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THE ECLOGITE-AMPHIBOLITE TRANSITION AT 650°C AND 6.5 KBAR PRESSURE, AS EXEMPLIFIED BY BASIC ROCKS OF THE UZERCHE AREA, CENTRAL FRANCE

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ABSTRACT

A petrographic study of mineral parageneses in aluminous gneisses and basic rocks of the Uzerche area, in Central France, has permitted the definition of physical conditions necessary to change amphibole eclogites to garnet amphibolites. The upper stabilities of staurolite, paragonite, zoisite, and sillimanite, found either in the gneisses or basic rocks, were used to deduce these conditions. This one point on the facies boundary is estimated to be at 650°C and 6.5 kbar at $P_{\text{total}} \cong P_{H_2O}$.

In the rocks of the Uzerche area, the pelitic gneiss mineral assemblages are in the first sillimanite zone of metamorphic facies, and the mineral assemblages in the basic rocks are considered to have formed near the boundaries of the eclogite, garnet amphibolite and the granulite facies. Nineteen new chemical analyses of rocks and constituent coexisting minerals are examined on the basis of the mineral facies in which they were formed.

INTRODUCTION

This study of a metamorphic series in the Massif Central of France is primarily concerned with the most apparent and latest, regional metamorphic facies in a principally gneissic series of metamorphic rocks. These rocks are interspersed with basic facies found most commonly in linear or very small massif form. No attempt is made here to relate the metamorphic petrology of the small region studied to that of the surrounding metamorphic terrain. Such a synthesis has, in fact, been made on a large scale by Roques (1941). His work serves as an adequate base for the more detailed study related here. It might be stated simply that the major series of rocks represents a complex massif of polymetamorphic history. The ratio of outcrop to covered or obscured terrain is such that a detailed structural study is rather difficult to make and more difficult to interpret. However, the metamorphic facies are sufficiently consistent to allow the conclusion that a general and regular regional metamorphism controlled the basic petrography of the rocks during the latest major tectonic events. Subsequent localized events changed the mineralogy slightly, *e.g.* scapolitization, prehnitization, chloritization of biotites, etc. The regional geology is considered sufficiently coherent on a large scale to permit generalization of the physical regime responsible for the meta-

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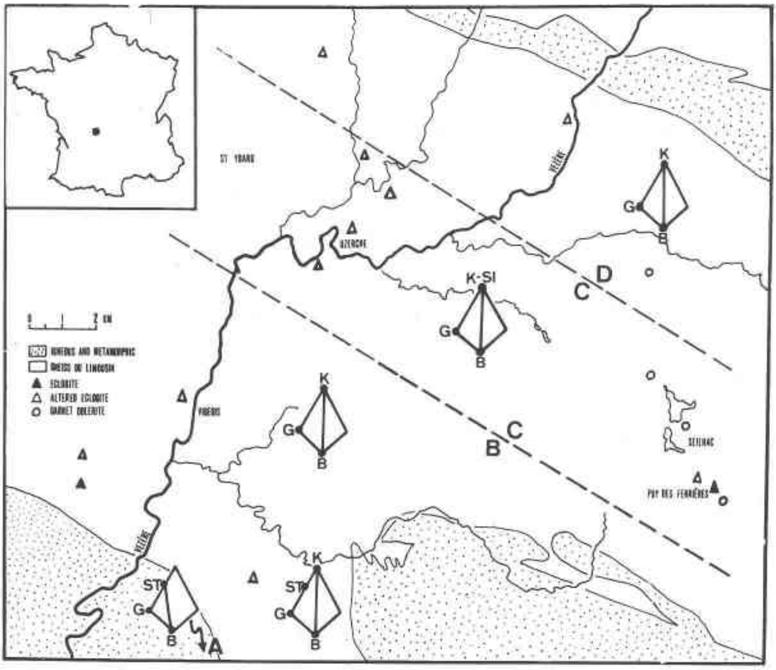

FIG. 1. The disposition of the various mineralogic zonations found are indicated on the sketch map of the area studied. The assemblages have been projected on an A–F–M surface, after the method proposed by Thompson (1957). The assumptions which permit the use of this projection, the presence of muscovite and quartz in all facies, are generally fulfilled in the rocks under investigation.

morphic facies which will be described in the small area under consideration here.

The area studied is located almost equidistantly around the town of Uzerche, 58 kilometers South of Limoges. The surface area is about 200 km². Major metamorphic rock units are outlined in Figure 1, and a preliminary survey of the structural ternds in the area can also be found in Hervé (1967).[1]

In order to establish the metamorphic conditions which influenced the mineralogy of the basic rocks found in the area, a detailed study has been made on the gneisses which constitute the country rock. The assumption is made that all rocks were equally influenced by the evolution of the regional metamorphic conditions, and that any pressure-temperature range determined for the gneisses is equally valid for the basic rocks.

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[1] Available, upon request, from the Laboratoire de Pétrographie.

PETROLOGY OF THE MAJOR ROCK TYPES: GNEISSES AND PELITIC ROCKS

The aluminous rocks which represent the dominant rock type of the area ("gneiss du Limousin") possess a mineralogic zonation whose boundaries extend roughly northeast-southwest (Fig. 1). These zones are delineated by the following parageneses:

Zone A

$$\left.\begin{array}{l}\text{gt—staur—musc—bio—ky}\\ \text{gt—bio}\\ \text{gt—bio—musc}\\ \text{bio—musc}\end{array}\right\} + \text{qtz} + \text{plag } (\text{An}_{20-30})$$

Zones B and D

$$\left.\begin{array}{l}\text{gt—bio—musc—ky}\\ \text{gt—bio—ky}\\ \text{gt—bio—musc}\\ \text{gt—bio}\end{array}\right\} + \text{qtz} + \text{plag } (\text{An}_{20-30}) \pm \text{Kspar}$$

Zone C

$$\left.\begin{array}{l}\text{gt—bio—musc—ky—sill}\\ \text{gt—bio—musc—sill}\\ \text{gt—bio}\\ \text{gt—bio—musc}\\ \text{gt—bio—amph}\\ \text{ky}\end{array}\right\} + \text{qtz} \pm \text{plag } (\text{An}_{40-50}) \pm \text{Kspar}$$

Roques (1941) reports the assemblage muscovite-biotite-garnet-staurolite-plagioclase-quartz, 10 kilometers to the south of the area.

Locally amphibole appears in the pelitic rocks in irregular bands. In some outcrops which show local faulting the biotite is chloritized, and sometimes also the garnet.

The central zone C, which contains sillimanite defines the highest grade of metamorphism in the area. The sillimanite occurs in three associations: an apparent breakdown product of biotite, or an exsolved phase, which is the most frequent occurrence; an apparent breakdown product of white mica; an epitaxic form on pre-existing kyanite. This last relationship, though rarely found, indicates that the last stage of metamorphism crossed, in terms of pressure and temperature, the polymorphic transition between kyanite and sillimanite into the stability field of sillimanite. Investigation of the composition of the white micas gives an indication as to the origin of sillimanite associated with them. Basal spacings for the micas in kyanite, and kyanite-sillimanite or sillimanite bearing rocks (Zones B–D and C) indicate a larger cell size for the micas in the sillimanite-bearing rocks. The average spacing for 4 micas in zones B and D is 9.955 Å, and for 6 from zone C it is 9.975 Å. Chemical analysis of micas

TABLE 1. ABBREVIATION OF MINERAL NAMES

amph = amphibole
bio = biotite
chlor = chlorite
clinozo = clinozoisite
cpx = clinopyroxene
ep = epidote
gt = garnet
il = ilmenite
ky = kyanite
K-spar = potassic feldspar
musc = muscovite
ol = olivine
op = opaque
opx = orthopyroxene
plag = plagioclase
qtz = quartz
ru = rutile
scap = scapolite
sill = sillimanite
sph = sphene
staur = staurolite
zo = zoisite

from zone B and C (Table 2) substantiate that this change in cell dimension is due to a decrease in the sodium content or an exsolution of the paragonite molecule from the white mica in the sillimanite zone. The reaction paragonite+quartz=sillimanite+albite, as an exsolution from white mica has been documented by Evans and Guidotti (1966). This reaction apparently occurred in the Uzerche area within the stability field of sillimanite, although in some cases it appears to have taken place in the presence of kyanite which did not convert to the apparent stable aluminium silicate phase.

TABLE 2. CHEMICAL COMPOSITIONS OF WHITE MICAS

	58 N[a]	117 N		58 N	117 N
SiO_2	45.27	46.99	Si	3.00	3.12
Al_2O_3	37.00	33.53	Al^{IV}	1.00	0.88
Fe_2O_3	0.30	0.85	Al^{VI}	1.89	1.72
FeO	1.16	1.58	Fe^{3+}	0.02	0.04
MgO	0.50	0.87	Fe^{2+}	0.06	0.09
MnO	tr	tr	Mg	0.05	0.09
CaO	tr	tr	Ti	0.02	0.07
Na_2O	1.48	0.77	Na	0.19	0.10
K_2O	9.50	8.95	K	0.81	0.77
TiO_2	0.34	1.37			
P_2O_5	0.12	0.15	% paragonite	20	12
H_2O^+	4.83	4.30			
H_2O^-	0.32	0.12			
Total	100.82	99.48			

58 = Kyanite-bearing gneiss; 117 = sillimanite-bearing gneiss.

[a] The letter following the number of the chemical analysis indicates, in all tables, the chemist. N = A. Nétillard; D = M. Doucet; V = N. Vassard (Laboratoire de Pétrographie, Faculté des Sciences de Paris).

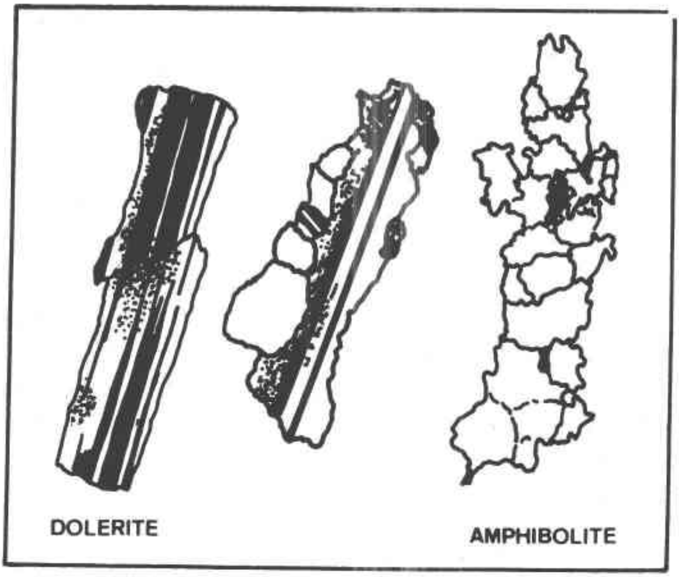

FIG. 2. The aspect of the feldspars in the metadolerites upon recrystallization is shown by the sketch.

The mineral assemblages noted above and shown in Figure 1 indicate a sequence of increasing metamorphic grade from southwest to northeast marked by the disappearance of staurolite, the appearance of kyanite and, in zone C, the presence of sillimanite. The elimination of staurolite from the pelitic assemblages can be explained in two ways: by simple destabilization due to increased temperature which produced garnet and kyanite (Richardson, 1968) or by combination with muscovite and quartz to produce biotite and an aluminium silicate in the presence or not of garnet. The observed assemblage garnet-staurolite-biotite-kyanite, all in textural equilibrium seems to indicate that the latter reaction took place but does not unequivocably argue so (see Chinner, 1965, for a discussion of the problem). In any event both reactions appear to take place at similar temperatures in the range of pressures where staurolite, kyanite and sillimanite are stable (Hoschek, 1968; Richardson, Bell and Gilbert, 1969). Both reactions have a strong tendency to be parallel to the pressure axis in this region of P—T space. The temperatures of staurolite stability given by Richardson and by Hoschek should be considered to be maximum values when the manganese content of the mineral compositions is taken into account (Ganguly, 1968). As a result, it can be estimated that the passage from zone B to C (Fig. 1) represents an isograd slightly below 650°C. The aluminium silicate polymorph transition kyanite-sillimanite would indicate pressures of about 6.5 kbar. A projection of the data of Yoder (1958) and Iiyama (1964) to this pressure would place the upper stability of paragonite+quartz at about the same temperature. As was observed above, the sodium content of micas in zone C, where sillimanite was found, is lower than in the kyanite zone indicating destabilization of this molecule in the mica structure. It would thus appear that the zone of maximum temperature was zone C. Figure 3 shows the mutual relationships of the mineral stabilities mentioned. The passage from zone B to C was probably caused by increase in temperature, since staurolite stability is only slightly pressure dependent at the pressure determined. However, the crystallization of sillimanite, and destabilization of paragonite could also have been produced by a decrease in pressure. This point will be taken up later.

A supposition which is made here is that $P_{H_2O} \cong P_{total}$, or that the activity of H_2O is high. There is no *a priori* justification for this other than that the rocks are composed largely of hydrous phases and that stability curves for the minerals, determined experimentally under high water activity, are interrelated in such a manner as to explain the petrographic observations. This discussion will be taken up later.

BASIC ROCKS

The implied restrictions of metamorphic pressure and temperature conditions indicated by the mineral facies of the gneisses of the region serve as a convenient framework to use in interpreting the very interesting mineral facies of the basic rocks which are found in the Uzerche area. These basic rocks, amphibolites for the most part, are found most commonly as irregular layers or lenses in the gneisses. They are usually linear in outcrop but can occur in small massif form. The latter is particularly the case for these rocks with the eclogite or amphibole eclogite mineralogy. It is evident from a study of the thin sections that the last phase of metamorphism was conducive to the almandine amphibolite facies.

In the well crystallized amphibolite rocks, which represent the great majority of cases, the following parageneses were noted:

$$\left.\begin{array}{l}\text{plag—amph}\\ \text{plag—amph—cpx}\\ \text{plag—amph—gt}\\ \text{plag—amph—cpx—ep}\\ \text{plag—amph—ep}\\ \text{plag—amph—bio—sill}\end{array}\right\} \pm \text{qtz} \pm \text{sph} \pm \text{il} \pm \text{apatite}$$

The plagioclase is 30 to 50 percent anorthite in composition. Occasionally, the rocks are scapolitized, chloritized, or prehnite-bearing. The pyroxenes are found as either bands where amphibole is absent, or in intimate association with amphibole. Clinopyroxene is never found with garnet in the recrystallized amphibolites.

Eclogites, *i.e.* bimineralic omphacite-pyralspite rocks, are not found in the area. However rocks composed of more than 90 percent clinopyroxene+garnet are found in one small massif (Puy des Ferrières) which has been previously described by Brière (1920a). These rocks will be referred to as eclogites. Amphibole eclogites, *i.e.* predominantly omphacite, garnet and amphibole-bearing rocks, are also found in the massif. One sample coming from a small band in the gneisses was found to contain the assemblage garnet—clinopyroxene—brown amphibole—biotite—plagioclase—zoisite; all phases were in apparent textural equilibrium. All of the eclogite or amphibole eclogites contain quartz and rutile as accessory minerals.

Other than the rocks which retain the eclogite or amphibole eclogite mineralogy, there are numerous examples scattered throughout the area studied of rocks which formerly had this mineralogy, but which now appear as altered eclogites. They maintain the garnet porphyroblasts but show a symplectite structure of pyroxene—plagioclase—quartz or amphibole—plagioclase—quartz in place of the omphacite. One sample had, in addition to symplectized clinopyroxene, finely recrystallized plagioclase laths, suggesting an original plagioclase phase. Infrequent original zoisite crystals have symplectite rims which probably contain garnet and plagioclase. Occasionally, garnets are rimmed by a radial keliphyte structure of blue-green amphibole and quartz. The original brown amphibole of the eclogites is frequently partially replaced by a new green variety. The state of recrystallization in the amphibole assemblage is more marked towards the garnets which are often replaced by other ferromagnesian phases such as amphibole or biotite. A particular feature of the amphibolitized rocks is the appearance of an opaque mineral surrounded by sphene. In some thin sections, rutile can be seen, partially replaced by this assemblage.

The following assemblages were found (minerals in parentheses indicate the alteration product of the garnet):

$$\left.\begin{array}{l}\text{gt---cpx---plag---amph}\\ \text{gt---amph---plag}\\ \text{(gt---chlor)---amph---plag}\\ \text{(gt---bio)---amph---plag}\\ \text{gt---amph---plag---ep---clinozo}\\ \text{gt---cpx---plag---scap (secondary)}\end{array}\right\} + \text{qtz} + \text{sphene} + \text{opaque}$$

Two assemblages reported in the literature, but not found in the course of the present study are kyanite—amphibole eclogite (Brière, 1920a), and an olivine—hypersthene—amphibole "eclogite" (Brière, 1920a, 1920b). Both assemblages were described as having symplectized clinopyroxenes, which indicates the instability of the assemblages under the latest metamorphic conditions. These two rocks represent extremes in compositional variation, aluminous and low-silica ultrabasic types.

The original, pretransition mineral assemblages observed or deduced from the above are:

$$\left.\begin{array}{l}\text{gt—cpx—amph}\\ \text{gt—cpx—amph—plag}\\ \text{gt—cpx—amph—zo}\\ \text{gt—cpx—amph—ky}\\ \text{gt—cpx—opx—amph—ol}\end{array}\right\} + \text{qtz} + \text{ru}$$

The importance of an aluminum silicate phase in metamorphic basic rocks has been discussed by Tilley (1937) and Lappin (1960). According to both authors, the aluminum silicate (kyanite) found in eclogites is not stable under amphibolite facies conditions. The kyanite reported by Brière (1920a) in Puy des Ferrières eclogites was observed to be altered upon amphibolitization of the rock. Thus the appearance of sillimanite in the amphibolite association listed above is notable. However, only one sample was found to contain this mineral and, as a result, any far-reaching conclusions might be premature, if not totally unwise. The rock in question is primarily composed of plagioclase, quartz, amphibole and biotite. The sillimanite occurs as fibrous masses in linear zones. It is frequently altered to muscovite or chlorite and does not appear to be derived from any specific pre-existing mineral but is frequently associated with biotite.

The explanation proposed for the suppression of an aluminum silicate during amphibolitization of eclogites is that both plagioclase and the amphibole are more aluminous than zoisite, garnet or clinopyroxene. Normal basic rocks do not contain enough alumina to produce an aluminum silicate in addition to plagioclase and hornblende. However the sillimanite amphibolite described here contains biotite, a mineral seldom found in eclogites. It might thus be assumed that the chemical composition of this amphibolite does not correspond to that of amphibole eclogites, or the majority of amphibolites. Nevertheless, sillimanite-amphibole rocks are rare. It is proposed here that they might represent a narrow zone of pressure-temperature conditions between micaceous amphibolites and pyroxene-bearing granulite facies rocks. The mutual relationships of these facies will be discussed later.

A fourth type of basic rock found to occur in the area is an apparent metadolerite. These rocks are characterized by large plagioclase laths which become progressively recrystallized as the rock is transformed to an amphibolite assemblage. This textural change is shown in Figure 2.

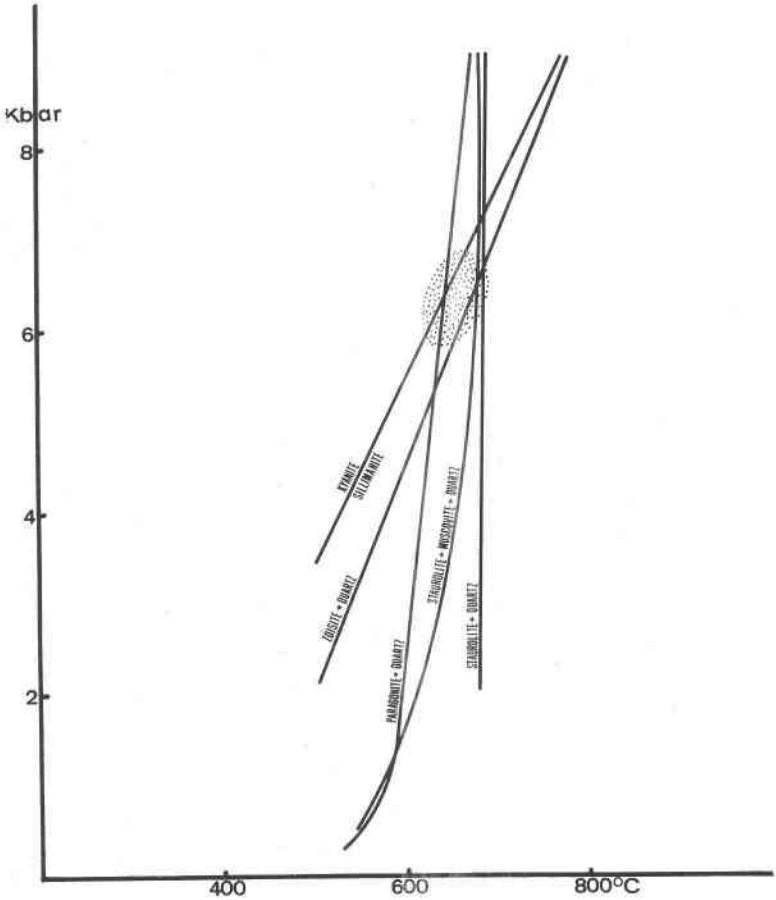

FIG. 3. Realtionships of the various mineral stabilities used in the study are shown on pressure ($P_{\text{total}} = P_{H_2O}$) temperature coordinates. The shaded area marks the passage from eclogite to amphibolite.

The composition of the plagioclase changes upon recrystallization, from about An_{60} to An_{40}, the latter composition being common to the amphibolites of the area. The extent of this amphibolitization is quite variable, being more marked towards the edges of the layers in which the dolerite texture is found. The least changed plagioclase crystals are frequently "dusty" in appearance, containing numerous minute inclusions. One rather unique feature of the dolerites is the existence of small garnets in the relatively unrecrystallized specimens. These garnets are automorphic, small in size (0.1 mm diameter) and appear neither to be related spatially to the original plagioclase, clinopyroxene, or opaques nor to be affected by the new phases of amphibole or biotite. There is no evidence of an initial olivine in the dolerites, nor is there evidence of exsolution in the original clinopyroxene. However, the dolerites are never completely fresh, and there is always the possibility that an initial phase has been recrystallized to a new mineral. The apparent original mineral assemblages in the dolerites were:

cpx—plag—il—qtz
cpx—plag—il—gt—qtz

and the metadolerites contain the stable assemblages:

plag—gt—amph—il—qtz
plag—amph—il—qtz

Sphene appears as an accessory phase in the more recrystallized metadolerites, *i.e.* those which mineralogically approach an almandine amphibolite. Frequently the opaque minerals are surrounded by a radially oriented amphibole rim. These amphibole grains tend to be darker in color than others in the rock.

This brief description of the dolerites immediately necessitates a comparison of these rocks with their apparent petrographic equivalents, the hyperites of Scandinavia, and meta-gabbros. Some examples of the hyperites have been described by Brögger (1934), Gjelsvik (1952), and Mitchell (1967); meta-gabbros or "coronites" by Shand (1945), Buddington (1952), and Warnaars (1967). A similar occurrence of a dolerite-amphibolite association has been described by O'Hara (1961). One similarity between all the examples cited is the transformation of a basic igneous rock mineralogy to that of the metamorphic amphibolite facies. This generally occurs near the edge of the initial igneous rock body, where the enclosing rocks present an amphibolite facies mineralogy. The cloudy feldspars seem to be common to these types of rocks.

Each author has attributed the appearance of garnet to a high-temperature metamorphism, either in a granulite or amphibolite metamorphic facies regime. However, the postulated origin of the garnet is not always the same in each case. Generally, excepting the example given by O'Hara, the garnet is present as a reaction product between two pre-existing phases and forms a ring around one of them, thus the name coronites. The rimmed mineral can be plagioclase, ilmenite, olivine, pyroxene, biotite or amphibole. Obviously, the composition of the garnets thus formed would be influenced by their mode of origin. The metadolerites from Uzerche do not, however, present garnets in ring or corona structures. Apparently, these garnets were not due to a bimineralic reaction and might, lacking evidence to the contrary, have crystallized from a melt or a glass. The one example of such a crystallization (O'Hara, 1961) has been demonstrated to have produced a garnet amphibolite assemblage. The Uzerche dolerites do not indicate instability of the garnet in the presence of amphibole, nor do they particularly indicate a necessity for the amphibole to accompany the garnet. However, upon more complete recrystallization of the rocks, the garnet phase is lost.

Gjelsvik (1952) has described dolerites or metadolerites from southern Norway which present many similarities with the mineral assemblages of the Uzerche rocks. He does find corona structures frequently, but they are less pronounced in olivine-free dolerites. The original dolerites were in a few instances transformed into a garnet—clinopyroxene—plagioclase assemblage which graded into an amphibolite towards the edge of the basic rock body. In one sample the final assemblage attained was garnet—clinopyroxene—biotite—plagioclase—quartz. The above two assemblages are represented in the Uzerche area by the eclogites and amphibole eclogites. It should be mentioned that the Sunnmøre area of Norway in which these metadolerites are found also contains many eclogites which were described by Eskola (1921). Gjelsvik, however, prefers to assign the garnet-bearing metadolerites to an intermediate origin between the granulite and eclogite facies.

In summary, the basic rocks in the area under study are of four types: garnet amphibolites; amphibolitized or symplectized eclogites; eclogites and amphibole eclogites; and metadolerites or hyperites. The most evident petrologic observation is that omphacite-bearing rocks became unstable in the late stages of metamorphic development in the area and were largely transformed to amphibolites. Symplectized zoisite and omphacites indicate that the destabilization of this facies was due to a change in physical conditions, as no new ions are necessary to produce the observed reaction products. The stability of zoisite+quartz (Newton, 1966) shown in Figure 3 is coincident with the stabilities of the other minerals cited at about 6.5 kbar pressure. It should be pointed out that the most common type of recrystallization, amphibolitization, indicates a net increase in water content for the silicate phases. It should also be noted that the eclogites or relicts thereof were found in all sectors of the area studied, irrespective of the mineralogy and deduced metamorphic zonation in the gneisses.

CHEMICAL COMPOSITION OF THE BASIC ROCKS

Table 3 lists the compositions and the CIPW norms of 5 eclogites and amphibole eclogites; 3 dolerites and 5 amphibolites. Only amphibolite

273 (Table 3, No. 7) appears to be distinct in composition from the other rocks, containing considerably more SiO_2 and Al_2O_3, factors which make it the only quartz and corundum normative rock. The chemical origin of this rock is probably different from that of the others.

The remaining samples can be described as nepheline or hypersthene normative basalt compositions. The silica content of all specimens is very constant, being very close to 47 weight percent. The normative calculations indicate variations in nepheline, albite, and magnetite content which might be more illusionary than real. The problem of Fe_2O_3—FeO analysis increases with the garnet content of the rocks: this mineral is brought into solution with difficulty, and hence the likelihood of iron oxidation during analysis is rather high. An undue Fe_2O_3 content tends to increase normative magnetite, with a corresponding suppression of virtual nepheline, should it be normally present. It can be seen that the eclogites have the highest normative magnetite content of the three rock groups. Nevertheless, the chemical analyses and normative calculations indicate very similar compositions for the three groups. It can be suggested that the mineral assemblages, dolerite, eclogite and amphibolite represent various alternatives for the same rock compositions. This is the prerequisite for the differentiation of mineral facies.

Chemistry of the Minerals in the Basic Rocks

Three mineral groups have been studied in some detail for the various rock types encountered in the study. The garnets, pyroxenes and amphiboles have been isolated from several rocks for comparison purposes. The results of chemical analyses and physical measurements of these minerals are shown in Table 4.

Physical properties were measured for garnets from five amphibolites, eight gneisses, eight eclogites, and three dolerites (Table 5). The chemical analyses of three garnets from the various types show that major components of solid solution are grossular, pyrope, and almandine; very little andradite and less than 5 percent spessartite are present. This being the case, use of Winchell's (1958) determinative tables allows a reasonable estimation of the compositions of the garnets based upon their physical properties. This method tends to underestimate the pyrope content for the samples by about 5 to 10 percent, when the chemically analyzed garnets are plotted in the diagram. The results are plotted in Figure 4. It is evident that the garnets from gneisses are much more almandine-rich than the other three types, a consequence of the difference in bulk composition of the rocks. This is reinforced by the intermediate composition of the garnet from the amphibole-bearing gneiss. The segregation of the amphibolite and eclogite garnet compositions indicates however a differ-

Table 3. Chemical Compositions and C.I.P.W. Norms of Some Basic Rocks from the Uzerche Area. Mineralogic Assemblages are also Given

	1	2	3	4	5	6	7	8	9	10	11	12	13
	168D	181D	180D	5 Brière	7 Brière	261D	273D	2 Brière	4 Brièere	1 Brière	355D	P6 V	— 251V
SiO_2	47.27	42.80	48.32	46.30	47.50	47.45	50.91	47.30	47.18	47.00	46.57	47.05	46.78
Al_2O_3	16.81	15.38	14.84	13.70	17.14	17.49	20.14	16.36	15.42	17.61	17.67	18.14	17.21
Fe_2O_3	5.04	2.57	5.36	5.51	2.00	1.72	1.37	3.88	2.58	2.25	0.93	1.15	1.37
FeO	6.32	5.76	5.05	10.80	6.04	7.20	12.80	7.38	7.07	6.78	9.14	8.55	9.56
MgO	5.72	5.68	8.04	6.98	10.37	5.95	3.19	7.38	8.29	8.78	8.20	8.26	8.77
MnO	0.12	0.22	0.21			0.07	0.13	tr			tr	0.11	0.21
CaO	12.40	17.27	14.52	11.90	13.61	16.15	6.67	13.60	15.58	14.90	10.53	10.83	9.83
Na_2O	2.79	2.82	3.16	2.66	1.42	2.37	1.06	1.47	2.02	1.14	2.79	2.77	2.68
K_2O	0.22	0.22	0.03	0.37	0.23	0.17	1.34	0.64	0.50	0.21	0.75	0.15	0.22
TiO_2	1.84	1.21	0.47	1.28	1.03	0.12	1.10	1.60	1.02	1.00	0.97	1.49	1.70
P_2O_5	0.24	0.13	0.06	0.30	0.14	0.08	0.10	0.20	0.03	0.40	tr	0.20	0.42
H_2O+	0.37	5.34	0.31	0.15	0.19	1.02	1.60				1.92	1.60	2.26
H_2O-	0.14	0.07	0.15		0.02	0.20	0.37	0.30	0.32	0.40	0.35	0.11	0.31
Total	99.28	99.47	100.52	99.95	99.69	99.89	100.78	100.11	100.01	100.47	99.82	100.41	100.42
Q							11.35						
Or	1.30	1.30	0.18	2.19	1.36	1.00	7.92	3.78	2.95	1.24	4.43	0.89	1.30
Ab	23.61	0.81	19.69	22.51	12.02	11.70	8.97	12.44	10.26	9.65	18.25	23.44	20.99
An	32.70	28.66	26.22	24.35	39.72	36.59	32.49	36.16	31.53	42.32	33.48	36.62	35.18
Ne		12.49	3.82			4.53			3.70		2.91		
C							5.04						
Di	21.94	43.43	36.12	26.98	21.55	35.34		24.27	36.77	23.54	15.33	12.96	6.22
Wo		1.06											
Hy	6.69			0.12	10.54		28.75	13.20		11.62		1.42	15.18
Ol	1.21		5.24	12.58	9.14	6.72		0.86	8.73	5.66	19.96	18.44	12.85
Mt	7.31	3.73	7.77	7.99	2.90	2.49	1.99	5.63	3.74	3.26	1.35	1.67	1.99
Ilm	3.49	2.30	0.89	2.43	1.96	0.23	2.09	3.04	1.94	1.90	1.84	2.83	3.23
Ap	0.52	0.28	0.13	0.66	0.31	0.17	0.22	0.44	0.07	0.87		0.44	0.92

Amphibole eclogites
- 168—gt, cpx symplectite, zo, bio, plag qtz, brown amph, op
- 181—gt, cpx-amph symplectite, brown amph, ru, calcite
- 180—gt, cpx, blue-green amph, plag, qtz, ru, zo
- Brière[a] 5—gt, cpx, amph, symplectite, qtz
- Brière 7—gt, cpx, ky, amph, ru, symplectite

Amphibolites
- 261—green amph, cpx, plag, qtz, sph
- 273—green amph, gt, plag, qtz, sph
- Brière 1—gt, amph symplectite, plag, qtz
- Brière 4—amph, plag, cpx, zo, sph

Dolerites
- 355—gt, plag, cpx, green amph, bio, op
- P 6—gt, plag, cpx, green amph, qtz, op
- 251—gt, plag, green amph, op

[a] Brière refers to Y. Brière (1920a)

TABLE 4. CHEMICAL COMPOSITION OF MINERALS FROM ROCKS OF THE UZERCHE AREA

	1	2	3	4	5	6	7	8	9
	58D	273N	180N	P 6N	261D	180N	261D	273N	181N
SiO_2	37.50	34.93	37.49	36.95	50.79	53.16	40.59	40.64	41.80
Al_2O_3	20.28	23.03	23.14	23.41	2.89	4.49	17.09	17.00	16.00
Fe_2O_3					0.05	3.41	1.28	0.51	1.08
FeO	37.93[a]	28.42[a]	21.13[a]	26.10[a]	8.98	6.74	14.64	16.34	11.84
MgO	3.77	2.04	6.17	6.58	13.00	9.92	7.46	8.06	11.62
MnO	1.58	1.02	0.49	0.46	0.05	tr	0.26	0.07	tr
CaO	0.44	7.13	9.96	5.33	23.26	16.25	12.48	11.19	12.07
Na_2O	0.23	0.13	0.23		0.49	4.65	2.09	1.22	2.50
K_2O	0.06	0.07	0.12		0.04	0.18	0.79	0.78	0.64
TiO_2	tr	0.40	0.21	tr	0.58	1.09	0.77	2.12	1.19
P_2O_5	0.07	0.18	tr	0.28	0.12	0.08	0.05	0.08	0.03
H_2O^+	1.40	2.52	0.84		0.36	0.17	2.10	2.39	1.79
H_2O^-	0.09	tr	tr			0.01	0.08	0.34	0.04
Total	98.35	99.86	99.78	99.11	100.61	100.15	99.68	100.74	100.60
Almandine	79	67	46	59					
Pyrope	16	9	25	25					
Grossular	1	22	28	15					
Spessartite	4	2	1	1					
N	1.807	1.798	1.772	1.773					
a Å	11.538	11.602	11.602	11.560					
γ					1.708	1.703	1.677	1.680	1.682
β					1.698	1.692	1.668	1.669	1.670
α					1.691	1.679	1.661	1.662	1.652
Tschermaks					4	1			
Acmite					0	10			
Jadeite					3	19			

Analyses 1 to 4: garnets; 5 and 6, clinopyroxenes; 7 to 9, amphiboles. Rock number 58, gneiss; 273, 261, amphibolites; 180, 181, amphibole eclogites; P6, dolerite.

[a] Total iron reported as FeO.

ence of physical conditions of formation as these rocks have similar bulk chemical compositions. The eclogite garnets are markedly more pyrope-rich than the amphibolite garnets. This observation has been made numerous times in the past by various authors, for example Eskola (1921), Tröger (1959), Yoder and Chinner (1960). The dolerite garnets are more scattered in their compositions than those of the other rock

Table 5. Physical Properties of Garnets

No. Sample	Mineralogy of rock	$n \pm 0.002$	$a \pm 0.009$ Å
Gneiss			
190	musc, bio, plag, K-spar, qtz	1.810	11.537
222	musc, bio, plag, K-spar, qtz	1.814	11.545
69	musc, bio, plag, K-spar, qtz	1.814	11.545
72	musc, bio, plag, gt, staur, qtz	1.805	11.547
165	bio, plag, K-spar, qtz	1.804	11.549
169	musc, bio, plag, qtz	1.807	11.550
323	plag, amph, bio, musc, qtz	1.792	11.604
Amphibolite			
296	amph, plag, qtz, op	1.797	11.611
367	amph, plag, qtz, sph	1.792	11.622
153	amph, plag, qtz, sph, op	1.797	11.621
SI	amph, plag, sph	1.792	11.634
Amphibole eclogite			
181	brown, amph, symplectite (cpx-amph) ru calcite	1.775	11.616
182	symplectite (cpx), plag, brown amph, ru, qtz	1.777	11.623
145a	symplectite (cpx-amph)	1.777	11.613
304c	symplectite (amph), sph-op, brown amph	1.777	11.617
138d	symplectite (amph), plag, brown amph, sph-op	1.777	11.618
168	symplectite (cpx), zo, bio, plag, qtz, brown amph, op	1.777	11.616
185	cpx, brown amph, bio, plag, clinozo, qtz, ru, op	1.778	11.599
Dolerite			
355	plag, cpx, amph, bio, op	1.778	11.620
251	plag, amph, op	1.766	11.574

types, but they do show a significantly greater pyrope content than the amphibolite facies garnets. Thus the metadolerites should be considered to be related to the eclogites and amphibole eclogites. The variation in their garnet compositions could be either due to variable physical conditions of formation for each rock, or to influence of a local chemical equilibrium between adjacent minerals.

The second mineral group treated is that of the clinopyroxenes, which were found in the amphibole eclogites and amphibolites (Table 4). The expected difference between the two types is the relatively high jadeite content of the eclogite pyroxene. This clinopyroxene can be considered typical of eclogite facies rocks, with a jadeite 20 percent and Tschermak's

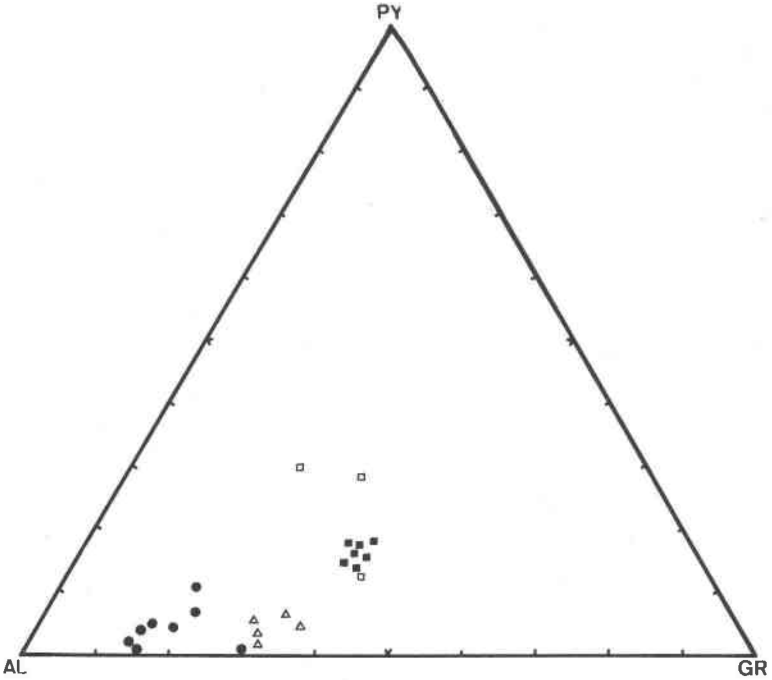

FIG. 4. Estimated compositions of garnets (Winchell, 1958) from four types of rocks in the Uzerche area are shown on pyrope-almandine-grossular coordinates. Chemical compositions of three garnets show the method to underestimate the pyrope molecule content by about 10 percent.

Circles = gneiss garnets; triangles = amphibolite garnets; solid squares = eclogite garnets; open squares = dolerite garnets.

1 percent molecular proportion (White, 1964). The jadeite content indicates, at a pressure of 6 kbar, a maximum temperature stability of 650°C for conditions of maximum solid solution (Kushiro, 1965). In fact, this temperature limit is undoubtedly too high considering that the pyroxene was not in equilibrium with albite, and that other pyroxene molecular species, such as acmite, are present.

The clinopyroxene from the amphibolite is notably low in Na_2O (0.49 percent) even though the rock from which it came contained 2.37 percent Na_2O. This is in contrast to the amphibole eclogite pyroxene containing 4.65 percent Na_2O, coming from a rock with 3.16 percent Na_2O.

Amphiboles from a garnet and from a clinopyroxene-bearing amphibolite were analyzed. These can be compared to one extracted from an amphibole eclogite (Table 4). The sodium and magnesium contents of the eclogite amphibole are somewhat higher than the others, but this difference is really not striking and cannot be used as a strong crystallochemical argument for delimitation of differing physical environments. However, the tendency for sodium enrichment has been noted by Binns (1967) in amphiboles from eclogites. It is most likely that the amphibole maintains a rather secondary role in the chemistry of the phases in amphibole maintains a rather secondary role in the chemistry of the phases in amphibole eclogites, the garnet, pyroxene and bulk composition dictating its chemistry.

PETROLOGIC CONCLUSIONS AND DISCUSSION

The descriptions of the gneiss and basic rock mineral assemblages given above, combined with the applicable experimentally-determined mineral stabilities, leads to the following description of the petrologic events believed to have taken place in the Uzerche area. The basic rocks were observed to have been modified by a late metamorphic event which left traces of preceeding assemblages. The most striking evidence of this phenomenon is the transformation of eclogite or amphibole eclogite into symplectized or amphibolitized assemblages. The gneisses show possible evidence of such an event in the production of sillimanite from the paragonite molecule of the white mica in rocks containing kyanite crystals. The small size (tens of meters in the smallest dimension) and irregular shapes of the basic rock bodies (sometimes found as bands or lenses in the gneissic country rock) indicate that both gneisses and eclogites suffered the same metamorphism; the eclogites were not introduced tectonically into the gneiss series.

It would appear that two types of metamorphism can be observed in the area. The first is the regional metamorphism of the gneissic rocks which appears to be zonal (Fig. 1). This zonation is marked by the instability of staurolite and then kyanite and paragonite (in solid solution in the white mica). The second metamorphism appears to be retrometamorphic, observed in the destabilization of the eclogite mineral assemblage. This was observed to have occurred throughout the area independently of position in the regional metamorphic sequence.

A recapitulation of the metamorphic history of the area is as follows: establishment of a regional metamorphic gradient during an orogenic episode which reached a maximum temperature near 650°C at 6.5 kbar, or greater pressures, permitting the eclogite mineral assemblage to be stable (where rock compositions were favorable) throughout the area, *i.e.* coexistence of garnet, omphacite, zoisite hornblende, and possibly plagioclase. A second phase of the orogenic cycle released anisotropic stresses, decreasing total pressure to lithostatic pressure, thus diminishing the total pressure enough to destabilize the eclogites, in particular the omphacites and zoisites. This produced the observed retromorphic effects.

Justification for the deduction of the second phase of metamorphism is made as follows. The symplectite textures found in the eclogites are typical of those incipient in eclogites known to have experienced pressure diminution in their metamorphic history: eclogite inclusions in basalts, serpentines, and kimberlites. These effects are particularly marked in the omphacites whose stability is pressure sensitive. Thus petrographic observation would seem to support a thesis of pressure decrease as a last phase of metamorphism. In order to have a relatively sudden release of pressure during metamorphism in the eclogite or amphibolite facies, either materials must be moved rapidly from depth by tectonic displacement or orogenic, anisotropic stress must be released at depth. Since there is no field evidence to support the former proposition (*i.e.* no large fault or thrust zones, no brecciated zones have been observed) the latter alternative must be entertained. However, the existence of anisotropic stress fields in rocks under high pressure and temperature conditions is, at the moment, a debated point. Experimental work would seem to indicate that some rocks deform by rupture when subjected to high fluid pressures and high temperatures for short periods of time (Towle and Riecker, 1969). Other materials, such as quartz, recrystallize relatively rapidly, deforming plastically under 1 kbar differential stress, at 8 kbar total pressure (Heard and Carter, 1968). A recent article by Sturt (1969) indicates that natural rocks, both hydrous and anhydrous (metasediments and a gabbro) can deform by rupture under amphibolite facies conditions, similar to those considered in the present study. The important point to know is the rapidity at which rock materials recrystallize under geologic conditions. Essentially, the experiments which would elucidate this problem have not been performed. This would involve taking a rock composed of a hydrous assemblage of minerals, and subjecting it to physical conditions believed to exist under crustal conditions. Heard and Carter (1968) indicate that quartzite recrystallizes more rapidly under hydrous than dry conditions, but nevertheless it can sustain one kbar differential stress at 8 kbar total pressure. This, however, does not involve either amphibolitic or eclogitic rocks. The recent observations by Sturt (1969) upon natural rocks, which show failure by wrench faulting under amphibolite facies conditions will be used by the present authors to substantiate their supposition that anisotropic stresses can develop at deep earth crustal conditions. We do however realize that the last word has not been said on the subject.

We would suggest that under the physical conditions deduced from the petrographic observations, maximum pressure need supercede lithostatic pressure by only 10 to 15 percent to produce the observed petrographic phenomena through a relaxation of the tectonic pressures.

The coincidence of the stabilities of zoisite+quartz, staurolite, kyanite−sillimanite and paragonite+quartz at 6.5 kbar and 650°C, at $P_{H_2O} = P_{total}$, lead the authors to believe the destabilization of the eclogites in the Uzerche area took place near these conditions during a pressure release at the end of an orogenic cycle.

The problem of interpretation regarding the dolerites and metadolerites (amphibolites) remains. These rocks, never found in massif shaped bodies but always in linear zones, appear not to have attained the eclogite paragenesis. This is evidenced by an absence of the symplectite structure replacing the pyroxene, an absence of porphyroblastic garnets, and the lack of rutile and consequent sphene-opaque structure, all of which are common features of the eclogites and transformed eclogites. Nevertheless, the dolerites do present the assemblage clinopyroxene-garnet-plagioclase which is not found in the amphibolites. The interpretation which seems most likely at the moment, and will be tentatively proposed here, is that they represent basic magma intruded into the rock sequence under physical conditions near those which produced eclogite, or amphibole eclogite rocks. They might however have crystallized at higher temperatures than the amphibole eclogites, due to their magmatic origin.

It is certain that many readers have, by this time, become quite exasperated by the lack of definition and discussion of the difference between the eclogite facies assemblages and those of the amphibolite and granulite facies. Certainly the assemblage omphacite-almandine garnet-plagioclase-amphibole, as noted in Table 5, presents some ambiguity as to its exact metamorphic facies. It should be remembered that the basic rocks found in the area form essentially two petrographic groups, although their bulk compositions are similar. One group, the amphibolites, represent typical garnet amphibolite facies rocks, in mineral assemblage and mineral compositions. The second group of rocks have been called here amphibole eclogites. They contain porphyroblastic garnets with about 25 percent pyrope molecule, and omphacitic clinopyroxene. These two phases are the major components of the rocks. However, occurring with these minerals, there are several others such as amphibole, quartz, sphene, and occasionally zoisite and plagioclase. The term amphibole eclogite is used, since the rocks are not strictly bimineralic, but the coexistence of omphacite and pyralspite garnet signifies a certain petrographic kindred. The term granulite facies was not used, and is not believed to be applicable, because the pyroxene is distinctly jadeitic (20 mole percent) and according to White (1964), it belongs to the eclogite type pyroxenes. Another point which has been demonstrated is that the garnet-clinopyroxene rocks alter during their last metamorphic recrystallization to amphibolites or symplectized assemblages. The interpretation, based upon petrologic deductions is that this recrystallization was due to a pressure release during late orogenesis. The amphibolites would then represent a lower pressure facies relative to the garnet pyroxene rocks, which is the generally presumed relationship between amphibolite and eclogite facies (see for example, Turner, 1968).

A very frequent phase in suites of granulite facies rocks is orthopyroxene, common to both basic and acidic, or pelitic types of rocks. Hypersthene is reported in only one rock of the Uzerche area. It is likely that its presence is controlled by a low silica content of the rock in which it occurs, as olivine is also present as a stable phase. However, in crustal granulite facies rocks, hypersthene is a common mineral (Turner, 1968). Since pressures near 6 kbar and 650°C are moderate enough to suggest a crystal origin for the Uzerche rocks, the extreme rarity of orthopyroxene in the metamorphic assemblages is taken as an indication that they do not represent the granulite facies as it is commonly defined.

The existence of plagioclase in these omphacite-pyralspite-garnet rocks is then of importance. Although zoisite is a common accessory mineral in crustal eclogitic rocks, plagioclase has generally been considered to be found only in granulite facies rocks. The two minerals are similar in composition, except that zoisite is hydrated. If the existence or nonexistence of plagioclase is a criteria to distinguish granulite from eclogite assemblages, the reaction anorthite=zoisite+aluminum silicate+quartz would delimit the two facies. However the observations made in the course of this study indicate that plagioclase can coexist with omphacite and thus be found in a rock which otherwise fulfills the requirements of being an eclogite. The existence of plagioclase in a garnet-clinopyroxene assemblage used by Ringwood and Green (1966) to distinguish between eclogite and granulite facies does not apply to the present study, in that the experiments these authors performed to establish this criteria were done under anhydrous conditions at pressures and temperatures well beyond the range of those deduced above. The major effect observed by Ringwood and Green was the solid solution of calcic plagioclase into diopside and garnet. These two substitutions are quite minor and almost constant for crustal eclogites (White, 1964; Tröger, 1959), frequently leaving the remaining "plagioclase" component in the form of zoisite.

Finally, the problem of the water content of the basic rocks should be discussed. The eclogite facies rocks are zoisite as well as amphibole bearing in the samples studied. It is thus evident that water was available in a great enough quantity to enter into the silicate phases under the physical conditions prevalent. However, the amphibolitized rocks are certainly more hydrous than those containing pyroxene. It appears that H_2O was never completely absent as a constituent during the metamorphic history of these rocks, nor was its presence necessary to destabilize the eclogite, since symplectites of anhydrous minerals replaced pyroxene and zoisite in some cases. It was observed that greater water availability did effect a more complete recrystallization near the edges of the eclogite, amphibole eclogite and dolerite bodies. Brief thermochemical arguments given by Essene and Fyfe (1967) indicate that eclogites represent a dense rock relative to emphibolites and are a result of higher total pressures of formation. Thus they can contain some hydrous phases but less total water than an amphibolite of similar composition. Destabilization of the eclogites in the presence of water would then result in their amphibolitization. However water availability (relatively high partial pressures of H_2O) is not the sole factor in amphibolitization of eclogites. The minerel stabilities used in the study to assess the physical conditions under which the rocks formed were for the most part determined under conditions of high water activity. If the coincidence of these curves, which correspond to observed mineral relations in the basic and gneissic rocks, indicates that all the observed or interpreted reactions took place under the same physical conditions, 6.5 kbar and 650°C then the activity of water in the rock systems must have been high. This is evidenced by the amphibolitization of the eclogites and amphibole eclogites.

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