-0	orange	11.516	1.745	3.76 ± .03
Kitura	6	6	orange	11.541	1.751	3.70 ± .02
Mayaha	8	8	orange	11.538	1.7535	3.75 ± .02
Mvelevele	9-R	9-R	orange red	11.548	1.7515	3.68 ± .02
	9-Y	9-Y	yellowish orange	11.537	1.7475	3.78 ± 0.1

TABLE 2 (cont'd)

Name of Pipe or Locality	Sample Number	Reference Number on Graph Fig. 8	Colour	a.	n.	G.
Makilawa Pipe No.1	11-0	11	orange	11.537	1.746	3.69 ± .02
Munyu	12	12	orange	11.533	1.749	3.72 ± .02
Kolongo	13-V	13-V	violet	11.533	1.743	3.78 ± .02
	13-0	13-0	orange	11.531	1.745	3.68 ± .02

Chapter 4.

ANALYSIS OF THE GARNETS

4.1 INTRODUCTION

Various diagrams relating physical properties to the chemical composition of the garnet group are cited in the literature. The earliest application of composition diagrams to the study of pyrope garnets was made by Ford (1915, p.33-45). Ford used a series of triangular diagrams, on which the three main components were plotted at the apices of the triangles. Fleischer (1937, p.751-759) redrew Ford's triangular diagrams using new values for the physical properties of the end members of the garnet series. As a result of his work on the garnet group, Fleischer arrived at the following conclusions: "Agreement between deduced and actual composition is excellent for grossularite and andradite garnets from a limestone contact zone." Fleischer's results for most pyrope garnets from kimberlites were fair, while the results from garnets from eclogites were unsatisfactory "because these garnets usually contained four components in significant amounts".

Sriramadas (1957, p.295-298) gives eight triangular diagrams correlating the unit cell edges and refractive indices with chemical composition of the garnets.

Kennedy (1947, p.561-573) also shows eight triangular diagrams, on which are shown the refractive indices and densities of the three components. All the diagrams mentioned already have one shortcoming in common; namely, they show only two of the three measurable physical properties: refractive index, lattice constant and specific gravity. Winchell (1958, p.595-600) overcame the problem of only showing two physical properties by making a graph using lattice constants as abscissae, refractive indices as ordinates and plotting the principal end members, almandine, pyrope, grossularite, andradite and spessartite on the one graph. The graph is then contoured with lines joining points having the same specific gravity. The resulting diagram has the form of a skew tetrahedron. It should be noted that the specific gravities of the end members of the garnet group used in the diagrams of Winchell (1958, p.597-598, Figs. 1 and 2) are not in agreement with the values determined by Skinner (1956, p.428-436). The values determined by Skinner are the best available values for the end members of the garnet group.

Winchell (1958, p.597-598) gives two tetrahedral diagrams but suggests that they could be combined in one diagram, if colored inks are used to show the different fields; the author has followed this procedure. On the diagram prepared by the author, (Fig.6) the specific gravity values of Skinner (1956) are used in place of those used by Winchell.

4.2 METHOD OF USING DIAGRAM (FIG.6) FOR CORRELATING THE PHYSICAL PROPERTIES WITH CHEMICAL COMPOSITION OF THE GARNETS

In the sample calculation worked out by Winchell (1958, p.599), he shows that spessartite is always a possible member of one of the triangular fields which compose the tetrahedron. By making a quantitative test for Mn, approximately the correct amount of spessartite may be shown in the analysis. By making a quantitative test for Cr, and using the methods of modal analysis (Holmes, 1921, p.402-404) the amount of Uvarovite may be shown, however, in this method one assumes that all the Cr goes to form uvarovite and that Cr_2O_3 does not, to some extent, replace Al_2O_3 in grossularite or andradite.

4.3 ACCURACY OF THE DIAGRAM (Fig.6)

The accuracy of the diagram depends upon three factors (Winchell, 1958, p.599).

1. The accuracy of the data used in the construction of the diagrams,
2. Adequacy of Vegard's law,
3. Accuracy of the data pertaining to the sample being analysed.

Effect of Minor Garnet Groups:

In the garnet groups proposed by Tröger (1962) and reproduced in part in Table 6, p.52, skiagite is a fairly common constituent. 3% ± 4 of skiagite is present in group XIV (Tröger) in which most kimberlite garnets fall. In the author's opinion, however, as the percentage of skiagite is usually small, its omission in the results of an analysis will not have much practical effect. The omission of skiagite would probably result in an increase of a few per cent in the amount of andradite and almandine.

4.4 VEGARD'S LAW

Vegard's law states as an empirical rule, a linear relation between the unit cell edge and the composition of a binary solid in the cubic system. If in a binary solid solution in which the volume effect of the two end members is additive, then the solution shows no volume change on mixing. This is not really true in the case of the garnets, but the volume change is small. Thus, only a relatively small error is introduced into the diagram by assuming constant volume (An-Zen, 1956, p.523-524).

4.5 SUMMARY OF VIEWS ON THE USE OF COMPOSITION DIAGRAMS IN THE GARNET SERIES

From a survey of the opinions expressed in the literature and from an examination of the data upon which the opinions were based, it is concluded that a reasonably good analysis of garnet can be obtained by measurement of the refractive index, density and lattice constants, and plotting them on a diagram, relating these variables to the chemical composition. In the case of the major constituents of the garnets, an error of 3% or 4% will probably not be sufficient to position the garnet in the wrong group.

For the reasons stated in the preceding paragraph, it was decided that the analysis of garnets by plotting the physical properties on a graph with chemical composition, referred to, subsequently in this thesis, as 'analysis by physical methods', would be sufficiently accurate for the purposes of this study. Accordingly, values were determined for lattice constants, refractive indices, and densities of the garnets, as described in subsequent sections of this chapter.

As a check on the results of the analyses by physical methods, it was decided to have chemical analysis made on two garnet samples.

4.6 ANALYSES OF THE GARNETS

Introduction:

The analyses were made in order to determine the percentages of the different garnet groups present in the samples. The modal composition of garnets can be determined either by wet chemical analysis and subsequent modal calculations or by physical methods of analysis as described in this thesis.

Disadvantages of Wet Chemical Analysis:

1. The amount of sample required is large (about 1 gram), and as few garnets from kimberlites weigh even half a gram, it is difficult to obtain a uniform sample of sufficient weight.
2. The procedure for wet chemical analysis, even by rapid methods is lengthy, and skilled personnel must be employed in making the analysis, with the result that it is very costly.
3. In many analyses, including those used in this thesis, some of the Fe_2O_3 is determined as FeO which will effect the modal analysis.
4. Random errors tend to be introduced during the calculation of the percentages of the groups, from the amounts of the oxides found by chemical analysis.

The limitations of analysis by physical methods have already been discussed in chapter 4, section 5.

Outline of Analysis by "Physical Methods":

The refractive index, n, the specific gravity, G, and the lattice constant, a, were measured as will be described in sections 7, 8 and 9 of this chapter. The values for a and n are then plotted on the tetrahedral diagram, Fig.6 and the composition of the garnets is calculated as described by Winchell (1958, p.599). In all the garnets analysed, it is found that spessartite is a possible component. In order to determine if spessartite is, in fact, present, spectroscopic analyses were made for Mn, at the same time the percentage of Cr was also determined so that the uvarovite molecule could be included where the analysis indicated it to be present.

4.7 MEASUREMENT OF REFRACTIVE INDEX OF THE GARNETS

The refractive index of the garnets was found by using the oil immersion technique as described by Rogers and Kerr (McGraw Hill, 1942, p.56-60). Sodium light was used as a source of illumination and the refractive index was found by observing the Becke line. During the determination the temperature was $25^{\circ} \pm 1^{\circ}$. The interval of refractive index between the liquids which were used was 0.005. The refractive index was first roughly determined and then the index oils were mixed to produce a series having an interval of 0.001 and a final determination was made. The indices of the mixed oils were determined using an Abbe refractometer. The method of determining the refractive index, which is described in the preceding paragraph, was used in preference to the system of mixing the oils on the individual slide and then determining the refractive index of the mixed oil, for the following reasons: the method used is more rapid, refractive index determinations only have to be made of a few mixed oils, and the determination itself is also more rapid, although some accuracy is sacrificed. The error introduced by using pre-mixed oils in place of mixing them to match the individual garnet is in the fourth decimal place and for practical purposes is not significant.

Accuracy:

In order to determine the effect of temperature on the index of refraction of the index-oils, a series of determinations was made at varying temperatures, using the refractometer. It was found that a change of one degree in temperature caused a variation of 0.001 in the refractive index. As the temperature was controlled at $25^{\circ} \pm 1^{\circ}$ during the measurement of the refractive indices of the garnets, the probable error due to temperature changes is ± 0.001, allowing an error of ± 0.001 in the actual determination the probable maximum error is ± 0.002.

4.8 DETERMINATION OF SPECIFIC GRAVITY OF THE GARNETS

Some considerable difficulty was experienced in obtaining accurate determinations of the specific gravities of the garnets. The author's observations and the procedure developed for accurate determination of specific gravities may be of use to others and will therefore be described in some detail.

The procedure used is a modification of that suggested by Berman (1939, p.434-440). The apparatus used was a Berman balance, manufactured by the Bethelem Instrument Company. An attempt was made to determine the specific gravity of single grains of garnet by the method outlined by Berman (1939) but the results of successive determinations were found to vary widely. There appeared to be two possible sources of error, assuming that the temperature is kept constant: (1) the retention of minute air bubbles either on the surface of the grains or in small cracks near the surface of them, (2) parallax in reading the scale. Parallax is virtually eliminated in the reading of the pointer by positioning the centre of the eye on the line engraved in the mirror, behind the pointer. The air bubbles were largely removed by boiling the grains in toluene (liquid used in the determination) under reduced pressure before making the determination. The error due to parallax in reading the dial of the instrument was overcome by using a viewing tube. This tube was constructed by placing a magnifying lens at the end of a tube about 20 cms. in length. A disk having a pinhole in the centre was placed at the other end of the tube.

Procedure Used in the Determination of the Specific Gravities:

The apparatus was set up and adjusted as suggested by Berman (1939, p.434-440).

Sample Preparation:

The garnets were examined under a binocular microscope and a grain was selected which was free or almost free from cracks and inclusions. The optimum weight of the grains is about 25 mgms., but good values were obtained with grains down to about 12 mgms. in weight. Samples weighing over 25 mgms. may also be used, by putting a counterweight on the left hand arm of the balance. Samples weighing between 25 and 32 mgms. should not be used as the 25 mgm. counterweight was found to weigh about 24.91 mgms. The uncertainty of the actual weight of the counterweight introduces an additional source of error. The uncertainty of the weight of the counterweights also introduces an error into the determination of samples weighing over 32 mgms. but in this case both the weight in air and the weight in liquid is affected and the error is to some extent cancelled out, while in the case of grains weighing between 25 and 32 mgms. the error is introduced only in the in air weighing.

The sample should be washed in acetone and any loose pieces or kelyphitic rinds, or portions of the grain containing inclusions or small cracks, should be removed. This can be done most conveniently by using a vibro-tool which can be operated under the binocular microscope.

For reasons which will be explained later, the weight in liquid is determined first. It is not desirable to boil the entire contents of the crystal dish containing toluene, as this would result in a large decrease in the temperature of the toluene, which would result in a change in its specific gravity. It is desirable to keep the temperature of the toluene constant during the course of the determination. In order to avoid the large temperature change in toluene during boiling, the sample was put in a small glass vial of about 1.5 cc capacity. This was then half filled with toluene and placed in a larger jar which was connected to a vacuum pump. The outer jar was immersed in hot water in order to minimize the cooling effect produced by the evaporation of the toluene during boiling. The jar containing the toluene was evacuated for about 2 minutes. The sample in the vial is then transferred, without the grains being exposed to the air, to the crystal balance dish, which should be about 3/4 full of toluene. The crystal dish is then put on the stand in the balance and the double weighing pan is placed on the hook in the right hand balance chamber. The level of the toluene is adjusted so that it covers the lower wire helix of the weighing pan and the sample transferred from the vial into the wire helix, without the grains of garnet coming in contact with air. The vial was then removed from the crystal dish and the level of the toluene adjusted so that the mark on the dish is level with the top of the wire helix. The dish should be filled to within about 0.75 cms. of the top. The weight of the sample in liquid is then taken, the sample is removed from the wire helix and placed in the vacuum jar to dry for 5 minutes. While the sample is drying, the temperature of the toluene is recorded, using a short thermometer which is suspended in the toluene in the balance chamber. Finally the weight of the sample in air is recorded. If the in air weighing had been made first, it would be difficult to adjust the level of the toluene to the same height after putting the crystal dish into the toluene as is necessary in carrying out the weighing in liquid.

Correction of the Specific Gravity of Toluene for Temperature Variations:

The variation of the specific gravity of toluene with temperature was determined by the American Petroleum Institute (Research Project 44, p.135). From the values determined in Project 44, a graph, showing the variation of specific gravity with temperature may be constructed. The density of the toluene is read off the graph at the temperature which was recorded during the determination. The following calculation is used in determining the specific gravity:

$$SG = \frac{\text{weight in air} \times \text{density of toluene}}{\text{weight in toluene} - \text{weight in air}}$$

Several determinations were made for each sample. If the same value is obtained in the first two determinations, this is taken as the specific gravity of the sample. If, on the other hand, the second reading differed from the first, more determinations were carried out until two readings were the same. In general it is found that the values range about 0.02 either side of the determined value.

Precision of the Determinations:

In order to test the precision, six determinations were made on one grain. From these determinations a standard deviation of ± 0.007 was calculated. In a second test, four determinations were made on another grain and a standard deviation of ± 0.004 was calculated. The precision also varies with the size of the sample, optimum results can be obtained with samples weighing 12 mgms. and greater. For samples weighing 8 mgms. the standard deviation is about ±0.05. Several samples which were determined twice, by accident, form an unbiased check on the precision; these are found to agree to within ± 0.01 of each other.

Accuracy:

The accuracy of the results, assuming good precision in the measurement, will depend upon the individual sample - its freedom from inclusions, cracks and alteration. In the case of carefully selected grains, a probable accuracy of ±0.02 might be expected. For grains weighing about 8 mgms. an accuracy of about + 0.10 can be expected. In instances where several small grains have to be used in place of one or two large ones, the precision is very poor and the accuracy is possibly around 0.10.

Conclusions:

The measured value for the specific gravity of many of the garnets is below the calculated value, which suggests that the measured values are rather too low. One matter that was overlooked in the determination of the specific gravities is the possible departure, of individual batches of toluene, from the graph of temperature versus density, worked out by the American Petroleum Institute. It has been found that there is considerable variation in the density at any given temperature, between different batches of toluene (personal communication A. W. Hunslow).

Alternative Methods of Determining Specific Gravities:

1. A micropycnometric method such as that devised by C. J. Ksanda and H. E. Merwin (1939, p.482) could be used. The micropycnometric method of determining specific gravities is very accurate, but it has several drawbacks: the apparatus would take some time to construct, a micro balance would have to be available. In addition, the temperature and humidity have to be controlled. For these reasons, and also due to the fact that each determination would take about one hour, the procedure is not very suitable where a large number of samples are involved.

2. A better method might be to use heavy liquids and a centrifuge. The procedure for this method consists of mixing the liquids and centrifuging the sample in the liquid. When the position of the sample in the tube does not change upon centrifuging, the density of the liquid then matches the density of the sample. The density of the liquid is then found using a pychnometer.

4.9 MEASUREMENT OF LATTICE CONSTANTS OF GARNETS

Standard techniques were used in determining the lattice constants of the garnets and accordingly are only briefly outlined here. Powder diffraction photographs were taken using a Debye Scherer camera of diameter 114.6 mm. Fe Kα radiation was used, with a Mn filter. A voltage of 30 kv. and a current of 10m. amps was used. Exposures varied from five to six hours. In order to calculate the lattice constants from the measured 2θ values, it was first necessary to find the indices of the planes corresponding to the different lines on the film. The indexing of the lines on the film was carried out as follows: a single crystal was first orientated with respect to one of the crystallographic axes using a Buerger Precession Camera. Once the crystal had been orientated, it was mounted in a Weissenberg camera. Equi inclinational photos were made using Fe Kα radiation. The points on the resulting photographs were indexed by plotting them on a polar projection; the method is outlined by Buerger (1942, chapters 14 and 15, p.252-311).

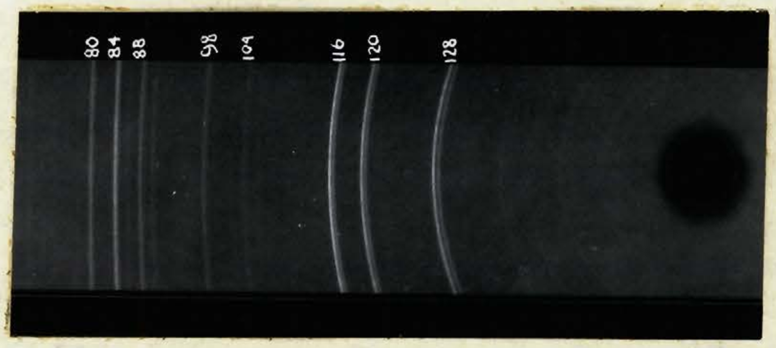
Method of Calculating Lattice Constants from the Powder Diffraction Photographs:

The indexed portion of the back reflection region of a powder diffraction photograph of one of the garnets is shown in Fig.7, p.44. Both the forward and the back reflection lines were measured on the film, and the shrinkage was calculated by the method described by Bijvoet (1951, p.29). Nine or ten values of 2 θ were calculated for each film and the lattice constants were calculated using the method of least squares (Azároff & Buerger, 1958, p.239-244). The least squares solutions were carried out on an I.B.M. Computer. Computer program for the calculation of lattice constants by the method of least squares was a personal communication from A. Frueh, Department of Geological Sciences, McGill University.

Accuracy of the Determined Lattice Constants:

In general the accuracy of powder diffraction photographs is very good, but there are several possible sources of error:

Figure 7.



Indexed portion of back reflection region of Powder Diffraction photograph of garnet.

1. The effect of temperature on the lattice constant. This source of error may be kept to a minimum by keeping the temperature constant during the course of the filming. In most of the determinations made in this study, the effect of changes in temperature is probably small, but in one or two cases where there was considerable difference between the values obtained in successive determinations, there may have been considerable changes of temperature.

2. Some error is almost unavoidable in the process of measuring the film, however with care and by repeating the measurements, errors from this cause may be kept to a minimum.

In order to test the accuracy of the method, several samples were filmed twice. A maximum variation of±0.002 was found, this was taken as the probable error.

4.10 SPECTROSCOPIC ANALYSIS

A rough quantitative determination of Mn and Cr was made by spectroscopic methods. The procedure used was a modification of the method for quantitative analysis of silicate rocks for major constituents, as set up in the Spectroscopic Laboratory of the Department of Geological Sciences, McGill University. The apparatus used was a Jaco 3-4 metre plan grating spectrograph.

Analytical Procedure:

Standards of the following concentrations were prepared:

MnO: 0.5%, 1.0%, 5.0%

Cr_2O_3: 1.0%, 5.0%, 10.0%

the garnet samples were mixed with lithium tetraborate and graphite. The lithium tetraborate was used as an internal standard. After the samples had been arced, the plates were developed, working curves were prepared in the usual way. The following analytical lines were measured: Mn 2801 Å, Cr 2835 Å, Li 2741 Å. Each sample was run at least twice as a check on the accuracy of the results. The analytical results are shown in Table 3, p.47.

Accuracy of the Determinations:

Due to the use of several grains of slightly varying refractive index in the preparation of many of the samples, the precision of the determinations is rather poor. The percentage of Mn found in all the samples showed a maximum deviation from the average value of ± 0.10, which is sufficiently accurate for the purpose required. In the case of Cr the deviation from the average is about ± 0.40.

TABLE 3

TABLE OF ANALYTICAL RESULTS FOR Cr AND Mn

Sample Number	% Cr	% Mn	Sample Number	% Cr	% Mn
OP-V	1.0	0.2	L7	2.0	0.4
OP2-O	1.5	0.25	MW	2.5	0.3
Br ex 2	0.5	0.4	GB	trace	0.3
L2A	1.5	0.25	3	0.7	0.4
KLP	1.0	0.3	4	0.85	0.35
KAF-O	1.0	0.3	5-r	4.0	0.35
KAF-V	2.8	0.2	5-V	3.5	0.4
JP	1.0	0.3	5-O	trace	0.45
LB-V	3.0	0.4	11-O	?	0.33
LB2-O	2.1	0.27	KS-13-O	0.5	0.4
BBK-O	0.3	0.4	16-O	0.8	0.6
FS	trace	0.4	16-V	3.0	1.0
Cl	2-4 ?	0.5	24-2	1.00	0.4
KP-O	trace	0.3	24-3	2.5	0.6
SL1	1.1	0.3	27-2	4.0	0.3
27-3	4.0	0.3	30	1.8	0.5
30-2	0.6	0.4	9-Y	0.5	0.4
			12	0.7	0.3

4.11 CHEMICAL ANALYSES

The compositions of garnets as determined by wet chemical analysis were compared with those derived by physical methods of analysis, as described previously in this thesis:

Only two wet chemical analyses were made as sufficient material was not available from other samples. The two garnets which were analysed are samples Kp and Mg (sample 46). Both analysed samples consisted of several grains of varying refractive index. All the grains analysed in each sample had the same colour and approximately the same colour density. The refractive index of the garnet of sample Kp varied from 1.743 to 1.755. The refractive index of garnets in sample Mg varied from 1.747 to 1.755. Due to the mixture of grains in the analysed samples, their compositions will only approximate that of any individual garnet in the samples.

The following is a brief outline of the method of determination of Fe_2O_3, by rapid chemical methods, as used in the Geochemical Laboratory of the Department of Geological Sciences, McGill University.

Part of the solution, containing the garnet is evaporated and the residue is dissolved in HCl, to which is added hexamethyleneamide. The resulting precipitate is dissolved in H_2SO_4, and to this solution is added amoniacle thioglycollic acid. The percentage of Fe_2O_3 is determined in the latter solution using a spectrophotometer.

The percentage of Fe_2O_3 determined by this method is too low for refractory substances such as garnet (personal communication, A. W. Hunslow, Department of Geological Sciences, Carleton University). A low determination of Fe_2O_3 would alter the calculated relative amounts of andradite and grossularite present. By comparison with the average composition of kimberlite derived by Tröger (1962, Table 5) the percentage of andradite in the analysis of garnet sample KP seems rather low, but in the case of garnet sample Mg it is about average.

TABLE 4

RESULTS OF CHEMICAL ANALYSES OF GARNETS

	Sample KP	Sample MG
SiO_2	41.51	41.02
Al_2O_3	22.93	22.75
Fe_2O_3	1.00	1.05
FeO	10.84	10.19
CaO	3.62	4.51
MgO	19.31	18.80
Na_2O	0.09	0.08
K_2O	0.01	0.01
P_2O_5	0.20	0.19
TiO_2	0.48	0.78
MnO	0.38	0.38
Cr_2O_3	tr.	tr.
TOTAL	100.37	99.76

Reduction of the percentages of the oxides given in Table 4 gave the following modal proportions, as set out in Table 5. The method of calculating the amounts of the different groups present from the chemical analyses is based on that outlined by Holmes (1921, p.396-402).

TABLE 5

END MEMBERS	GARNETS SAMPLE Kp % by Chemical anal.	 % by phys. anal.	 SAMPLE Mg % by chemical anal.	 % by phys. anal.
Pyrope	64.54	72.18	62.78	60.66
Almandine	23.89	19.32	23.23	27.56
Grossularite	7.06	?	9.15	7.40
Spessartite	0.83	0.70	0.83	no anal.
Andradite	0.17	7.80	3.22	4.38
Uvarovite	tr.	tr.	tr.	no anal.
Skiagite	3.15	-	3.72	-

For the purpose of comparison, the analyses of the two samples Kp and Mg derived by physical methods are shown on Table 5 along with the results derived from chemical analysis.

4.12 COMPARISON OF THE RESULTS OF CHEMICAL ANALYSES WITH THOSE FROM ANALYSES BY PHYSICAL METHODS

Chemical Analysis:

For reasons stated on page 57, the percentage of andradite is probably too low while the percentage of grossularite is proportionately too high.

Analysis by Physical Methods:

Garnet Sample Kp. The measured specific gravity was below the lowest calculated value and as a result no grossularite shows up in the physical analysis, this is probably incorrect. If one added say

3% of the grossularite molecule to the analysis, it would result in a decrease in the amount of andradite, a decrease in the amount of pyrope and an increase in the percentage of almandine. Bearing in mind these modifications there is a fair agreement between the analysis by chemical methods and that derived by physical methods.

Garnet sample Mg. The measured specific gravity for this garnet falls within the calculated range and the analysis by physical methods is probably reasonably accurate. This is borne out by a good agreement with the results from chemical analysis.

Conclusions:

Considering the comparison of the results of garnet analysis by physical methods and by chemical analysis, discussed in the preceding paragraphs, the author concluded that the result derived from a good analysis by physical methods is quite satisfactory. In garnet samples KP and MG, both the analysis by physical and by chemical methods fall in group XIV (Tröger, 1962).

Tröger (1962, p.663-693) divides the garnet family into paragenetic groups. Out of 700 garnet analyses, found in the literature, Tröger selected 480 as being satisfactory. Coordination of these garnets with the parent rocks produced 28 paragenetic groups, which are as a rule defined within narrow limits by a characteristic rock type. The following table is a reproduction of Table 5 (Tröger, 1962, p.669).

TABLE 6

GARNET FAMILY	GROUPS			
	XIV	IV	XVI	XVII
Pyrope	67½ ± 8%	49½ ± 12 %	43½ ± 7%	16½ ± 4%
Almandine	16½ ± 10%	24½ ± 9 %	38 ± 7 %	54 ± 6 %
Spessartite	½ ± ½ %	½ ± ½ %	1 ± 1%	3½ ± 3 %
Grossularite	2 ± 3%	22 ± 4 %	14 ± 6 %	20 ± 5 %
Andradite	4½ ± 4%	3 ± 3 %	3½ ± 4%	6 ± 4 %
Uvarovite	6 ± 3%	½ ± ½ %	0	0
Skiagite	3 ± 4 %	0	0	0

XIV 15 garnets from griquaites and kimberlites (anal. 191-205)*
XV 5 garnets from griquaites and kimberlites (anal. 206-210)*
XVI 14 garnets from eclogites (anal. 211-224)*
XVII 21 garnets from amphibolites and glaucophane schists (anal. 225-245)*

* numbers refer to analyses in Tröger's article (1962, p.676-683).

TABLE 7

RESULTS OF GARNET ANALYSIS

Garnet Family	KLP	KAF-O*	KAF-v	JP*	BBK*	BR2 ex.	L7*	SL1*	OP-v	OP-O*	BR-V*	L2A*	LB-V*
Pyrope	68.47	75.64	74.40	75.64	66.45	69.70	75.35	70.61	78.04	75.22	74.32	72.18	68.53
Almandine	14.18	11.06	6.62	11.06	21.86	16.66	8.02	13.06	8.93	14.01	15.57	10.55	6.41
Spessartite	0.68	0.68	0.43	0.68	0.90	0.89	0.84	0.68	0.50	0.59	-	0.57	0.81
Grossularite	7.64	?	1.68	?	?	1.68	?	?	2.03	?	?	?	?
Andradite	6.03	9.62	7.87	9.62	9.81	9.50	9.29	12.04	9.52	8.68	10.11	11.70	14.27
Uvarovite	3.00	3.00	9.00	3.00	0.99	1.60	6.50	3.60	1.00	1.50	?	5.00	10.00

	LB2-O	FS*	C1*	GB	MW	KP*	3*	4*	5-V	5-O	6*	8	11-O*
Pyrope	66.13	71.19	65.17	58.72	67.43	72.18	69.69	76.63	60.71	66.09	74.12	69.52	77.83
Almandine	12.48	16.73	13.16	27.64	12.23	19.32	16.69	6.67	13.97	22.93	13.48	18.40	9.19
Spessartite	0.56	0.90	1.09	0.70	0.64	0.70	0.88	0.78	0.80	1.10	?	?	0.80
Grossularite	6.06	?	?	3.85	1.82	?	?	?	6.47	8.54	?	1.86	?
Andradite	7.76	11.18	11.58	9.11	9.88	7.80	10.74	12.93	6.56	1.36	12.40	10.22	12.18
Uvarovite	7.00	? -	9.00	? -	8.00	?	2.00	3.00	11.50	tr.	?	?	4-13?

In garnets marked with an asterisk (*) the measured specific gravity is lower than either of the calculated values. In garnets marked with this symbol (#) the measured specific gravity is higher than either of the calculated values.

TABLE 7 (cont'd.)

Garnet Family	KS 13-V#	KS 13-0*	16-V	16-0*	24-2	24-3	24-5	26-2	26-3*	27-2*
Pyrope	62.37	76.69	62.88	70.11	36.61	49.91	30.54	53.77	71.78	64.69
Almandine	22.40	9.84	11.93	14.38	32.38	22.98	30.47	29.86	15.34	10.75
Spessartite	?	0.89	2.07	1.36	0.87	1.26	?	?	?	0.61
Grossularite	15.23	?	6.61	?	21.54	6.63	34.42	10.75	?	?
Andradite	-	10.98	6.52	11.55	5.62	9.23	4.56	5.62	12.88	10.97
Uvarovite	?	1.60	10.00	2.60	3.00	10.00	?	?	?	13.00

	27-3*	30-2*	30-1*	30	32-0	46	9-R*	32-V	9-Y	12
Pyrope	66.50	63.63	69.29	58.78	67.43	60.66	74.37	80.22	56.29	70.47
Almandine	8.67	11.09	15.83	13.73	17.91	27.56	11.58	10.44	25.54	14.40
Spessartite	0.61	0.88	?	1.13	?	?	?	?	0.89	0.69
Grossularite	?	?	?	16.73	5.68	7.40	?	2.81	15.70	1.57
Andradite	11.21	22.39	14.88	3.62	8.98	4.38	14.05	6.54	-	10.90
Uvarovite	13.00	2.00	?	6.00	?	?	?	?	1.60	2.00

The values of the garnet families, listed in the above table, for each garnet sample are in percentages.

Chapter 5

A REVIEW OF THE RESULTS OF THE GARNET ANALYSES

5.1 COMPARISON OF ANALYTICAL RESULTS

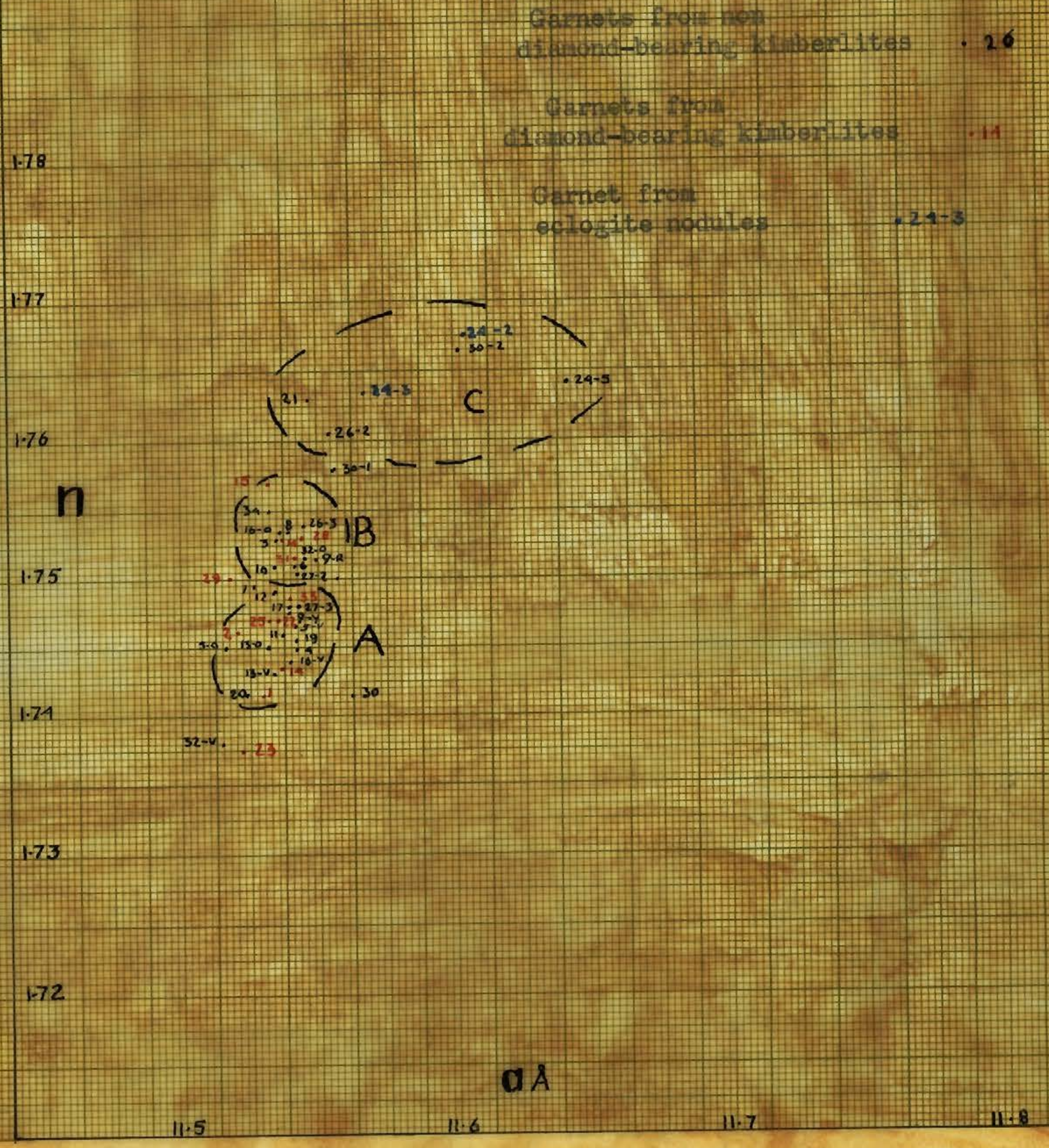
The analytical results may be compared in two ways: (1) The percentages of the garnet groups determined by the author for each sample are compared with the garnet groups of Tröger, given in Table 6, p.52, of this thesis. (2) The garnets are plotted on a graph, using lattice constants (a) as abscissae and refractive indices (n) as ordinates, see Fig. 8, p.56.

Most of the garnets analysed by the author fall into Tröger's group XIV (shown in Table 6 of this thesis). The percentage of andradite in most samples is considerably higher than the values given by Tröger for group XIV, this may be because the measured specific gravities, determined by the author, are too low. The inability to show the skiagite component on Fig.6 may also cause an apparent increase in the amount of andradite in the analyses. With the exception of garnet sample No.9, the precision of the measured specific gravities is good; the maximum deviation from the values listed in Table 7, pp. 53 and 54, is ± 0.03. Seven determinations were made on sample 24-5 and all fell within ± 0.02 of the value listed for this garnet on Table 7.

Due to the possible presence of cracks and microscopic inclusions in the garnet crystals, it is difficult to estimate the accuracy of the specific gravity determinations. By comparing the

Figure 8.

Graph of garnet distribution



measured specific gravities with the lowest values found for garnet samples on Fig.6, it appears that most of the measured values are too low by about 0.05, or less.

The result of raising the specific gravities would be to add about 3% of grossularite to the samples. The increase in grossularite would lead to a proportional decrease in the amount of andradite and pyrope and an increase in the amount of almandine. In the case of pyrope the change would be small, around 2%.

Garnet sample 24-2, which is from an eclogite nodule, falls into group XVI (Tröger), this garnet is probably derived from a disintegrated eclogite nodule (personal communication from G. Mannard).

Garnet sample 30. On graph Fig.8, garnet sample 30 falls somewhat outside group 'A' but in that general area of the graph. The high percentage of grossularite in garnet sample 30 puts it into group XV (Tröger), while from its position on graph Fig.8, it might be expected to fall into group XIV.

Garnet sample KS-13-V falls into Tröger's group XV in Table 6, p.52, and into group 'A' of graph Fig.8, p.56. The measured specific gravity of garnet KS-13-V is too high when compared with the highest specific gravity found for this sample on Fig.6. Lowering the specific gravity of sample KS-13-V by a maximum of 0.05 would not, however, make it fall into a group other than group XV.

The garnets in group XV appear to resemble those of the eclogite group XVI rather than those of the kimberlite group XIV (see Table 6, p.52). A possible explanation for the resemblance of kimberlite group XV with the eclogite group XVI, is that the garnets which fall into group XV may have originated in eclogites and may subsequently have been incorporated into the kimberlite. The high pressures connected with the formation of diamond in the kimberlite may have altered the composition of the eclogite garnets so that they approach the composition of those derived from kimberlite.

The garnets which were plotted on Fig.8, p.56, fall into two main groups, those derived from kimberlites and those derived from eclogites. The distribution of points on graph Fig.8 suggests that the kimberlite group might be divided into two sub-groups, A and B. The eclogite group is designated by the letter C. If more garnets were plotted on the graph Fig.8, the apparent gap between sub-groups A and B might be eliminated. It might be argued that instead of sub-groups A and B, the mean of the two should be taken as representing the average composition of the kimberlite garnets studied in this thesis. If a garnet, corresponding to the average composition of the combined sub-groups A and B, is plotted on graph Fig.8, it would fall in an area of the graph which does not represent the composition of any of the garnets studied in this thesis. Despite the fact that the average composition of sub-groups A and B does not correspond to that of any of the analysed garnets, a standard deviation could be worked out which would modify the average composition to include most kimberlite garnets. With reference to graph Fig.8, a mean refractive index of 1.75, with a standard deviation of ±0.009, would include in its range most of the garnets which are derived from kimberlites.

As an independent check on the validity of the division of the kimberlite garnets, analysed by the author, into sub-groups A and B, as on graph Fig.8, a Student's t-Test (Moroney, 1962, p.230) was performed on the two sub-groups. A value of 1.3 was found for t. This value is below the 5% probability level and thus there is probably no significant difference between the garnets of sub-groups A and B.

Since there is probably no difference between the author's sub-groups A and B, the average of the two sub-groups is taken as representing the average composition of the kimberlite garnets studied in this thesis. The average composition of sub-groups A and B is listed, along with Tröger's group XIV in Table 8. With the exception of the percentage of andradite, which is too high, the average composition of sub-groups A and B is in good agreement with the composition of Tröger's group XIV. As was explained on page 55, the high percentages of andradite found in the author's analyses are probably due to inaccuracies in the method of analysis. In order to complete the comparison of the different garnet groups, all the groups are listed on Table 8, p.60, and brief comparative description of the groups is presented in section 2 of this chapter. Finally, in section 3, the compositions of some garnets from the Zarnitsa kimberlite in Siberia are listed and compared with the composition of the African kimberlites.

5.2 COMPARISON OF SUB-GROUPS A AND B AND GROUP C WITH GROUPS XIV, XV AND XVI

SUB-GROUP A AND GROUP XIV

Sub-group A contains a higher percentage of pyrope than group XIV, the percentage of almandine in sub-group A is correspondingly lower. Sub-group B corresponds very closely to group XIV, except that in it the percentage of andradite is higher. However, as was explained on page 55, the high values found for the andradite molecule from analysis by physical methods is probably due to an inherent error in the system of analysis. Group C corresponds closely with group XVI except that the percentage of almandine in group C is lower.

TABLE 8

	A	B	C	D‡
Pyrope	71.50 ± 9	67.48 ± 7	44.93 ± 14	69.49 ± 9
Almandine	11.36 ± 9	15.90 ± 6	28.06 ± 5	13.63 ± 8
Spessartite	0.77	0.89	0.92	0.83
Grossularite	2.37	1.17	15.11	1.77
Andradite	8.85	10.50	6.68	9.68
Uvarovite	5.15	4.01	4.25	4.58
Skiagite	-	-	-	-

	XIV	XV	XVI
Pyrope	67½ ± 8	49½ ± 12	43½ ± 7
Almandine	16½ ± 10	24½ ± 9	38 ± 7
Spessartite	½ ± ½	½ ± ½	1 ± 1
Grossularite	2 ± 3	22 ± 4	14 ± 6
Andradite	4½ ± 4	3 ± 3	3½ ± 4
Uvarovite	6 ± 3	½ ± ½	0
Skiagite	3 ± 4	0	0

‡ D represents the average of sub-groups A and B.

5.3 A COMPARISON OF PYROPE GARNETS FROM THE ZARNITSA KIMBERLITES WITH THOSE FROM THE AFRICAN KIMBERLITES

Table 9 shows that the garnets from the Zarnitsa deposits are very similar to those from the African kimberlites. Most of the garnets from the Zarnitsa pipe correspond closely with those of group A. The absence of grossularite in analysis numbers 1, 2, 3, 5 and 6 casts some doubt on the validity of the conclusion that the percentages of grossularite determined by physical methods of analysis, for many of the samples in this thesis, is too low. However, the percentages of andradite, as determined by physical methods of analysis, definitely seems too high compared with the values given in Table 6, this being the case, the percentages of grossularite must be too low. The average percentage of the pyrope end member of the garnets from Zarnitsa, i.e. 72.46% ± 3.8 is higher than in Tröger's group XIV, i.e. 67½ ± 8, but the significance of the difference, if any, is not known.

TABLE 9

(After Smirnov (1959, p.28)

Sample Number	1	2	3	4	5	6	7	8
Pyrope	75.3	72.90	71.7	73.2	70.8	70.9	69.1	76.2
Almandine	10.0	12.9	10.8	14.1	13.4	13.1	18.6	13.4
Spessartite	0.30	0.3	0.7	0.3	0.3	0.3	-	-
Grossularite	-	-	-	2.0	-	-	5.2	5.4
Andradite	4.3	0.6	5.1	4.1	6.9	8.1	6.1	2.5
Uvarovite	7.2	11.8	11.3	5.2	4.1	1.6	1.0	1.5
Skiagite	1.9	1.0	0.4	-	2.4	0.3	-	-

TABLE 10

TABLE SHOWING THE GROUPS INTO WHICH THE ANALYSED GARNETS FALL

Garnet Sample	Tröger's Group	Author's Group	Garnet Sample	Tröger's Group	Author's Group
KLP	XIV	A	6-0	XIV	B
KAF-0	XIV	A	8-0	XIV	B
KAF-V	XIV	A	11-0	XIV	A
JP	XIV	A	13-V	XV	A
BBK	XIV	B	13-0	XIV	A
BR 2 ex.	XIV	B	16-V	XIV	A
L7	XIV	A	16-0	XIV	B
SL1	XIV	B	24-2	XVI	C
OP-V	XIV	A	24-3	XV	C
OP-0	XIV	A	24-5	XVI	C
BR-V	XIV	A-B	26-2	XVI	C
L2A	XIV	A	26-3	XIV	B
LB-V	XIV	A-B	27-2	XIV	B
LB2-0	XIV	A	27-3	XIV	A
FS	XIV	B	30-2	XIV	C ?
C1	XIV	B	30-1	XIV	B
GB	XV	C	30	XV	A
MW	XIV	A	32-0	XIV	B
KP	XIV	A-B	46	XIV	B
3	XIV	B	9-R	XIV	B
4	XIV	A	32-V	XIV	A
5-V	XIV	A	9-Y	XV	A
5-0	XIV	A	12	XIV	A

Chapter 6

RESULTS AND CONCLUSIONS

6.1 SUB GROUPS IN THE KIMBERLITE GARNET SERIES

From this study of the analytical data on the garnets, it is evident that the garnets from kimberlites can be divided into two main groups:

1. Those garnets genetically related to kimberlites.
2. Those garnets genetically related to eclogites.

The division of garnets from kimberlites, into two genetic groups, confirms the hypothesis of Mannard (1962, p.303-304, Figs. 109, 109a) who found that the garnets from the Shinyanga and Singida districts of Tanganyika fell into two genetic groups: (1) those derived from kimberlites, (2) those derived from eclogites.

There does not appear to be any correlation between groups XIV and XV (Tröger) and sub-groups A and B of the author. Some garnets in group XV fall in sub-group A, others in sub-group B. This suggests that the grouping of the kimberlite garnets into sub-groups A and B on graph Fig.8, p.56, is just fortuitous. The result of the Student's t-test referred to on page 59, confirms the view that there is probably no justification for making two sub-groups (A and B) out of garnets derived from kimberlites. Many of the garnets analysed by the author fell into Tröger's group XV, Table 6, p.52. The genetic significance of group XV is not clear, but it is tentatively suggested by the author that the garnets of this group may have originated in eclogites and may later have been incorporated in the kimberlite. The composition of the garnets might have been changed when they were incorporated with the kimberlite.

6.2 A COMPARISON OF PYROPE GARNETS FROM THE DIFFERENT KIMBERLITE PROVINCES

The pyrope garnets from the different kimberlite provinces of Africa, and also those from Siberia, are remarkably similar. The similarity of the garnets is reflected in the similar petrology of the kimberlites from the different provinces. No difference was found between pyrope garnets from diamond-bearing kimberlites and those from non diamond-bearing kimberlite deposits.

6.3 EVALUATION OF ANALYSIS BY PHYSICAL METHODS

The analysis of pyrope garnets by physical methods was first proposed by Ford (1915). Since then, the subject has been reviewed periodically and new methods have been developed, the latest method being that of Winchell (1958). To the author's knowledge, no practical work has been done, prior to this, to evaluate the results of analysis by physical methods.

From the results of the present study, it may be concluded that for practical purposes, analysis of pyrope garnets by physical methods is almost as good, and in the case where only small samples are available, possibly better, than analysis by chemical methods. From a practical point of view, analysis by physical methods has several advantages over wet chemical analysis:

1. Rapidity,
2. Low cost,
3. Determination can be made on small samples.

1. Rapidity. Using the method outlined in this thesis, an analysis of a garnet can be made in about eight man hours. By comparison, wet chemical analysis would take several times as long. By using algebraic equations as suggested by Levin (1950, p.285-286) in place of the diagram Fig.6 after Winchell, to obtain the composition of the garnets from the measured physical properties, and by programming the entire operation for an I.B.M. computer, the time for each analysis would be reduced to about four man hours.

2. Cost. The difference between the cost of analysis by physical methods and that by wet chemical analysis is very large. A wet chemical analysis would cost about $100.00, whereas an analysis by physical methods could be made at a cost of from ten to twenty dollars.

3. Sample size. At least one gram of sample is required for wet chemical analysis, whereas an analysis by physical methods could easily be made on a sample weighing 20 mgm. or even less with improved methods of specific gravity determination.

6.4 COLOUR OF GARNET AND ITS SIGNIFICANCE

Some standard method of reporting the colour of garnets is needed. The colour tends to vary to some extent with the thickness of the grains. The author proposes that the colour should be described from grains of approximately 0.1 mm. in thickness. Using this method, most grains of pyrope can be classified as either of two colours: (1) orange, (2) violet (or lilac). Some grains occur which are between orange and violet in colour, these might be classed as purple. Some grains also occur which are pale yellowish-orange in colour. Frequently the pale yellowish-orange coloured crystals are very shattered, and although no proof is offered, the yellowish colour may be due to the breaking up of the crystal rather than to any difference in composition from the normal orange coloured garnets.

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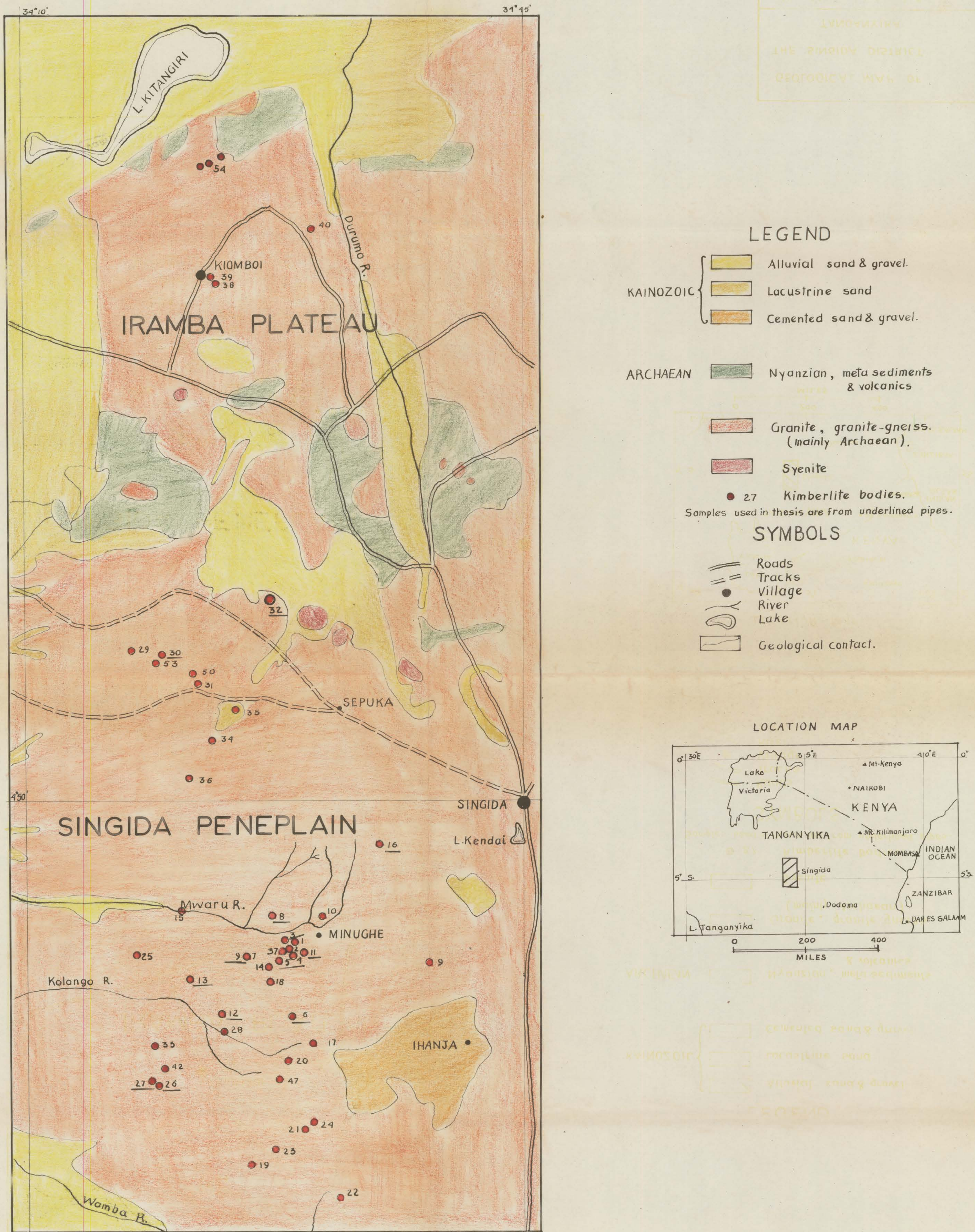
Figure 3.

SINGIDA DISTRICT

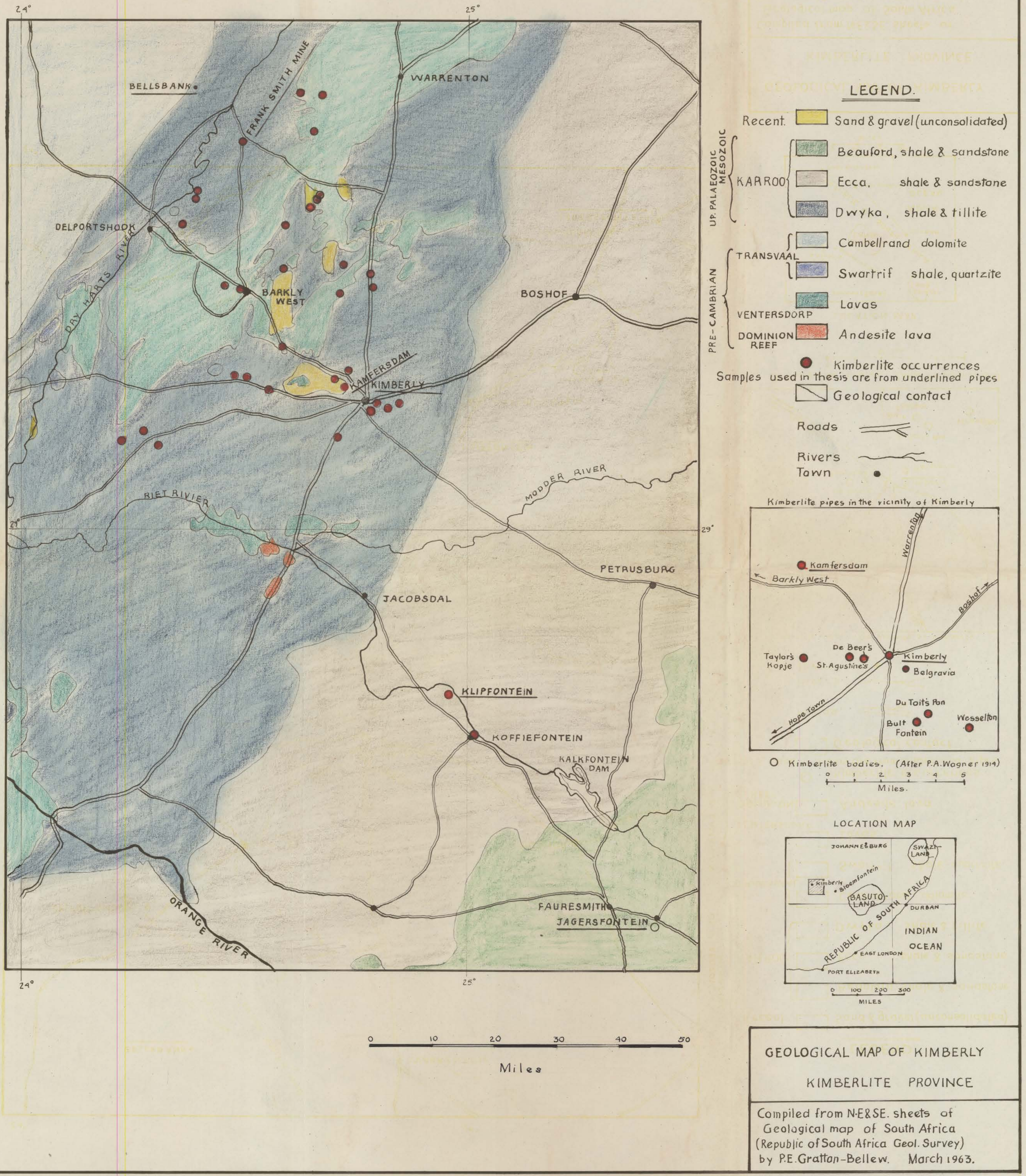


GEOLOGICAL MAP OF
THE SINGIDA DISTRICT
TANGANYIKA

After Mannard (1962) &
1:2,000,000 Geological Map
of Tanganyika (T.G.S. 1959)

Compiled by P.E. Grattan-Bellew
March 1963

Figure 5.



GEOLOGICAL MAP OF KIMBERLY

KIMBERLITE PROVINCE

Compiled from N.E & S.E. sheets of
Geological map of South Africa
(Republic of South Africa Geol. Survey)
by P.E. Gratton-Bellew. March 1963.

Figure 6.

Chart for correlation of physical properties with composition in the garnet group. (Modified after Winchell, 1958)