The paragenesis of kyanite-eclogites.

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[Read June 25, 1936.]

In Haüy's original definition of eclogite [1], the presence of kyanite as an accessory constituent was recognized, and it is apparent that he was familiar with examples from the Sau Alps and Styria. The best known of eclogites—those of the Bavarian Fichtelgebirge (e.g. Silberbach, Weissenstein, and Eppenreuth)—contain significant kyanite interspersed among the omphacite grains or associated with accessory quartz and muscovite in the rocks. Of these rocks rather extended descriptions have been published [2]. Analyses of the minerals and the rocks themselves belong to an early date and do not reach the standard of modern analyses. Later, Düll (1902) [3] published a systematic account of these Bavarian eclogites and has added an analysis of an eclogite with kyanite from Unterpferdt near Silberbach and an analysis of a garnet from a Silberbach eclogite.

Kyanite-eclogites are also known from Alpine regions, from the Bachergebirge (Yugoslavia) [4], Sau Alps (Carinthia) [5], Oetzthal (Tirol) [6], Kor Alps (Carinthia and Styria) [7], Graian Alps (Italy) [8], and several regions in France [9].

An important contribution to our knowledge of the composition of the kyanite-bearing eclogites has been made by Mlle Brière [9] in her memoir on the French eclogites. Still later a summary of the eclogites (or griquaites) of South Africa and Tanganyika has been given by Williams [10] in his book 'Genesis of the Diamond'. Among these, kyanite-eclogites are recorded and new analyses are available. Despite these contributions, the significance of kyanite in eclogites remains a matter for further inquiry, though Eskola [11] in his discussion of the eclogite facies has commented briefly on the relationships of the kyanite-bearing varieties of this rock.

The typical Fichtelgebirge eclogites (Silberbach and Weissenstein) consist essentially of omphacite, garnet, and kyanite with accessory quartz, rutile, zoisite, iron ores, and white mica. In the discussion that follows, attention will be focused particularly on eclogites of this type poor in such minerals as amphibole or zoisite.

The ordinary pyroxene-eclogite may be considered as essentially a bimineralic rock composed of garnet and omphacite. To discuss the paragenetic relations of these and kyanite-bearing eclogites a knowledge of the composition of the constituent minerals is

TABLE I. Analyses of pyroxenes from eclogites.

	1.	3.	20.	W.	6.	2.	9.	8a.
SiO_2 ...	54·49	55·56	52·82	54·48	54·21	54·03	53·48	54·88
Al_2O_3 ...	2·50	7·17	6·42	8·20	10·91	11·54	9·52	10·44
Fe_2O_3 ...	1·63	2·82	2·30	0·48	3·12	5·62	3·00	5·80
TiO_2 ...	trace	0·15	0·25	0·57	0·46	0·54	1·04	0·39
FeO ...	1·98	2·06	3·07	1·23	1·33	4·09	5·84	3·31
MnO ...	0·06	0·05	0·03	0·02	—	0·05	—	—
MgO ...	16·74	11·32	13·49	12·72	10·03	5·13	6·34	6·41
CaO ...	21·40	16·85	19·06	19·40	14·61	11·82	14·87	12·94
Na_2O ...	0·83	3·92	1·82	2·88	4·51	6·81	3·97	5·31
K_2O ...	0·40	0·57	trace ?	0·10	0·92	0·20	0·63	0·34
H_2O+ ...	} 0·12	} 0·08	0·48	nil	—	} 0·29	0·73	0·23
H_2O- ...			0·15	nil	0·05		nil	—
	100·38	100·55	99·89	100·08	100·15	100·12	99·42	100·05

1. Almklovdalen, Norway ([12], p. 28); also Cr_2O_3 0·20, NiO 0·03. 3. Silden, Norway ([12], p. 38). 20. Hurry Inlet, Greenland ([13], p. 19). W. Weissenstein, Bavaria (new analysis). 6. Burgstein, Tirol ([16], p. 447). 2. Vanelvsdalen, Norway ([12], p. 32). 9. Glenelg, Scotland [14]. 8a. Fay, France ([9], p. 92).

essential. As regards kyanite-free eclogites analyses are available of the constituent garnets and pyroxenes of specimens from the following localities: (*a*) Almklovdalen, (*b*) Vanelvsdalen, (*c*) Silden (Norway) [12], (*d*) Burgstein (Oetzthal) [6], (*e*) Hurry Inlet (east Greenland) [13]; and single analyses of garnets or pyroxenes are recorded from eclogites of Fay (pyroxene) [9], Glenelg (pyroxene) [14], (garnet) [15].

From kyanite-eclogites, no modern analyses of their contained pyroxenes are available, but of their garnets we have analyses from kyanite-eclogites from St. Philbert de Grandlieu [9] and Silberbach [3]. To obtain further data, new analyses have been made of garnet and pyroxene from a kyanite-eclogite from Weissenstein [1] (more probably Silberbach ?), Fichtelgebirge, Bavaria.

[1] This specimen from Krantz is labelled 'Weissenstein', but it shows great similarity to the well-known eclogite from Silberbach—particularly in the parallel orientated silky lustred omphacite (cf. descriptions by Düll [3], p. 141).

The comparatively simple mineral composition of the typical eclogite suggests that some correlation between the compositions of the two essential minerals—pyroxene and garnet—might be established by comparison of a series of analyses. With this purpose in view the analyses of the pyroxenes of eclogites of which the compositions of the associated garnet are known, are tabulated on p. 423. Two further analyses of eclogite pyroxenes are given under 9 and 8 a.

These analyses though showing a considerable variation in alumina content have uniformly a high silica content. It is clear that the major part of the Al replaces metals in the structural formula of the pyroxene and only a small fraction replaces silicon.

The new analysis of pyroxene from the Bavarian eclogite in table I (W) can be interpreted as follows:

	%	Metal atoms on basis of 6 oxygen atoms.			
SiO_2	54·48 ...	1·94		2·00	
Al_2O_3	8·20 ...	0·34	0·06		
			0·28		
Fe_2O_3	0·48 ...	0·01			
TiO_2	0·57 ...	0·02		1·03	
FeO	1·23 ...	0·04			1·97
MnO	0·02 ...	—			
MgO	12·72 ...	0·68			
CaO	19·40 ...	0·74	...	0·94	
Na_2O	2·88 ...	0·20			
K_2O	0·10 ...	—			
	100·08				

Analyst, Miss Hilda Bennett.

The properties of this pyroxene are specific gravity 3·30, α 1·670, β 1·680, γ 1·694, $\gamma : c = 43°$, $2V_\gamma$ 64°.

The composition of the garnet associated with this pyroxene is given on p. 425.

Before a comparison of these pyroxenes and their associated garnets is instituted it is of importance to note their associated minerals. Eclogites 1 and 3 are practically bimineralic, containing only accessory quartz, rutile, and a little white mica. Eclogite 20 contains some hornblende partly as fringes to the garnet and a little symplectite associated with the pyroxene. Eclogite W, besides accessory quartz, rutile, and iron ores, contains a small amount of β-zoisite the significance of which will be discussed later. Eclogite 6 contains some hornblende and a little diopside-plagioclase symplectite (?) from the omphacite. Eclogite 2 has only accessory apatite, iron ores, rutile, and diopside-plagioclase symplectite. It appears a reasonable assumption that the development of small amounts of retrograde hornblende as fringes to the pyroxene and garnet of these eclogites has not affected the compositions of the fresh garnets and pyroxenes which have been subject to analysis.

Analysis of garnet from eclogite from Weissenstein, Bavaria.

	%	Metal atoms on basis of 12 oxygen atoms.		
SiO_2	39·64	2·92	0·08	3·00
Al_2O_3	24·19	2·09		2·01
Fe_2O_3	1·15	0·06		
TiO_2	0·26	0·01		
FeO	13·63	0·84		
MnO	0·33	0·02		2·98
MgO	12·90	1·42		
CaO	7·98	0·63		
H_2O+	nil			
H_2O-	0·08	Sp. gr. 3·760, *n* 1·756.		
	100·16			

Analyst, Miss Hilda Bennett.

The following list presents the compositions of the garnets associated respectively with the pyroxenes (1–2) of table I. The composition is given in terms of the divalent elements (molecular) without regard to the trivalent elements.

1. $Fe_{26}Mn_1Mg_{61}Ca_{12}$.
3. $Fe_{40}Mn_2Mg_{43}Ca_{15}$.
20. $Fe_{27\cdot6}Mn_{0\cdot3}Mg_{51}Ca_{21}$.*
9 a. $Fe_{37\cdot4}Mn_{1\cdot5}Mg_{41\cdot8}Ca_{19\cdot3}$.
W. $Fe_{28\cdot7}Mn_{0\cdot7}Mg_{48\cdot9}Ca_{21\cdot7}$.
6. $Fe_{42\cdot5}Mg_{35\cdot3}Ca_{22\cdot2}$.
2. $Fe_{57}Mn_2Mg_{16}Ca_{25}$.
7. $Fe_{38}Mg_{34}Ca_{28}$.

In addition to these six analyses, the figures for two other garnets from eclogites are given in the list: 9 *a* (Glenelg) and 7 (St. Philbert de Grandlieu). Of other available garnet analyses reference may be made to Philipsborn's data [16]—stated in the form of molecular percentages—the original detailed analyses having apparently not been published. They are as follows:

Eclogite, Zöblitz (Erzgebirge)—garnet $(Fe,Mn)_{24}Mg_{60}Ca_{16}$.
Eclogite, Böhrigen (Saxony)—garnet $(Fe,Mn)_{41\cdot5}Mg_{31}Ca_{27\cdot5}$.
Eclogite, Weissenstein (Bavaria)—garnet $(Fe,Mn)_{49\cdot5}Mg_{20}Ca_{30\cdot5}$.

* Analysis of this garnet shows a figure of 6·02 % Fe_2O_3 and offers some difficulty in structural interpretation.

It may be noted here that several of these garnets lie outside the field of miscibility in the system almandine-pyrope-grossular as deduced by Boeke [17] in his statistical study of garnet analyses. Heritsch [18] has recently analysed a garnet (not of eclogitic para-

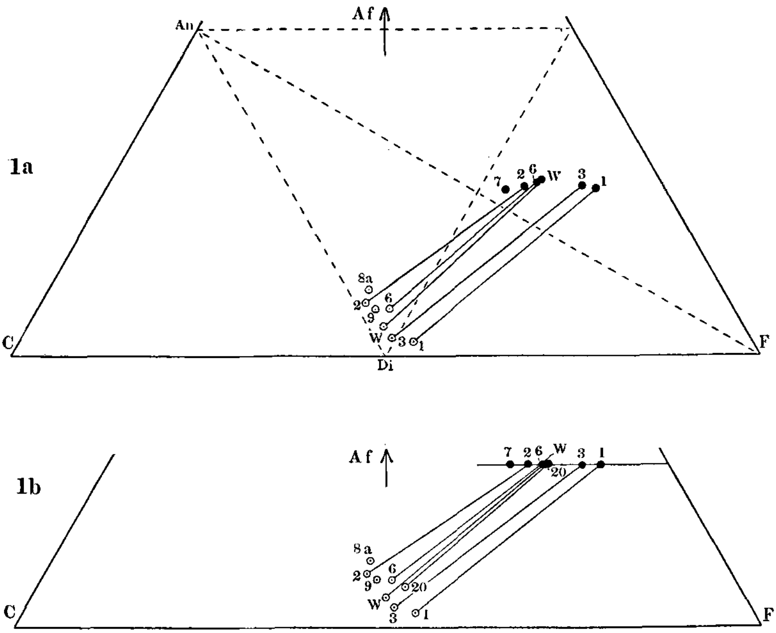

FIG. 1. Triangular plot of chemical analyses of garnets (black dots) and associated pyroxenes (ringed dots) from eclogites.

genesis) which lies still farther from the miscibility field given by Boeke.[1] This garnet, whose composition is $(Fe,Mn)_{45\cdot5}Mg_{7\cdot6}Ca_{46\cdot9}$, occurs in druses associated with quartz, calcite, and felspar at the junction of pegmatite with garnet-gneiss, amphibolite, and augite-garnet skarn (pseudo-eclogite) at the Lieserschlucht, Spittal on the Drau (Carinthia) (cf. H. Wieseneder, Tschermak's Min. Petr. Mitt., 1935, vol. 46, p. 185).

The relations between the compositions of the garnets and the associated pyroxenes can be appreciated if the analyses are plotted in a triangular diagram. In fig. 1 a the analyses are plotted

[1] The miscibility gap between grossularite on the one hand and pyrope-almandine-spessartite on the other from Boeke's data is given as 20–75 % MO (= MgO + FeO + MnO) where CaO + MO = 100. [17], p. 157 and fig. 2.

on an Af–F–C. diagram, where Af = $Al_2O_3 + Fe_2O_3 - (Na_2O + K_2O)$, F = $(FeO + MgO + MnO + TiO_2)$, and C = CaO, all expressed in molecular numbers. In fig. 1 b the plot is identical except that the compositions of the garnets are expressed in terms of (Fe,Mn,Mg) : Ca along the theoretical grossular–(almandine-pyrope) join.

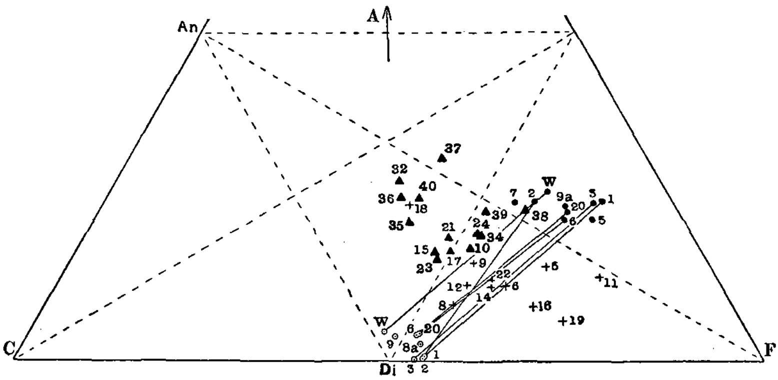

FIG. 2. Triangular plot of chemical analyses of kyanite-eclogites (black triangles) and kyanite-free eclogites (crosses).

The numbers refer to rocks from the following localities: Norway, 5, 11, (Eskola) [12]; Greenland, 19, (Sahlstein) [13]; France, 8, 12, 14, 15, 16, 17, 18, 21, 22, 23, (Brière) [9]; Tirol (Oetzthal), 6, 10 (? kyanite type), (Hezner) [6]; Fichtelgebirge, 24, (Düll) [3], 40 (new analysis); Glenelg, Scotland, 9, (Alderman) [14]; Tanganyika, 32 (Williams) [10]; South Africa, 34, 35, 36, 37, 38, 39, (Williams) [10].

Other numbers refer to minerals (cf. fig. 1 and table I).

The *paragenetic conjugation-lines* in the diagram indicate clearly the sympathetic variation of the two constituents of the several eclogites. Of these series of analyses only that of the Bavarian eclogite (W) represents a garnet-pyroxene assemblage with kyanite. The diagrams do not, however, make clear the chemical factor which it may be supposed leads to the appearance of kyanite in the mineral assemblage.

The conjugation-lines of eclogites (2) and (6) have a position beyond that of the kyanite-eclogite (W), and in addition the solitary pyroxene analyses (8 a) and (9) occupy a similar position (cf. fig. 1 b).

Inspection of the omphacite analyses of table I shows, however, that the extreme positions of these points and lines is controlled by the Fe_2O_3 content of the minerals, as the following figures show:

	Per cent. Fe_2O_3 in garnet.	pyroxene.
W	1·15 ...	0·48
2	1·80 ...	5·62
6	5·45 ...	3·12
9	— ...	3·00
8a	— ...	5·80

The plotting of Fe_2O_3 as a separate component in a quaternary system would leave the position of the WW conjugation-line little affected owing to the low values of Fe_2O_3 in the analyses, but the position of conjugation-lines (2) and (6) would be materially displaced, as may be readily seen by constructing such a tetrahedron plot.

A ternary diagram in which Al_2O_3 is plotted separately from Fe_2O_3, though not rigorous in its application, may serve to illustrate the importance of Al_2O_3 content in determining the presence or absence of kyanite in the eclogite assemblage.

The same analyses are plotted in fig. 2 where the value A is now $Al_2O_3 - (Na_2O + K_2O)$, and Fe_2O_3 (expressed as mols. FeO) is added to FeO and plotted with it as F.

The position of the paragenetic conjugation-line for the Bavarian eclogite (W) now emerges beyond those of the other eclogites, as an extreme boundary, owing to the low content of Fe_2O_3 in its pyroxene compared to the pyroxenes (2) and (6).

Among the listed pyroxenes (2) is exceptional in its high Na_2O and Fe_2O_3 character. The construction of the plot assumes the removal of Al_2O_3 selectively with Na_2O as jadeite, leaving little excess Al_2O_3. The relations envisaged would still be maintained were a proportion of Na_2O removed with Fe_2O_3. In this connexion the limited field of existence of jadeite (as a high-pressure mineral–contrast acmite) should be remembered. As indicated in a later paragraph little study has as yet been made of the paragenesis of chloromelanite and jadeitic pyroxenes.

Inspection of this plot leads to the suggestion that the appearance of kyanite as a mineral phase in an eclogite results from the presence of alumina in excess of that amount which can be incorporated in the bimineralic pyroxene-garnet assemblage.

This suggestion can be further tested if the analyses of eclogites, including kyanite-eclogites, are plotted in the diagram. In recalculating the modern analyses to the co-ordinates of the plot accessories, such as apatite, rutile, magnetite, and ilmenite, have been allowed for wherever possible by subtracting the equivalent amount of CaO for P_2O_5 in the analyses, and FeO, Fe_2O_3, and TiO_2 where modes have been given.

The resultant points are given in the diagram (fig. 2). The plotted positions of the kyanite-eclogites are seen to fall above the paragenetic conjugation-line for the Bavarian eclogite (W), while those of kyanite-free eclogites fall below it.

It is clear that only those analyses should be plotted the rocks of which contain preponderant pyroxene and garnet with or without kyanite. The presence of notable quantities of plagioclase (anorthitic) or zoisite in an eclogite may cause its plotted position to fall within the region of the kyanite-eclogites. Such is the case with eclogite 18 (Piedpain [9], p. 172) rich in zoisite and free from kyanite.

The position of the pyroxene-garnet conjugation-line is clearly dependent on the chemical composition of the rock, but the critical conjugation-line for the entry of kyanite may be expected to vary with the physical conditions (pressure and temperature) under which the eclogite has crystallized.

Here it is important to note the minerals associated with garnet and pyroxene. The Bavarian kyanite-eclogite (W) of which analyses of garnet and pyroxene have been made, contains in addition, as already mentioned, a small amount of β-zoisite. Though there is no indication that the zoisite is developing from either garnet or pyroxene, it is conceivable that in a higher grade facies the constituents of zoisite would be represented in the composition of the garnet and pyroxene. In such a case the position of the critical conjugation-line in a zoisite-free eclogite would lie still farther towards the $CaO–Al_2O_3$ boundary of the figure.

The occurrence of garnets with high lime values in kyanite-eclogites—e.g. 7 of fig. 2 from the kyanite-eclogite of St. Philbert de Grandlieu—is perhaps to be interpreted in this light.

Nature of kyanite-eclogites.- -In table II is given a new analysis of a kyanite-eclogite from Weissenstein. The constituents are omphacite, garnet, kyanite, some β-zoisite, and accessory rutile, magnetite, quartz, and muscovite. A significant feature is the high content of alumina. Its plotted position in fig. 2 lies well beyond the extreme garnet-pyroxene conjugation-line. Subtraction of the small amount of β-zoisite would not affect appreciably its plotted position.

In table II this eclogite is compared with basic igneous rocks of similar chemistry. In general the compositions of kyanite-eclogites fall within the triangle diopside-anorthite-F (hypersthene, olivine, iron ores); thus clearly in the field of igneous rocks, like the kyanite-free eclogites. They extend, however, farther in this field towards the anorthite apex.

TABLE II. Analysis of kyanite-eclogite (with other rocks for comparison).

	1.	2.	3.	4.	5.
SiO_2	50·75	48·34	47·28	50·80	48·02
TiO_2	0·12	0·95	0·28	0·43	0·23
Al_2O_3	20·02	20·10	21·07	19·42	20·01
Fe_2O_3	0·42	1·97	3·52	0·97	1·13
FeO	3·87	6·62	3·91	6·67	7·29
MgO	9·34	5·49	8·06	5·78	10·05
CaO	13·07	13·16	13·42	12·68	11·42
Na_2O	1·14	1·66	1·52	1·60	0·51
K_2O	0·15	0·98	0·29	0·37	0·05
H_2O+	0·70	0·44	0·53	0·86	0·57
H_2O-	0·50	0·02	0·13	0·25	0·10
P_2O_5	trace	0.04	trace	—	trace
MnO	0·05	0·32	0·15	—	0·18
CO_2	nil	0·11	—	—	0·25
&c.	—	0·10	0·04	0·01	0·17
	100·13	100·30	100·20	99·84	99·98
Sp. gr.	3·386	—	2·90	—	2·98

Norm of (1)	
Quartz	1·74
Orthoclase	1·11
Albite	9·96
Anorthite	48·65
Diopside	12·91
Hypersthene	23·72
Ilmenite	0·15
Magnetite	0·70

(II) 3. 5. 5. 0.

Anorthite content of normative plagioclase 83·0 %.

1. Kyanite-eclogite, Weissenstein, Fichtelgebirge, Bavaria. Analyst, W. H. Herdsman.
2. Gabbro, Leac an Leathaird, Mull. (Washington's Tables, 1917, p. 538.)
3. Olivine-gabbro (eucrite), Coir' a' Mhadaidh, Skye. (Ibid., p. 538.)
4. Quartz-diabase, Kerr Lake mine, Cobalt, Ontario. (Ibid., p. 528.)
5. Norite, McKinsley's mill, Cecil Co., Maryland. (Ibid., p. 666.)

In the language of the norm the appearance of kyanite in eclogites is favoured by high normative anorthite. Their analyses can be matched with those of eucrites, hypersthene-gabbros, norites, and some quartz-dolerites thus typically with rocks which in the Hebridean region would be described as of porphyritic central magma type.

It is worthy of remark that sillimanite has been recorded only rarely as a constituent of eclogites. The observation of Williams ([10] vol. I, p. 334) that the Tanganyika eclogites carry sillimanite as well as kyanite is remarkable and these eclogites are clearly worthy of further study in this connexion. Normally under the conditions of crystallization of eclogites—whether primary or metamorphic—

the pressures seem to have been sufficiently high to give the densest form of aluminium silicate.

Chloromelanitites and Jadeitites.—Hezner [6] and Eskola [11] have pointed out that a close relation exists between eclogites, chloromelanitites, and jadeitites. These latter rocks are much richer in pyroxene and consist at times almost wholly of pyroxene with only accessory minerals including garnet. Rocks of this type containing garnet deserve a much closer study than has yet been devoted to them. The work of Franchi [8] has shown that chloromelanite-rocks occur in some abundance in the Graian Alps. As examples may be taken the jadeite-rock (in the form of a stone axe) described by Hezner from Schaffis, Bieler See, Switzerland, and a chloromelanite-rock from Oropa, Biella, Piedmont, referred to by Franchi.

The plots of the analyses of the pyroxenes of these two rocks depart considerably from the plotted positions of the pyroxenes discussed in this paper. The Schaffis specimen (analysis conducted on not quite pure material) has co-ordinates A 29·2, F 35·3, C. 35·4, thus falling above the grossular-almandine join, while the pyroxene of Oropa falls inside the triangle (CaO-diopside-anorthite). The compositions of their associated garnets is unknown. Closer examination of such assemblages in view of the possible miscibility gap in the garnet solid-solution series should prove an instructive paragenetic study. To these problems I hope to return later.

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