The miscibility of the pyralspite and grandite molecules in garnets

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Summary. Though the transitional members between the pyralspite and grandite series occur only very sporadically, there exists under favourable conditions a perfect miscibility between grossular on the one hand, and spessartine or almandine or pyrope on the other. The conditions favouring this miscibility are discussed.

BASED on all the garnet analyses available, Boeke constructed in the year 1914 a diagram showing the participation of different end-members in the composition of garnets. In this diagram a broad gap is visible between the grossular–andradite and the pyrope–almandine–spessartine series pointing to a restricted miscibility between these series. Pyralspites with a grandite content of more than 35 mol. % and grandites having more than 35 mol. % pyralspite were not encountered. Since then, however, as garnet analyses grew in number, garnets have been found falling in this composition gap. Nowadays it may be said that there exist, even if only under special conditions, continuous transitional series to grossular from spessartine or almandine as well as from pyrope. The number of such garnet analyses, though not considerable (about 2 % of all published garnet analyses), enables us to reach some conclusions on the conditions of the origin of these garnets with unusual composition, which is the object of the present paper.

Table I lists all the reliable analyses taken from the literature accessible to the present author concerning garnets, the calcium component of which falls within the limits of 35 and 65 mol. % together with recalculations to molecular percentages of the end-members. Garnets displaying unusual constituents, such as calderite, blythite, and others were not included. The description of the occurrences of the garnets under consideration follows the sequence of facies they belong to.

The pyroxene-hornfels facies. From the Victory mine, Gabbs, Nevada, Lee (1962) published data on garnets (nos. 1 to 3) with dominant grossular and spessartine; these garnets occur in a rock designated by

TABLE I. Analyses of garnets containing 35 to 65 mol. % ugrandite

No.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	36·84	36·22	36·52	38·0	36·73	37·57	37·84	38·16	36·88	37·39	36·3	37·91
TiO_2	tr.	0·28	0·18	0·18	—	—	0·42	0·05	0·25	0·91	0·4	0·15
Al_2O_3	19·78	21·96	20·74	20·2	15·71	18·98	18·52	17·45	18·22	17·28	22·2	18·73
Fe_2O_3	2·44	0·64	1·07	1·3	7·20	3·47	3·38	4·55	3·12	4·94	4·6	2·66
FeO	5·49	4·58	5·72	18·0	19·02	7·45	8·68	10·10	23·87	14·09	23·6	26·46
MnO	12·02	15·63	19·66	8·9	9·34	16·50	7·62	15·57	0·78	2·91	0·7	0·81
MgO	tr.	—	tr.	1·1	0·17	0·23	0·02	0·35	1·67	0·41	1·5	0·90
CaO	23·68	20·43	16·25	12·2	12·06	15·80	21·22	13·04	14·94	22·89	10·9	13·09
Sum	100·25	99·74	100·14	99·9	100·23	100·00	100·05	99·38	99·73	100·82	100·2	99·95
a (kX)	11·77	—	11·72	11·66	—	—	—	—	11·66	11·70	11·60	—
Molar percentages of end-members												
Andradite	7·5	—	2·5	4·5	22·6	10·6	10·5	13·9	9·5	17·8	16	8·5
Grossular	55·8	55·8	42·1	30·5	12·4	34·5	51·8	24·8	31·6	44·6	20	28·4
Almandine	11·5	10·9	12·8	40·7	42·9	16·6	19·9	23·4	50·8	29·9	56	57·9
Spessartine	25·2	33·3	42·6	20·0	21·5	37·3	17·7	36·3	1·8	6·2	2	1·7
Pyrope	—	—	—	4·3	0·6	1·0	0·1	1·6	6·3	1·5	6	3·5

1, 2, and 3. Gabbs, Nevada, in feldspathized granodiorite with scheelite, diopside, and phlogopite (scheelite skarn ?) Lee, 1962.

4. Cazadero, California, in aragonite-bearing glaucophane schist. Lee *et al.*, 1963.

5. Gavia, Ortler, Alps, in pegmatitic orthogneiss. Emiliani and Pirani, 1959.

6. Kotakarra, Vizagapatam, Madras, in kodurite. Lee, 1962 (anal. Godbole).

7. Bastjärn, central Sweden, in manganese skarn. Also Na_2O 0·30, K_2O 0·98, H_2O^+ 0·21, CO_2 0·79, F 0·12. Magnusson, 1940 (anal. Berggren).

8. Fornäsfältet, central Sweden, in manganese skarn. Lindroth, 1919.

9. Mezilesí at Měděnec, Krušné hory, Czechoslovakia, in garnet skarn. Anal. Červená.

10. Kadov, western Moravia, in garnet skarn. Anal. Červená.

11. Hammerunterwiesenthal, Krušné hory, Czechoslovakia, in amphibolite. Lange, 1964 (anal. Volle and Kreher).

12. Ukraine, in diopside-plagioclase gneiss. Also Na_2O 0·13, K_2O 0·02, H_2O^+ 0·07, H_2O^- 0·02. Usenko, cited in Sobolev, 1964.

TABLE I—*continued*

No.	13	14	15	16	17	18	19	20	21	22	23	24
SiO_2	38·88	38·20	37·10	36·91	38·26	38·4	40·70	40·76	41·95	40·04	41·60	41·06
TiO_2	0·75	0·24	0·18	0·22	0·00	0·26	0·34	0·30	0·19	0·34	0·10	0·18
Al_2O_3	20·05	19·45	21·14	19·24	19·93	20·7	20·41	22·76	22·20	22·06	22·28	23·45
Fe_2O_3	1·15	1·98	0·51	5·04	4·87	1·3	0·80	1·71	1·93	2·22	2·77	1·80
FeO	21·81	20·51	21·32	19·58	20·40	22·7	8·02	7·86	12·18	8·58	5·80	5·02
MnO	1·84	1·10	0·50	0·42	0·04	0·57	0·15	0·27	0·26	0·56	0·22	0·16
MgO	1·12	2·30	1·91	1·93	3·94	2·5	4·58	10·57	6·55	7·52	7·01	12·03
CaO	13·68	16·07	17·13	16·61	12·02	13·7	23·57	15·85	14·88	18·50	19·92	16·16
Sum	99·56	99·85	99·79	99·95	100·06	100·1	100·32	100·08	100·16	99·88	99·78	100·01
a (kX)	11·64	—	—	11·67	11·58	11·62	—	11·63	11·62	11·65	11·66	11·62
Molar percentages of end-members												
Andradite	2·5	5·9	1·3	12·8	7·5	4·5	2·4	1·5	—	2·8	—	—
Grossular	37·8	35·0	43·0	34·1	26·9	34·2	62·5	40·6	42·6	46·8	54·6	42·2
Almandine	50·7	47·0	47·1	44·4	50·0	50·3	17·2	18·5	30·9	20·5	17·5	13·5
Spessartine	4·3	2·6	1·0	1·1	—	1·3	0·3	0·7	0·7	1·4	0·3	0·3
Pyrope	4·7	9·5	7·6	7·6	15·6	9·7	17·6	38·7	25·4	28·3	27·1	44·0

13. Kiachta, Buriat region, in diopside–plagioclase gneiss. Also H_2O^+ 0·12, H_2O^- 0·06. Khlestov and Ushakova, 1963 (anal. Zinchuk).

14. Giga river, Aldan, in diopside–plagioclase gneiss. Moskhin, 1962.

15. Povla river, Aldan, in calciphyre. Moshkin, 1962.

16. Liserschlucht, Spital, Carinthia, in fissures in a pseudoeclogite. Heritsch, 1933.

17. Russian River, California, in an actinolitized glaucophane-bearing eclogite. Also H_2O^+ 0·12, H_2O^- 0·48. Pabst, 1931.

18. Cazadero, California, in eclogite. Lee *et al.*, 1963.

19 to 23. Zagadochnaya, Yakutsk region, in a kyanite eclogite. In 19, also Na_2O 0·73, H_2O^+ 1·02; in 21, also Cr_2O_3 0·02; in 22, also Cr_2O_3 0·06; in 23, also Cr_2O_3 0·08. Sobolev *et al.*, 1966.

24. Obnashennaya, Yakutsk region, in a corundum eclogite. Also Cr_2O_3 0·05, Na_2O 0·03, K_2O 0·07. Sobolev and Kuznetsova, 1965.

Lee as a feldspathized granodiorite, which was subject to mylonitization. Garnet in it is accompanied by scheelite, fluorite, diopside, and phlogopite, this assemblage being called by Lee a high-temperature one. According to this description the rock in question might perhaps be taken as a rock of the skarn type. In fact, the scheelite skarns are known (cf. Karpova and Ivashchentsov, 1954) to contain garnets mainly of the grossular type, which are sometimes rich in spessartine. Thus, e.g. in a grossular from the scheelite skarn at Dchenitschke, Central Asia, analysis no. 2279 of Morkovkina's compilation, 1964, the share of the spessartine and almandine moles is 31 %, which already approaches our limit concentration. The garnets described from Gabbs represent perhaps the extreme case of an otherwise current enrichment of scheelite skarn grossulars by manganese. This enrichment, however, is of such a type that in one garnet sample (no. 3) the pyralspite molecule is even prevailing.

The glaucophane schist facies. From the Californian coast ranges one garnet analysis falling chemically within the limits stated by us is reported by Lee and others (1963) from a glaucophane-bearing rock of the metacarbonate type (type III E of Coleman and Lee, 1963). This peculiar rock appears as narrow beds, lenses, or veins within metabasalt glaucophane rocks, having undergone the metamorphism along with them. It is very rich in calcium carbonate, the dominant phase being aragonite. In addition to this, further constituents of the rock, from which garnet no. 4 was recovered, are quartz, glaucophane, muscovite, pyrite, and lawsonite. The garnet is grossular–almandine–spessartine. Lee *et al.* (1963) give also garnet analyses from other glaucophane-bearing rocks (metabasalts, metacherts, meta-ironstones); they are all of similar character, showing a preponderance of almandine, a high share of spessartine (17 to 61 mol. %), and grossular mostly exceeding 25 %. These garnets evidently are bound by a continuous series with normal almandines and spessartines. Our sample no. 4 represents an extreme case of their common enrichment by the Ca-constituent, attaining closely the selected limit of 35 mol. %.

The almandine-amphibolite facies. Regionally metamorphosed pegmatites. From Gavia, Ortler, Alps, Emiliani and Pirani (1959) give an analysis of a garnet (no. 5) consisting mostly of the almandine, spessartine, and andradite molecules. They call the rock from which it was recovered a pegmatitic orthogneiss. The coarse grain size (the garnet attains as much as 2 cm in diameter) as well as some rock constituents (schorlite) make it evident that the rock under consideration was originally a pegmatoid igneous rock. This rock contains predominantly quartz, feldspar, and muscovite. The high share of almandine–spessartine moles encountered in garnet no. 6 is no surprise, for manganese is one of the elements typical of the crystallization of residual granite magmas. These magmas, however, are very poor in calcium and consequently the garnets of corresponding parageneses (i.e. types I and II of Tröger's compilation, 1960) are extremely low in the grandite component. Emiliani and Pirani (1959) are surely right when pointing to the possibility of a material mobilization having taken place in the rock in the course of its epizonal tectonic metamorphism. From the data they give no picture can be drawn, however, of the character of this mobilization, especially as concerns a possible import of Ca. As shown by the analyses of further garnets from the same rock, there exists a gradual transition from garnet no. 5 to almandines and spessartines that are essentially calcium-poorer (28·0, 20·9, 15·5 mol. %). Nevertheless, their grandite component is still too high for the paragenetical type, so that the garnets under consideration are exceptional and quite peculiar in their chemical composition.

Regionally metamorphosed manganese ores and manganese skarns. Among different Mn-garnets of unusual composition, which originated through metamorphism of Mn-ores in India, Fermor (1925) described a garnet, the analysis of which is given in table I, no. 6. Spessartine and grossular are its main constituents. Its parent rock is a kodurite, an archean orthogneiss consisting mainly of potassium feldspar, spandite, and some other manganese-rich minerals, such as Mn-amphibole, knebelite, Mn-magnetite, and rhodochrosite. This rock probably arose through resorption of manganese sediments by a granite rich in potassium, which afterwards was converted to an orthogneiss. The origin of garnet no. 6 was evidently conditioned by the high manganese content of these rocks (about 10 wt. % MnO, on the average), which also called forth the crystallization of a special manganese garnet, called by Fermor spandite. It contains blythite and calderite molecules as its essential constituents (the presence of these constituents in the garnets of this type was confirmed by new analyses—cf. Sastri, 1963). The paragenesis discussed is of such exceptional character in its geochemical features that the number of garnet analyses available from it up to the present is insufficient to establish the relation of the garnets similar to no. 6 to the spandites.

Two garnets listed in table I are grossular–almandine–spessartines. They originate from the manganese-rich skarns of Central Sweden, which are taken for original Mn-rich sediments, having later been deeply regionally metamorphosed. No. 7 comes from the Bastnäs mine, being probably a constituent of a garnet–biotite skarn. This skarn type developed there at the contacts of manganese skarns, consisting mostly of Mn-knebelite and Mn-grunerite, with leptites, as a product of their mutual chemical exchange (Magnusson, 1940). The paragenesis mentioned can be inferred from the unusual high potassium content given by the analysis. This potassium was for the great part probably introduced in the garnet as mica impurities, a fact that might reduce the value of this analysis. The second sample (no. 8) originates from another manganese skarn locality, Fornäsfältet. According to Lindroth (1919) these grossulars and spessartines in Swedish skarns are commonly derived through regional metamorphism from manganese-rich limestones. As follows from further analyses given by the same author, this garnet type is connected by continuous transitions with normal almandines and spessartines.

Regionally metamorphosed iron-ore skarns. The occurrence of grossulars and almandines is one of the most typical features of metamorphosed skarns of the Bohemian Massif (Němec, 1967*a*, *b*). The genesis of these rocks is not yet completely elucidated. They are probably of high-temperature metasomatic origin, afterwards regionally metamorphosed under abyssal conditions. Pyroxene (sahlite or ferrosalite) and garnet are dominant constituents, amphibole being present only in subordinate quantities. These rocks appear in the Krušné hory Mountains and in the Bohemian–Moravian Highland. In the first-named area the grossulars and almandines were encountered only seldom (from this area comes sample no. 9, which formed a monomineralic garnet skarn; see also p. 402). In contradistinction to this area, grossular–almandine represents the most common garnet type occurring in the garnet skarns of the Bohemian–Moravian Highland, even though not all these garnets possess the grandite component in such a share as to fall within the limits selected by us. The distribution of their lattice constants in a great number of garnet samples suggests that there exists a continuous series leading from grossular to almandine. The grossular section seems to be better represented by the data. In the intermediate members, as well as in those approaching almandine by their composition, the share of the spessartine molecule is raised (cf. no. 10), attaining 25 mol. % in one sample from a skarn of the Bohemian–Moravian Highland. The grossulars and almandines from the metamorphosed skarns of the Krušné hory Mountains are distinctly poorer in manganese.

Garnet amphibolites. Among all the garnets analysed from amphibolites listed in the literature so far known to me, only one sample (no. 11) falls by its composition within the range interesting us. This garnet was recovered from an amphibolite intercalation in limestones (Lange, 1965). In addition to garnet the rock under consideration contains amphibole and altered plagioclase as major constituents and calcite as a minor one. In origin it is a metamorphosed basic igneous rock. The garnet is an almandine–grossular–andradite. Six further garnets analysed from different amphibolite localities of the same area, the Krušné hory Mountains, Saxony, consist mostly of the almandine, grossular, and pyrope molecules, the grandite component of these garnets ranging from 29 to 31 mol. %. Garnet no. 11 of our analyses with its 36 mol. % of the grandite component is the very extreme reached by the amphibolite garnets, just within the range interesting us.

The granulite facies. The garnets transitional in composition between the grandite and pyralspite series are in the first place known from pyroxene–plagioclase gneisses (granulites) of abyssally metamorphosed complexes. Table I includes three such garnets (nos. 12 to 14), the associates of which in the rock are a monoclinic pyroxene (either diopside or sahlite) and a calcic plagioclase with An_{90} on the average. In addition to these constituents, Moshkin (cited by Marakushev, 1965) gives from the rock of the Giga River also biotite and amphibole. Garnets of the same type were described also from similar rocks having high calcite content, a calciphyre (no. 15) and another rock from Carinthia (no. 16). In the last-named case, however, the rock type remains unclear. The insufficient description of the original rock (Heritsch, 1933, calls it an eclogite; the garnet, according to him, is accompanied by quartz, feldspar, and calcite) caused further authors, making use of this garnet analysis, to designate the rock by different names (Tröger, 1959, a lime-silica-hornstone; Sobolev, 1963, a contact of pseudoeclogite with pegmatite). The present author inserts it tentatively into the granulite facies.

All the garnets considered in this paragraph are almandines and grossulars by composition. The pyralspite component predominates in them, the grandite one, however, reaching nearly 50 mol. %. This is an upper limit of almandine saturation by the grandite component possible under the pT-conditions governing the granulite facies, being brought about by the high chemical activity of the environment (see the presence of calcite and anorthite in these rocks). As shown by Sobolev (1964), the decrease of the calcic component in plagioclase is coupled with a corresponding diminution of the amount of the grandite present in coexisting garnet, so that it already falls below the lower limit of the grandite share conventionally set in our considerations.

The eclogite facies. Garnets of the transitional type were recorded in two different types of eclogite rocks, viz. in a normal eclogite type (association garnet and omphacite) and in kyanite eclogites (called 'grosspidites' by Bobrievich and others, 1960). Both the eclogite garnets belonging to the first-named class come from the area of Californian glaucophane schists. Garnet no. 18 originates from an eclogite of metabasalt type of the Cazadero locality (Lee and others, 1963), its associates in the rock being omphacitic pyroxene as well as products of its retrograde alteration (epidote, muscovite). This alteration is still more pronounced in the rock from which garnet no. 17 was recovered. In fact this garnet is the only relic mineral of the rock, omphacite being entirely converted to actinolite exhibiting some glaucophane fringes. Pabst (1931) originally designated this rock as a glaucophane schist, but Lee and others (1963) showed convincingly that the chemical constitution of the garnet differs essentially from those of glaucophane schists, being quite consistent with the constitution of the eclogite garnets. Garnets nos. 17 and 18 are both essentially almandine–grossulars.

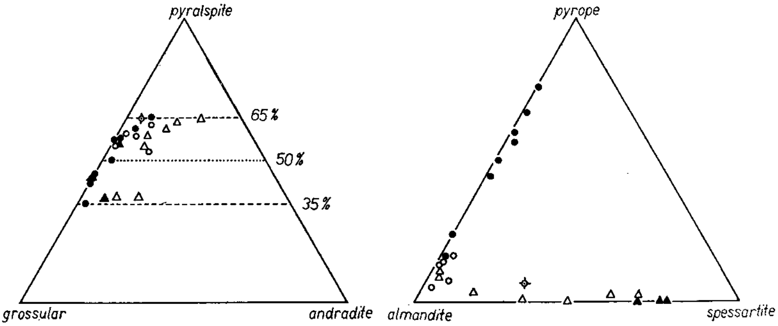
The garnets from eclogites display a wide range of composition, which is related more directly to the mode of occurrence than to the bulk rock composition (Lee and others, 1963). The largest amounts of the ugrandite moles are present in those from Alpine-type metamorphic rocks (Group C of Coleman and others, 1965) that are, at the same time, characterized by low pyrope content. In eclogite garnets from Cazadero, for example, the grandite constituent varies from 28 to 39 mol. %. Garnet no. 18 represents the very extreme of these calcium-rich almandines of Group C eclogites.

Grossulars and pyropes are common constituents of the kyanite eclogites of the Yakutsk region. Keeping in mind the special conditions during the crystallization of this eclogite type it should be taken as an independent subfacies of the eclogite facies. This rock occurs as xenoliths in kimberlite pipes (Milashev, 1960), their constituents being garnet, pyroxene, kyanite, and sometimes also corundum (Bobrievich and others, 1960). The garnets are predominantly grossulars and pyropes, sometimes with a considerable admixture of the almandine component. As shown by Sobolev and others (1966), there exists here a continuous series filling up the whole interval between 35 and 65 mol. %

of the grandite component. These garnets are connected by a continuous transition with grossular.

Conditions for the formation of intermediary garnets

From table I, as well as from figs. 1 and 2, it is obvious that under certain conditions there exists an unlimited miscibility of grossular with spessartine, almandine, and also pyrope. Owing to crystallochemical properties a higher miscibility may be expected, in the case of the pyralspite type of garnet, with grossular than with andradite. This agrees with the experimental facts (fig. 1). In the case of andradite, the maximum miscibility can be expected with spessartine. This is generally supported by the existence of another garnet with a considerable calderite content ($MnFe^{3+}$, Fermor, 1925). In our case table I shows that intermediary types of garnet with an increase of andradite have simultaneously a somewhat higher content of spessartine.



Figs. 1 and 2. Fig. 1 (left). Triangular plot of garnets listed in table I. The corners of the diagram feature grossular, andradite, and the pyralspite component. Garnets from: ▲ rocks of the pyroxene hornfels facies; △ rocks of the almandine amphibolite facies; -△- rocks of the glaucophane schist facies; ○ rocks of the granulite facies; ● rocks of the eclogite facies. Fig. 2 (right). Triangular plot of the pyralspite components listed in table I, recalculated to 100 %. The corners of the diagram feature almandine, spessartine, and pyrope. Symbols as in fig. 1.

The suitability of cations Mn^{2+}, Fe^{2+}, and Mg for the structural type of garnet was recently discussed by Zemann (1962) on the basis of more accurate structural-crystallographic information. He showed that owing to their spatial requirements, the most suitable are Mn ions, Fe are less suitable, and Mg are least suitable. Because of that, as was shown by Miyashiro (1953), Mn is usually more concentrated in the garnet in comparison with other coexisting minerals, whilst Mg on the contrary, shows a deficiency. This fact also can be observed in the case of the intermediary garnet type. In the Gabbs and Gabia districts the high concentration of Mn in the garnet follows from the nature of the mineral association of the parent rock, poor in Mn. In the regionally metamorphosed skarns of the Moravian Heights there are also garnets of the intermediary type that are richer in Mn than in other minerals of the association. Table II gives quantitative data on the relative contents of MnO and MgO in the garnet and in the parent rock of some samples studied.

TABLE II. The ratio of MnO and MgO contents (wt. %) in rocks and their constituent garnets

Locality	Rock	Garnet sample No	Ratio of MgO in garnet to MgO in rock	Ratio of MnO in garnet to MnO in rock	Reference
Cazadero	eclogite	—	0·3	5·7	Lee and others, 1963
Hammerunter-wiesenthal	amphibolite	12	0·2	3·5	Lange, 1964, 1965
Óbnashennaya	kyanite eclogite	24	1·3	2·7	Sobolev and Kuznetsova, 1965

The relative suitability of cations Mn^{2+}, Fe^{2+}, and Mg for the structural type of the garnet is clearly apparent in the synthesis of garnets. Preparation of pure spessartine was achieved even at atmospheric pressure and low temperatures, almandine was synthesized at medium to high pressures and 900° C (Coes, 1955), the preparation of pyrope required extremely high pressure and temperature (at least 17 000 atm and 1100° C, Boyd and England, 1959). These data are in agreement with the observed frequent occurrence of above-mentioned types of garnets in the formations of individual metamorphic facies. For garnets of grandite composition, it is not possible at present to make any easy comparison of experimental data with the observation of nature. Such garnets have so far been prepared at high pressures (Coes, 1955), whilst in nature they obviously originated at high temperatures and relatively low pressures (in primary skarns) as well as, for example, under the conditions of higher-grade facies of almandine amphibolites (e.g. in Aldan, *vide* Kadenskaya, 1966). Probably, up to now, suitable pressure and temperature conditions for this synthesis have not been found.

From the observation of nature it follows that the limits of the stability of grandite are obviously wider than those of individual members of the pyralspite series. Grossular and andradite, which were formed in the primary skarns by a high-temperature metasomatism (in the facies conditions of pyroxenic hornstones) can exist without a change even where these rocks were influenced by regional metamorphism in the facies conditions of almandine amphibolites—a case which is probably realized in regionally metamorphosed Fe-skarns of the Moravian Heights (Němec, 1967). However, if on the contrary almandine mica-schists are subjected to thermal metamorphism, almandine does not become stable, but changes into a mixture of cordierite and magnetite (Miyashiro, 1953). If we therefore consider that grandites are stable even in conditions in which some marginal members or mixtures of the pyralspite series are unstable, we arrive at the conclusion that the miscibility of grandite components with individual members of the pyralspite series is determined by the degree of the stability of the members of the pyralspite series. This is, of course, valid only for mixtures with a large share of grandite and pyralspite components, and not simply because of presence of one of the constituents in a negligible admixture.

Let us now observe the occurrence of intermediary garnets in individual metamorphic facies (fig. 2). In the rocks of pyroxenic hornstone facies we can establish only the occurrence of grossular–spessartines (nos. 1 to 3). Of the garnets of the pyralspite series, spessartine is apparently the only member stable at low pressures, dominant in this facies. For the glaucophane schist facies, low temperatures and relatively high pressures are typical (for Californian occurrences, Essene *et al.*, 1965, estimate the temperature at 150 to 300° C, pressures at 5 to 10 Kb), for this reason also grossulars–almandines can occur as well. The same is also valid for the almandine amphibolite facies with their high temperatures and considerable pressures (3 to 12 Kb, Fyfe *et al.*, 1959), for which almandine is almost a typomorphic mineral. According to the nature of the environment, mixtures rich either in the almandine component (nos. 9, 12) or in spessartine (6, 7, 8) occur here. In the granulite facies we find a considerable miscibility of grossular and almandine. Finally, in kyanite eclogites from Yakutsk, in which crystallization progressed at extremely high pressures and temperatures (Sobolev *et al.*, 1966, estimate pressures at 20 to 30 Kb), there originated even grossular–pyrope mix-crystals, in spite of considerable differences of ionic radii of Mg and Ca. Similar mixtures were synthesized at analogous pressures under laboratory conditions (Chinner and Schairer, 1962).

From the previous account it follows that as the degree of metamorphism increases, an unlimited crystallochemical miscibility applies progressively to more diverse types of garnet. In the pyroxene hornstone facies a grossular–spessartine mixture appears, in the almandine amphibolite facies grossular–almandine mixtures occur, and at the highest grades of eclogite facies even grossular–pyrope mixtures appear. In formations of approximately equal chemical composition, the upper limit of saturation by the grandite component of the pyralspite type of garnet is determined by the pressure and temperature. This limit grows, as is well known, from the almandine amphibole facies via the granulite to the eclogite facies. This also is demonstrated in our specimens (in the garnets from amphibolites, the established maximum proportion of the grandite molecule is 36 %, in the pyroxenic gneiss 41 %; in kyanite eclogites from Yakustsk there is already an unlimited miscibility of pyralspite and grandite molecules).

Further it is seen that increased pressure has a considerably greater influence than temperature on the origination of the intermediary type of garnet. This plainly follows from a comparison of primary skarns (caused by a high-temperature metasomatism in the conditions of pyroxene hornstone facies) with the same formations that were metamorphosed in conditions of almandinic amphibolite facies (lower temperatures and higher pressures than in the previous case). Garnets of primary skarns belong exclusively to the grossular–andradite group, their content of pyralspite is low (below 10 %, Sobolev, 1964). On the contrary, in the regionally metamorphosed skarns of the Moravian Heights, grossulars and almandines are the predominant types of garnet. The important part played by the pressure is understandable if we consider that pyrope and almandine, which have divalent cations in 8-coordination (this is an unusually high coordination number for Mg and Fe^{2+} when compared with other types of structures) are typical high-pressure forms (Zemann, 1962).

Apart from the pT conditions, a high chemical activity of elements forming the constituents of intermediary garnets are required. So in the regionally metamorphosed Fe-skarns the occurrence of grossular–almandines is conditioned by a high Ca and Fe concentration in the formation, in the kyanite eclogites of Yakutsk the origination of grossulars and pyropes is again conditioned by a high concentration of Ca and Mg. The influence of the environment is obvious especially in those cases where the garnet represents the Ca extreme of pyralspite garnet of a special rock-formation type. From table I it follows, for example, that in all metamorphic facies there is a maximum saturation of the pyralspite garnet by the Ca component in formations where this is accompanied in the rock by a synmetamorphic calcium carbonate. So, in glaucophane slates of various origins from the Californian Cazadero district, only the garnet from metacarbonate formations (which contain a high proportion of aragonite) show contents of the grandite component above 35 mol. % (no. 4). In the amphibolites of the Krušné hory similar contents of grandite are only found in the garnets from amphibolites forming layers in limestone (no. 11). Similarly, in the granulite facies, intermediary type garnets from rocks rich in calcite (nos. 15, 16), have the highest Ca components.

Fig. 2, which demonstrates the division of the pyralspite in the marginal members of the intermediary type of garnet under observation, shows that mixtures of grandite molecules exist either with only one marginal member of the pyralspite series (e.g. grossular–almandine) or with two (almandine and spessartine, almandine and pyrope). There is a notable absence of pyrope–spessartine mixtures in the pyralspite portion. The situation demonstrated by fig. 2 agrees completely with the conditions that we find in pyralspites without a considerable admixture of the grandite component as is shown, for example, by fig. 10 of Matthes (1961). The fact that laboratory synthesis of garnets of so energetically unsuitable a composition as $Mg_3Fe_2^{3+}(SiO_4)_3$ is possible would suggest that even spessartine–pyropes (possibly also spessartine–pyropes with a considerable share of grandite molecules) could originate in favourable conditions (at high chemical activity of Mg and Mn and under high pressures and temperatures). Similar conditions were not achieved in nature, however.

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Note added in proof: Another grossular–almandine from the Antonín mine, Boží Dar, Krušne hory, Czechoslovakia, recently analysed, gave:

$$(Fe^{2+}_{2\cdot89}Mn_{0\cdot13}Mg_{0\cdot22}Ca_{2\cdot72})_{5\cdot99}(Al_{3\cdot34}Fe^{3+}_{0\cdot50}Ti_{0\cdot15})_{3\cdot99}Si_{5\cdot98}O_{24}.$$