THE MINERALOGY AND CHEMICAL COMPOSITION OF GARNETS FROM THE SCHIST-COMPLEX OF NELLORE.

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The occurrence of almandite in the mica schists and in the accompanying rocks of Nellore is well known. For instance, King[1] has recorded that the eastern half of the schist-complex of Nellore includes many well-defined garnetiferous rocks the prominent one running from Saidapuram in the South, to Tummulatalappur in the North. He further noticed that the mica pegmatite masses of this area do not often contain garnets, in spite of their association with the garnetiferous strata. Since then, little systematic work has been done on these garnets except by Swaminathan,[2] who carried out the chemical analyses of some of the garnets from the pegmatite area near Saidapuram. At present, however, only one of his analyses[3] is available for study and it has been quoted in this paper for the sake of comparison. The present work deals with well-crystallised specimens of garnet obtained by the author from the Saidapuram-Tummulatalappur area mentioned above. Garnets from the typical mica pegmatites are not employed in this work.

Megascopic and Microscopic characters.—The characreristic form of these garnets is rhombic dodecahedron (110). Other forms like trapezohedron (211), and hexoctahedron (321) usual in garnet crystals are not often met with. Twinned crystals are rarely seen. Most of the individual dodecahedral crystals are more developed along one of the axes than along the other two, thus acquiring a more or less elongated form. The colour of these garnets is usually dark reddish-brown ; other colours are also met with.

The garnets studied include five different types which exhibit slight variations in colour and other physical properties and also in chemical composition. In some garnets, especially the striated ones, parting parallel to *d* (110) (Fig. 1), and *a* (100) (Fig. 2), is very distinct. The parting is so well developed that it could be easily mistaken for cleavage. Fracture is sub-conchoidal to uneven ; lustre, vitreous to resinous. Hardness varies from 7 to 7·5. All these specimens have nearly the same refractive index and specific gravity except for slight variations brought about

Partings in garnet

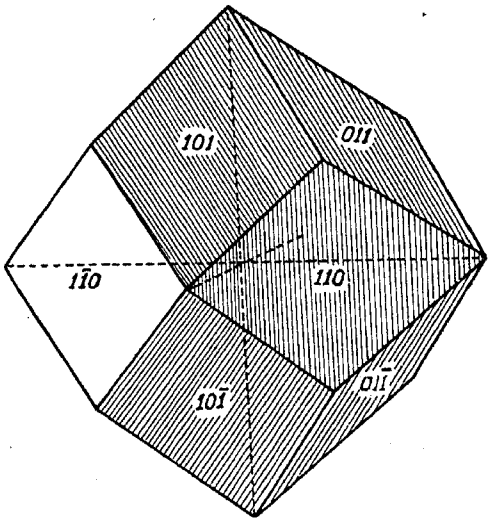

FIG. 1.
Parting parallel to *d* (110)

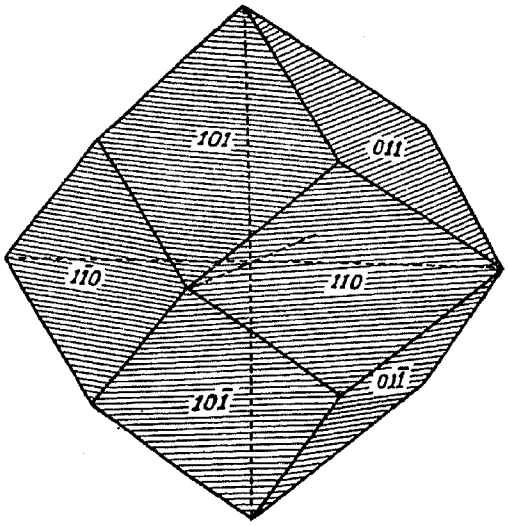

FIG. 2.
Parting parallel to *a* (100)

by the variation in composition. The striations often noticed on these granets, though very regular and prominent, are not true striations, because they indicate neither an oscillatory combination of forms nor are they the result of repeated twinning.[4] From the nature of the parting found only in these striated crystals, it is possible to conclude that these striations are only traces of the parting planes on the crystal faces. When examined visually, the crushed garnet reveals the presence of pink to brownish-red garnet grains along with clear white quartz and a shining black mineral. The megascopic and other characters of the various specimens examined are given in Table I.

TABLE I.

Specimens	A	B	C	A/1552	S
Colour ..	Dark brownish red tinged with pink	Pale dirty brownish red	Dark reddish pink to deep red	Similar to A but pink tint more pronounced	Similar to A but slightly darker
Transparency, etc.	Subtranslucent	.. Crystals present a granular appearance	Translucent to transparent	Subtranslucent	Substranslucent
Parting ..	..	..	Striations not very prominent. Parting planes not visible	..	Well striated. Highly developed parting planes
Sp. Gravity	4·007	3·938	4·008	3·895	4·000
Ref. Index	1·800	1·810	1·800	1·790	1·800

When a thin section of the mineral is examined in plane polarized light, it shows two kinds of inclusions, one of a transparent and colourless mineral and the other of an opaque, black mineral. A brownish-yellow film, probably of limonite, is invariably found in cracks and isolated patches in the garnet section. In some sections, however, one could see a few small crystals of pale greenish-blue tourmaline as inclusions which exhibit distinct pleochroism; *viz.*, pale greenish-blue parallel to O, and pale brownish-green parallel to E. The absorption is O > E. These crystals show negative elongation and straight extinction. Between crossed nicols all the inclusions, excepting the black ones, stand out prominently due to the dark background supplied by the isotropic garnet.

The Acicular inclusions.—When the garnet sections are examined under the microscope under low power, the main garnet mass is clear and pure, whereas under high power numerous needles of a doubly refracting mineral are visible. Such needles have not so far been reported to be present in the garnets of this area. Similar acicular inclusions were, however, observed by Holland[5] in the garnets of the Charnockite series, and subsequently also by Fermor[6] in a garnet from a pegmatite dyke in Biradavole (Nellore District).

On close examination these acicular inclusions show a great regularity of arrangement, lying almost parallel to a definite group of dodecahedral edges of the garnet, thus showing that they are oriented with some reference to the crystallographic habit of the garnet which encloses them. This feature reveals that sections taken parallel to any of the dodecahedral faces would show the same phenomenon and such was actually found to be the case. Further, this arrangement of the inclusions would imply that a section cut parallel to a dodecahedral face should reveal not only the parallel sets of needles referred to above, but in addition, the cut ends of the other groups of needles lying parallel to the other dodecahedral faces. These points, however, could not be detected under the microscope, even under very high powers. Nor could they be detected when the sections were examined between crossed nicols.

These needles are highly birefringent and show slight variations in optical properties between crossed nicols although they exhibit uniformity of shape and arrangement, *e.g.*, needles of almost all the parallel sets, excepting one, show straight extinction and have positive elongation. The needles of one set, however, show oblique extinction; the extinction angle is generally small, but occasionally, it is as high as 30°. Further, the needles differ in length in the various sets. The longer needles are found

to lie on the plane of the section whereas the short needles which exhibit oblique extinction are perhaps due to the tangential sectioning of a system of needles not lying in the plane of the section.

In sections cut parallel to the dodecahedral faces they form two definite parallel sets, the needles of one set intersecting those of the other at angles of approximately 70° and 110° respectively. Almost all the needles lie in the plane of the section and they are of almost equal length. They show straight extinction and are positive in character.

Sections cut parallel to the faces of the octahedron, show three sets of needles intersecting one another at an angle of 60°. A similar observation was made by Holland[7] in his investigations of the garnet from the Charnockites. Of these three sets of needles, two lie in the plane of the section and show straight extinction, but the third set which does not lie in the plane of the section gives oblique extinction. The needles of the latter set are shorter than those of the other two.

Sections cut parallel to the faces of the cube show two sets of needles of more or less equal length, intersecting each other almost at right angles. These two sets of needles show straight extinction and positive elongation.

Owing to the extreme fineness of these needles, it was not found possible to carry out a detailed microscopic study with a view to investigate their precise mineralogical nature, or optical properties. Hence it was not possible to study these needles in detail and compare them with those examined by Holland[7]. There is some evidence, however, to believe that these needles differ from those examined by Holland. He noticed in addition to the minute points of light representing the cut ends of the needles between crossed nicols that oblique extinction was more common and therefore concluded that the mineral was biaxial, whereas in the present study, straight extinction was more generally met with in all the sections. Further, these specimens possessed fewer sets of needles than those examined by Holland. The microscopic characters cited above—excepting for those needles which show slight oblique extinction—indicate them to be either sillimanite or rutile, as was suggested by Fermor[6] in his work on similar needles in the garnet specimen from Biradavole. This view was tested as follows: The titanium content of the entire garnet was first determined. Then the grains of the black mineral which were visible in the crushed garnet were separated and as it was suspected that they were ilmenitic, their titanium content was carefully determined. A micrometric estimate was also made of the percentage of the black inclusions in the entire garnet. The results are given in Table II.

TABLE II.

Specimens ..	M	N	O	P	Q
TiO_2 content ..	1·05	1·25	65·9	0·01	0·007 per cent.

Specimens M and N were two different crystals of garnet, and O was the black inclusions separated from M and N. Specimens P and Q were the residues of M and N after removal of O. The micrometric estimates of the black mineral in specimens M and N were roughly 1·6 and 1·9 per cent. respectively.

From these data, which are given in Table II, it appears obvious that all the titanium contained in the garnet was traceable to the presence of the black inclusions, thus suggesting that the acicular inclusions contained no titanium, and therefore could not be rutile. So these inclusions are probably sillimanite. The calculated mineral composition of these garnets (Table V) also supports this view as there is an excess of Al_2SiO_5 present in these garnets.

Other inclusions.—The black opaque inclusions[8] found in these garnets present sometimes a streaky and granular appearance suggesting replacement of some other mineral originally present in the garnet. Further, these inclusions are not affected by the parting planes present in the striated garnets.

The larger transparent inclusions are mostly quartz, but there is also present some white mica and tourmaline. The quartz crystals sometimes show corroded borders, but are usually rounded in appearance, although prismatic crystals are also met with. They range in size from very fine granules to considerably large crystals which can be easily seen even with the naked eye. Sometimes the quartz inclusions occur in such abundance that the garnet presents a more or less spongy appearance. These quartz crystals have no definite orientation and are not evenly distributed throughout the enclosing mineral. Further, these inclusions were seldom observed near the periphery of the garnet crystals.

The microscopic characters of the specimens taken for chemical analysis are shown in Table III.

TABLE III.

Specimens	A	B	C	A/1552	S
General appearance	Free from cracks	Granular and traversed by numerous cracks	Specimen appears to be purer than the others	Similar to A and C	Similar to A but the limonite films are more pronounced than in the other garnets
Inclusions :					
(*a*) Acicular	Acicular inclusions present	Similar to A	Acicular inclusions visible only under very high power	Similar to A	Similar to A
(*b*) Other types	The quartz inclusions are rounded in shape. A few minute inclusions of a black opaque mineral resembling ilmenite are also met with	Similar to A, but the amount of quartz is more than in the other specimens. A few minute inclusions (not acicular) of rutile are present in addition to the black inclusions	Similar to A, Black inclusions are present, but not so abundant as in A	Similar to A	Similar to A. A few minute crystals of tourmaline are also noticed
Colour ..	Pale pink	Similar to A, but deeper and tinted yellow	Same as A	Pale pink to colourless	Similar to A, but darker
Parting planes	Absent	Absent	There is an incipient development of the parting planes	Absent	The parting planes are very regular, appearing as well-developed parallel cracks
Micrometric estimates of the constituent minerals in the specimens.					
Garnet ..	= 95	87	96	94	94 per cent.
Quartz ..	= 3	10	2·5	4	4 ,, ,,
Ilmenite ..	= 2	3	1·5	2	2 ,, ,,

Methods of chemical analysis.—The material for chemical analysis, determination of specific gravity, and also for preparing sections was taken from the same specimen. Separate crystals were, however, used to estimate the rare earths, alkalies and beryllium.

The complete analysis of the various specimens was carried out as follows. The finely powdered specimen was fused in a covered platinum

crucible with nearly four times its weight of a mixture of the anhydrous carbonates of sodium and potassium in the ratio of 3 : 1. Other fluxes were not so effective. The mineral was completely decomposed in about 45 minutes.

The cooled melt in all the cases was bluish-green revealing the presence of manganese. The melt was dissolved in HCl, and the silica and the other oxides like Al_2O_3, Fe_2O_3, CaO and MgO were estimated in the usual manner, calcium being precipitated twice as oxalate to effect complete separation from magnesium as these two were present in more or less equal quantities. Titanium and magnanese were determined colorimetrically.

Alkalies.—After careful testing of the reagents, three Lawrence Smith fusions were carried out on separate portions of the mineral for determining the amount of alkalies present. These garnets were, however, found to be practically free from alkalies, containing probably less than 0·01 per cent.

Ferrous iron.—The hydrofluoric acid method of Pratt, modified by Hillebrand,[9] was followed with slight modifications. The method was found to be very reliable when worked with standard ferrous sulphate solution. No appreciable change in the result was noticed even after heating the solution for a long time on the water-bath in an atmosphere of steam and CO_2. The error in the determination due to the divalent manganese present was negligible.

Rare earths.—Search for the rare earths was made in the usual manner by oxalate precipitation from a sulphuric acid solution of the mineral. A minute trace of rare earths was detected in specimen A.

Beryllium.—Test for beryllium was carried out by using the organic indicator quinalizarin (tetrahydroxy-anthraquinone). A minute trace of beryllium was also detected in specimen A.

The results of the chemical analyses are given below in Table IV. The figures under specimen X are those given by Swaminathan.[3] Specimen Y is obtained from A by removing most of the inclusions by magnet and a heavy liquid (methylene iodide). Specimen Z is obtained from A/1552 after removing all the black inclusions by magnet.

TABLE IV.

Garnets	A	B	C	A/1552	S	Y	Z	X
SiO_2 ..	38·90	42·99	39·02	39·85	39·55	38·40	39·90	36·10
Al_2O_3 ..	22·66	20·38	21·18	21·07	23·43	21·90	21·20	21·57
Fe_2O_3 ..	nil	nil	1·27	0·08	2·44	0·22	0·30	27·78
FeO ..	26·69	25·82	26·83	26·36	25·60	27·84	25·50	4·24
TiO_2 ..	1·05	1·46	1·07	1·25	0·92	0·14	0·007	0·48
MnO ..	0·25	0·09	0·11	0·03	0·21	0·26	0·03	trace
CaO ..	6·37	6·23	3·47	5·80	3·19	6·89	5·85	5·86
MgO ..	4·25	2·23	6·30	5·58	4·69	4·60	5·60	3·92
Loss on ignition	0·12	0·12	0·16	0·11	0·06	..	..	..
Total ..	100·29	99·32	99·41	100·13	100·09	100·25	98·39	99·95

The specimen X analysed by Swaminathan reveals a preponderance of ferric iron over ferrous iron whereas in the specimens employed for this work, the reverse is always the case.

The results given in Table IV show that these specimens vary in chemical composition. This is due to fluctuations in the distribution of the individual types of garnet and also of the inclusions. These factors afford an explanation for the variations in colour and other physical properties observed in different specimens.

The amount of silica present varies from 36 to 43 per cent. roughly as is usual in such garnets. But when the results are converted into garnet molecules (Table V) all the analyses show an excess of silica and alumina. This alumina is expressed as $Al_2O_3SiO_2$ and any silica left over is expressed as quartz. All of them except specimens A and B, show the presence of ferric iron, which is due partly to the limonite present in the mineral and partly also to a slight oxidation of the ferrous iron during the determinations. The ferric iron is, therefore, expressed as ferrous iron and excess of oxygen (Table V). Specimen B shows a relatively high percentage of

TiO_2 which is probably due to small isolated grains of rutile in addition to the ilmenite present in all the specimens.

The percentage amounts of minerals present in the specimens are calculated as usual from the results given in Table IV. Table V presents the mineralogical compositions of these garnets. These results agree with the micrometric estimates which were carried out in a few cases. The percentage of sillimanite in Table V obtained from chemical data is much higher than that from microscopic evidences. Further work is necessary to elucidate this anomaly.

TABLE V.

	Garnets	A	B	C	A/1552	S	Y
Garnet proper	Spessartite ..	0·50 (0·55)	0·17 (0·21)	0·25 (0·28)	0·05 (0·06)	0·50 (0·57)	0·50 (0·51)
	Pyrope ..	14·10 (15·47)	7·50 (9·25)	21·10 (22·63)	18·76 (20·22)	15·68 (18·03)	15·41 (15·54)
	Almandite ..	59·39 (65·16)	56·72 (69·94)	62·55 (67·09)	58·31 (62·85)	62·22 (71·53)	64·72 (65·27)
	Grossularite ..	17·16 (18·82)	16·71 (20·60)	9·33 (10·00)	15·66 (16·87)	8·58 (9·87)	18·52 (18·68)
	Total pure garnets	*91·15* (100·00)	*81·10* (100·00)	*93·23* (100·00)	*92·78* (100·00)	*86·98* (100·00)	*99·15* (100·00)
Other constituents	Sillimanite ..	4·64	4·86	1·73	1·30	7·45	0·76
	Quartz ..	2·36	10·65	2·52	3·60	3·72	0·32
	Loss on ignition calculated as H_2O ..	0·12	0·12	0·16	0·11	0·06	..
	Ilmenite* ..	2·13	2·74	1·98	1·98	1·82	0·25
	O_2 ..	..	..	0·13	0·01	0·24	0·02
	Total ..	100·40	99·47	99·75	99·78	100·27	100·50

* The black mineral observed under the microscope is assumed to be Ilmenite as its real constitution is not yet fully known. Figures within brackets indicate the percentage amounts of the respective garnets in the total garnet.

In all these specimens the garnet mass is an isomorphous mixture of four types, *viz.*, almandite, pyrope, grossularite and spessartite, the amount of spessartite however being very low. Comparison of the data given in Table I with those specimens given in Table V indicates that in specimens containing large amounts of almandite, the intensity of the pink tint noticed visually varies with the amount of pyrope present in them. This observation helps us to explain the intense rose colour of rhodolite garnet which is known to carry large amount of pyrope. Observations of the sections under the microscope, however, indicated that the intensity of the pink colour of the section (Table III) varied with its almandite content.[10]

These garnets possess the accepted constitution as can be seen from Table VI where their chemical compositions are expressed in terms of the molecular ratios $3RO : R_2O_3 : 3SiO_2$.

TABLE VI.

Specimens	3RO	R_2O_3	$3SiO_2$
A ..	2·74	1	2·92
B ..	2·73	1	3·59
C ..	2·97	1	3·09
A/1552	2·99	1	3·21
S ..	2·50	1	2·87
Y	2·93	1	2·99

The above ratios show a fair agreement with the theoretical requirement 3 : 1 : 3, but most of them show an excess of R_2O_3 group as well as of silica. This excess over the normal ratio is accounted for as stated earlier by the presence of sillimanite on the one hand, and of quartz on the other.

Discussion.

The chemical composition of garnets has been plotted by Fermor[11] in a diagram which shows the general relationship between their mode of occurrence, composition and mutual relationship. In Fig. 3, the percentages of the various individual garnets occurring in each specimen are plotted in a straight line parallel to the Y axis, and the points so obtained

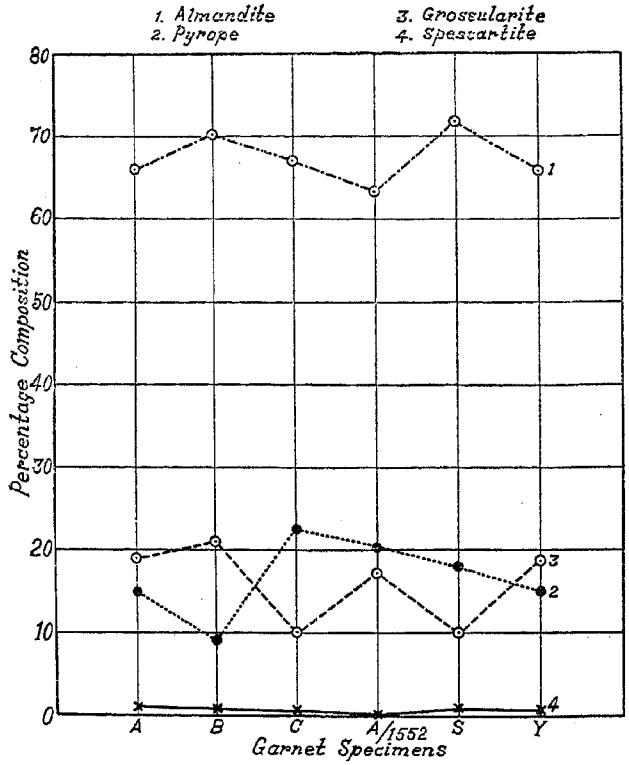

FIG. 3.
Diagram showing the composition of the garnets.

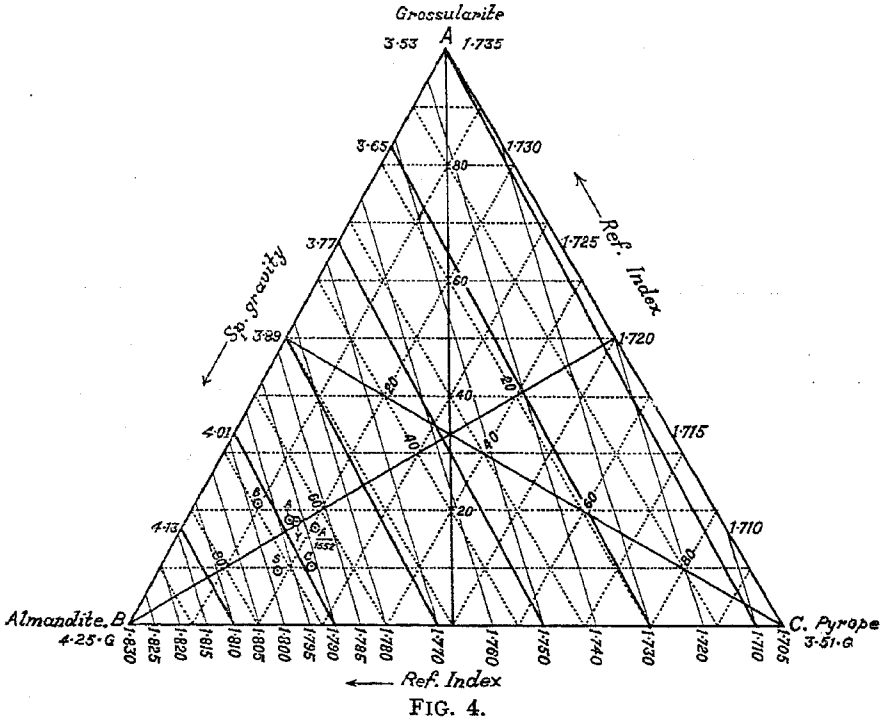

FIG. 4.
Diagram showing the relationship existing between chemical composition, sp. gr. and ref. index of these garnets.

for each are joined by straight lines. This diagram shows the abundance of each garnet in the various specimens thereby revealing their mutual relationship. The curves do not show marked fluctuations from the horizontal and therefore indicate that these garnets belong to a definite and single series, ranging from the pyralmandites proper to the Calc-pyralmandites. These curves when transposed on to the diagram of Fermor suggest that these garnets occur either in argillaceous crystalline schists or granite-pegmatites which intrude into the former. This suggestion is in conformity with the results given in this paper.

The composition of these garnets can also be plotted in a triangular diagram as has been done by Ford.[12] In Fig. 4, the garnet molecules of the three main types met with in this work, *viz.*, pyrope, almandite, and grossularite, are represented at the three corners of an equilateral triangle and their specific gravities and refractive indices are also indicated. The three meridians are divided to show the relative abundance of the three types composing the total garnet. The heavy lines show specific gravities, while the thin lines show the refractive indices. Each of the six circles, B, A, Y, etc., shown in the diagram represents the relative abundance of the three types of garnet in the corresponding specimens examined.

It is seen from the diagram that all the six circles lie between two of the refractive index lines, *viz.*, 1·800 and 1·785 and between two of the specific gravity lines, *viz.*, 3·95 and 4·05. The refractive indices obtained from this triangular diagram are in close agreement with those of actual determinations. The location of the points which indicate the composition of the garnet mass reveals the complete isomorphism of almandite and pyrope on the one hand, and almandite and grossularite on the other. It also indicates that isomorphism between pyrope and grossularite could exist when almandite is present to a large extent, and not otherwise.

Summary.

Specimens of garnet from the mica schist of the Nellore area have been examined by physical, chemical and optical methods. The following conclusions can be drawn from the results obtained :—

1. There is considerable variation in the properties, both physical and chemical, among the specimens examined. Each specimen has been found to comprise a mixture of four types of garnet, *viz.*, almandite, pyrope, grossularite and spessartite, the proportion of the last named being very small.

2. The abundance ratios of the four types of garnet vary among the specimens examined. This offers an explanation for the variation in colour and other physical properties among the specimens.

3. The inclusions noticed visually in the garnet specimens consisted of quartz, and ilmenite, and these were found to be present in different amounts in the specimens examined. The variations in the colour and other physical properties in the specimens were also traceable to this cause. Careful microscopic examination revealed the presence of acicular inclusions in all the specimens, but to different extents. These acicular inclusions appear to be sillimanite and not rutile.

4. The composition of the garnets studied have been plotted in a triangular diagram which expresses the relationship between composition, specific gravity and refractive index of garnets.

5. The composition of these garnets have been plotted in a diagram, which shows the mutual relationship of these garnets.

In conclusion, the author wishes to express his grateful thanks to Dr. K. R. Krishnaswami, for his keen interest and constant encouragement in the course of the work as well as for guidance in conducting the chemical analysis of these garnets, and also for much helpful criticism in the preparation of this paper. His grateful thanks are also due to Sir C. V. Raman for affording facilities to carry out the microscopic examination of these garnets, and to the Director of the Geological Survey of India for the gift of a specimen from the Nellore area.

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