PETROLOGY

PRELIMINARY NOTES ON GLAUCOPHANE-BEARING AND OTHER CRYSTALLINE SCHISTS FROM SOUTH EAST CELEBES, AND ON THE ORIGIN OF GLAUCOPHANE-BEARING ROCKS *)

BY

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(Communicated by Prof. H. A. BROUWER at the meeting of Sept. 30, 1950)

During the year 1949 the author had the opportunity to make a brief study of a collection of crystalline schists from South East Celebes; the investigated samples were collected some tens of years ago by BOTHÉ, HETZEL, and STRAETER of the "Dienst van de Mijnbouw". Since the general results of this study may be valuable to other investigators, they are published in advance in this preliminary note.

The investigated collection comprises more than 170 samples of crystalline schists, most of which have been collected in the Rumbia Mts, in and N. of the Mendoke Mts, and near the lower course of the river La Solo (see map). Some data on the petrology of these regions have already been published by WUNDERLIN (1913).

The investigated crystalline schists belong essentially to three groups,

corresponding to those recognized in a paper on the geology and petrology of the neighbouring island of Kabaena (DE ROEVER 1950):

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1°. rocks that have mainly been metamorphosed in the amphibolite and epidote-amphibolite facies (La Solo region),

2°. low grade dynamometamorphic phyllites and blastopsammitic quartzites (La Solo region), and

3°. strongly recrystallized rocks that have mainly been metamorphosed in the glaucophane-schist facies and that are devoid of relics of older metamorphic facies (Rumbia and Mendoke Mts).

The rocks of the first group, which have mainly been metamorphosed in the amphibolite and the epidote-amphibolite facies, have only been recognized as occurring in a narrow zone along the SW border of a large mass of peridotites and serpentines near the lower course of the river La Solo. They are characterized by the presence of large crystals of amphibole of a blue-green or green colour, and by the occurrence of minerals of the epidote-group (a.o. piedmontite), garnet, biotite, and non-alkaline metamorphic clinopyroxene. The garnet shows alteration into chlorite. Hysterogene pumpellyite was found in two samples. Hysterogene glaucophane and lawsonite, which have so frequently been found in the corresponding rocks of part of eastern Central Celebes (DE ROEVER 1947), have not been observed here. The rocks of this group do not show any features not yet known from eastern Central Celebes or Kabaena.

The low grade dynamometamorphic phyllites and blastopsammitic quartzites have been found in a zone adjoining that of the rocks of the first group on the SW side, in which direction the glaucophane-bearing rocks have been found at a larger distance. The rocks of the second group have apparently been metamorphosed in the greenschist facies.

The investigation of the rocks that have mainly been metamorphosed in the glaucophane-schist facies and that are devoid of relics of older metamorphic facies, from the Rumbia and Mendoke Mts, has yielded interesting results, and indicated a closer analogy between the geology and petrology of Celebes and that of the Alps than was hitherto supposed to exist. Almost sixty of the samples studied were found to contain lawsonite or glaucophane; crossite was recognized in only one of the samples. Though no relics of older metamorphic facies have been observed, almost all samples were recognized to be polymetamorphic, the polymetamorphism being illustrated by the alteration and deformation of the lawsonite and glaucophane. Minerals of the epidote-group and fibrous colourless to light green amphibole were found in many of these rocks. By far the majority of the rocks containing the latter minerals in addition to lawsonite and glaucophane were found to show features indicating a younger age for the minerals of the epidote-group and the fibrous colourless to light green amphibole, and an older age for the glaucophane and lawsonite, viz. alteration of the lawsonite into chlorite, minerals of the epidote-group, sericite, albite, and carbonate, alteration of the glaucophane into chlorite and albite, and the occurrence of rims of colourless to light green amphibole around the glaucophane. Complete pseudomorphs after

glaucophane or lawsonite were found in many of the rocks studied, also in a number of rocks in which no original lawsonite and glaucophane were left. Only in two of the rocks studied the minerals of the epidote-group and the fibrous colourless to light green amphibole were not accompanied by relics of lawsonite or glaucophane, or by pseudomorphs after these minerals. Furthermore the crystals of lawsonite and glaucophane have often been bent or broken. The minerals undoubtedly belonging to the younger phase of metamorphism, viz. the minerals of the epidote-group, the fibrous colourless to light green amphibole, and the chlorite, sericite, albite and carbonate resulting from the alteration of the lawsonite and glaucophane are indicative of the greenschist facies (TURNER 1948).

Almost half of the lawsonite- or glaucophane-bearing rocks studied was furthermore found to contain garnet, while chloritoid was observed in several of these rocks, sometimes together with garnet, lawsonite, and glaucophane. The occurrence of the garnet and chloritoid was found to be independent of the intensity of the younger metamorphism in the greenschist facies, and the mode of occurrence of the minerals mentioned indicated the contemporaneous development of garnet, chloritoid, lawsonite, and glaucophane. The garnet may also have been altered, into chlorite, while the crystals of chloritoid have sometimes been broken. Thus the rocks of the Rumbia and Mendoke Mts apparently belong to a hitherto unknown subfacies of the glaucophane-schist facies, characterized by the occurrence of garnet, chloritoid, lawsonite, and glaucophane, the *garnet-lawsonite-glaucophane-schist subfacies.*

Though most lawsonite- and glaucophane-bearing rocks of the collection were determined as paraschists, a number of orthoschists containing these minerals has also been observed. These orthoschists generally contain relics of igneous titaniferous augite with its characteristic colour. This titaniferous augite was found to have been altered along the rims and in veins into a green, apparently jadeite- and aegirine-bearing clinopyroxene. In the rocks of the Rumbia and Mendoke Mts the alkaline pyroxenes seem to be confined to these orthoschists. Perfect blastophitic structures were observed in several of the clinopyroxene-bearing rocks. In one instance, where the identity of the original felspar was established beyond doubt by the well-developed blastophitic structure, the original felspar was found to have been mainly altered into glaucophane. Other alteration-products of the original ophitic felspar are mainly albite, lawsonite, and chlorite.

The only structural relics of the lawsonite- and glaucophane-bearing paraschists are represented by a fine graphitic banding. In some crystals of lawsonite several folds of these bands have been found enclosed (definitely not S-shaped structures produced by rotation during the growth of the crystals), indicating that a phase of folding occurred before the formation of the lawsonite.

Some of the glaucophane- and lawsonite-bearing rocks were further

found to contain pumpellyite; in one of these the pumpellyite is clearly of a younger age than the glaucophane, as indicated by the zonary structure of crystals of amphibole that protrude from the main body of the rock into pumpellyitic lenses; these crystals show cores of glaucophane and rims and tips of very pale green amphibole.

Before discussing the results of the investigations described here we may first summarize our knowledge of the crystalline schists of eastern Central Celebes and Kabaena (DE ROEVER 1947 and 1950). Arguments were given for the existence of large scale overthrusts in these regions. An older metamorphism in the amphibolite and epidote-amphibolite facies, which is older than the radiolarites and the spilitic igneous rocks of the alpine geosyncline, could be distinguished from a younger metamorphism in the lawsonite-glaucophanite subfacies, which is younger than the radiolarites and the spilitic igneous rocks. The metamorphism in the amphibolite and the epidote-amphibolite facies was considered to belong to a pre-alpine orogenetic cycle, the original rocks consequently being of paleozoic or greater age. The mutual age-relations of the metamorphism in the amphibolite facies and the metamorphism in the epidote-amphibolite facies have not yet been adequately elucidated. The mineral pumpellyite was assumed to belong to a separate metamorphic facies, containing among others colourless amphibole, albite, quartz, and carbonate as other typical minerals. The pumpellyite is younger than the radiolarites and igneous rocks, but was found to be older than the glaucophanitic metamorphism in a number of rocks. Therefore the metamorphism in the pumpellyitic facies was considered as a kind of precursor of the metamorphism in the lawsonite-glaucophanite subfacies. This mineral, however, was also found in a number of rocks without critical minerals of the lawsonite-glaucophanite subfacies, occurring in a zone along the boundary of the region occupied by the rocks affected by the glaucophanitic metamorphism. The metamorphism in the lawsonite-glaucophanite subfacies could further be separated from a younger phase of dynamic metamorphism, which apparently accompanied the paroxysm of the overthrust movements. In Kabaena this younger phase of dynamic metamorphism expresses itself mainly in the deformation of the crystals of the characteristic minerals of the lawsonite-glaucophanite subfacies, the alteration of which is only slight. In Central Celebes alteration of these minerals was only locally observed (DE ROEVER 1947, page 98 and 114), while WILLEMS described the occurrence of deformed crystals of glaucophane in a number of rocks from western Central Celebes (1937). The dynamic metamorphism accompanying the great overthrust movements is possibly of post-Eocene age, since phyllitic rocks with Eocene fossils have been found in northern Celebes (BROUWER 1947, page 15—16). The original material of strongly recrystallized paraschists of the lawsonite-glaucophanite subfacies without relics of older metamorphic facies was furthermore argued to be of mesozoic age. These schists, which are widely

distributed in Central Celebes and Kabaena, are considered as metamorphic geosynclinal deposits of the alpine orogene, and have been compared with the "Bündnerschiefer" or "schistes lustrés" of the penninic overthrust sheets of the Alps. In both regions these schists apparently represent the lowermost tectonic unit(s) exposed. In Kabaena, and probably also in eastern Central Celebes they are covered by a tectonic unit that has only been affected by the youngest phase of dynamic metamorphism. In Kabaena this dynamometamorphic unit in its turn is covered by the rocks of the epidote-amphibolite and the amphibolite facies, which occur at the base of a large mass of peridotites and serpentines. A zonal distribution corresponding to this superposition was found in South East Celebes.

The lawsonite-glaucophanite subfacies, the existence of which was proved by the author, is a subfacies of low grade metamorphism, since the rocks of this subfacies grade into non-metamorphic rocks. Type-minerals of this subfacies in eastern Central Celebes are mainly glaucophane and crossite, jadeite and jadeite-aegirine, lawsonite, quartz, albite, muscovite, chlorite, carbonate, titanite, and hematite. In the slightly stronger metamorphic rocks of Kabaena chloritoid was also found. The lawsonite-glaucophanite subfacies is a.o. characterized by the instability of garnet and minerals of the epidote-group.

As to the origin of the glaucophanitic metamorphism the following may be quoted from the paper on Kabaena (DE ROEVER 1950): "Since the glaucophanitic metamorphism is definitely older than the dynamometamorphism accompanying the paroxysm of the overthrust movements, the glaucophanitic rocks have apparently not been originated under the influence of stresses producing large scale overthrusts, but under conditions governing after the sedimentation of part of the geosynclinal deposits, and before the paroxysm of the overthrust movements. For a metamorphism like that of the lawsonite-glaucophanite subfacies, apparently having its centre in the central part of the geosyncline, we then may conclude to conditions mainly determined by the geosynclinal situation of the metamorphism, with a relatively high hydrostatic pressure and more subordinate thermal influence and shearing stress, i.e. the metamorphism in the lawsonite-glaucophanite subfacies is a characteristic geosynclinal metamorphism, predominantly governed by the hydrostatic pressure inherent to its geosynclinal environment, with more subordinate thermal influence and shearing stress..... The above conclusion for the origin of the rocks of the glaucophane-schist facies is corroborated by two entirely independent facts. Firstly, in the Alps the essential distribution of the glaucophane-bearing rocks is in the penninic overthrust sheets; here the glaucophanitic metamorphism is older, too, than the paroxysm of the orogenetic movements, as indicated by the alteration of the glaucophane into chlorite, albite, and calcite....., and by the occurrence of zones of green amphibole around the glaucophane..... Secondly, many of the minerals of the glaucophane-schist facies are of a relatively high

specific gravity, indicating that hydrostatic pressure was an important factor governing their production."

According to their petrological characteristics and their tectonic position the rocks from South East Celebes that have mainly been metamorphosed in the amphibolite and epidote-amphibolite facies are to be compared with the corresponding rocks from Kabaena and eastern Central Celebes; their original material is considered to be of paleozoic or older age, while the metamorphism in the amphibolite facies and the epidote-amphibolite facies apparently took place during an orogenetic cycle of pre-alpine age.

The phyllites and blastopsammitic rocks of the second group have only been affected by the dynamic metamorphism accompanying the paroxysm of the overthrust movements; their original material is considered to be of mesozoic and possibly also eocene age.

The strongly recrystallized rocks that have mainly been metamorphosed in the glaucophane-schist facies and that are devoid of relics of older metamorphic facies correspond to the paraschists of comparable metamorphism in Kabaena and Central Celebes. So they are considered as metamorphic geosynclinal deposits of the alpine orogene, the original material being of mesozoic age. Main argument for this assumption is the absence of relics of older metamorphic facies, especially of epidote, in the corresponding rocks from Kabaena and Central Celebes. The resemblance to the "Bündnerschiefer" or "schistes lustrés" of the Alps is even more complete in South East Celebes, owing to the presence of orthoschists and owing to the greater intensity of the younger phase of dynamic metamorphism, which intensity may be compared to that of the corresponding metamorphism in the Alps.

The mode of occurrence of the mineral pumpellyite in the glaucophane-schists of South East Celebes leads to the supposition that the metamorphism in the glaucophane-schist facies has been adjoined in space and time by the metamorphism in the pumpellyitic facies: in a number of rocks from eastern Central Celebes the pumpellyite was found to be older than the glaucophanitic metamorphism, further it was also found there in rocks that have not been affected by the glaucophanitic metamorphism and that have been collected in a zone along the boundary of the region occupied by the glaucophanitic rocks, and lastly it was found as a younger mineral in the glaucophane-schists from South East Celebes. During the production of the mineral pumpellyite the confining pressure was probably lower than during the metamorphism in the glaucophane-schist facies; the temperature was probably also lower, while the relative importance of stress is insufficiently known.

The garnet-lawsonite-glaucophane-schist subfacies is apparently the adjoining higher metamorphic equivalent of the lawsonite-glaucophanite subfacies, which in Celebes represents the lowest grade of glaucophanitic metamorphism. Both subfacies are characterized by the instability of epidote, the latter also by the instability of garnet. The garnet-lawsonite-

glaucophane-schist subfacies may also be termed garnet-lawsonite subfacies of the glaucophane-schist facies; for the lawsonite-glaucophanite subfacies the name of lawsonite-chlorite subfacies may also be used, which, however, need not imply that chlorite is unstable in all types of rocks of the garnet-lawsonite subfacies. With rising intensity of the glaucophanitic metamorphism chloritoid apparently appears before garnet: chloritoid has not been found in the rocks with a very low grade of glaucophanitic metamorphism from eastern Central Celebes, whereas in the stronger metamorphic rocks of Central Kabaena chloritoid, but no garnet has been found, and whereas chloritoid and garnet appear together in the strongest metamorphic glaucophane-schists yet described by the author. The jadeite-rich alkalipyroxenes and crossite seem to be confined to the rocks of the subfacies with a lower grade of metamorphism. This is indicated by the important role of these minerals in eastern Central Celebes, and their comparative rareness in Kabaena and South East Celebes; the association of older crossite with younger glaucophane in a number of rocks from eastern Central Celebes points in the same direction. Jadeite and other jadeite-rich alkalipyroxenes are apparently formed during low grade glaucophanitic metamorphism, a statement that may also hold true for the occurrences of jadeite in other parts of the world. The low grade metamorphic origin of jadeite was already mentioned in a former paper (DE ROEVER 1947, page 164); the low temperature of origin has been confirmed by YODER (1950).

Glaucophane-schists with garnet and chloritoid, apparently belonging to the garnet-lawsonite-glaucophane-schist subfacies, have already been described from other localities in Celebes, too (a.o. DE ROEVER 1947, page 114).

As to the origin of the glaucophane-bearing rocks some additional remarks may be made, especially since TURNER (1948) doubts the existence of a separate glaucophane-schist facies.

The metamorphism in the glaucophane-schist facies has its main development in the metamorphic geosynclinal deposits of the deeper central parts of younger orogenes, like that of Celebes. There it is a genuine regional metamorphism. On the other hand glaucophane, etc. may be of irregular distribution in the peripheral or upper parts of these orogenes, as e.g. in part of eastern Central Celebes and in California (TALIAFERRO 1943). Though the rocks of California have not been studied from a facial point of view (occurrence of zonary amphiboles!) TALIAFERRO has sufficiently proved the importance of metasomatic processes for their formation; in California the development of glaucophane, etc. instead of the normal products of such metasomatic processes, like albite, etc. during or after this additive metamorphism, in the chemically adapted rocks, however must also have been controlled by physical factors, as indicated by the results of the investigations of the present author.

Though arguments for the existence of a separate glaucophane-schist

facies have already been given in a former paper (DE ROEVER 1947), this question here may be dealt with in a more elaborate way. The occurrence of lawsonite is confined to regions with glaucophane-bearing rocks, while lawsonite and glaucophane have been found in intimate association in numerous metamorphic rocks of very different character and varying chemical composition (original igneous and sedimentary rocks as well as previously existing metamorphic rocks). In the rocks from Celebes and Kabaena the lawsonite is not accompanied by contemporaneous anorthite, zoisite or clinozoisite, but it appears instead of these minerals. Further the absence of glaucophane or allied minerals in lawsonite-bearing rocks is apparently due either to the chemical composition of the rocks in question, or to alteration of the glaucophane, etc. So it is not only the occurrence of glaucophane alone that we have to explain, but also that of the mineral association lawsonite-glaucophane. This gives an entirely different aspect to the problem, since lawsonite, unlike glaucophane, is not of a peculiar chemical composition. The occurrence of such a special lime-mineral of normal composition in intimate association with glaucophane is not explained by the assumption of an essentially metasomatic or allied origin of the glaucophane, which therefore has to be rejected. On the contrary, the development of lawsonite instead of the chemically almost similar or resembling minerals anorthite, zoisite or clinozoisite must be due to special physical conditions, i.e. lawsonite must belong to one or more separate metamorphic subfacies, in which neither anorthite nor zoisite and clinozoisite appear as stable minerals. The intimate association of lawsonite with glaucophane described above indicates definitely that glaucophane is a stable mineral of these separate subfacies. In these subfacies glaucophane and allied alkalipyroboles appear as wide-spread minerals. Should the development of glaucophane be essentially controlled by metasomatism or allied causes, then metasomatism would be abnormally important in the rocks of these special subfacies as compared to those of other subfacies, which is very improbable. So the development of glaucophane in lawsonite-bearing rocks of suitable chemical composition may be assumed to be controlled by special physical conditions. So far we have only been dealing with glaucophane that occurs in intimate association with lawsonite. It would be the merest chance when the stability conditions of lawsonite and glaucophane were exactly similar to each other; therefore we may expect these minerals to have different areas of stability. So the glaucophane of regions without lawsonite may safely be assumed to have a mode of origin comparable to that of the glaucophane of lawsonite-bearing regions. Another strong argument for the essential unimportance of metasomatism for the development of glaucophane is furnished by the fact that most glaucophane-schists are not specially sodic rocks. The arguments mentioned imply the conclusion that the development of glaucophane in rocks of suitable chemical composition is controlled by special physical conditions, i.e. that there exists a separate

glaucophane-schist facies. Similarly as in other metamorphic facies metasomatism according to the principle of enrichment in the most stable constituents has occurred in the rocks of the glaucophane-schist facies. In the deeper central parts of younger orogenes like that of Celebes the glaucophane-schist facies is of regional distribution; near the boundaries of its stability-area, however, its distribution is irregular owing to the unequal distribution of the controlling physical factors.

Since the occurrence of the critical minerals of the glaucophane-schist facies, like lawsonite and glaucophane, is confined to chemically suitable rocks, these minerals may be rather scarce, like in the western part of eastern Central Celebes (excepting the Poso fault trough); many other type-minerals correspond with those of other facies, like quartz, albite, muscovite, chlorite, and calcite, so that the distribution of the glaucophane-schist facies is often obscured. The distribution of the glaucophane-schist facies furthermore may be difficult to recognize on account of the occurrence of minerals originated during a younger phase of dynamic metamorphism, like in the Alps and South East Celebes. In fact, the mode of origin of the glaucophane-schists contended by the author implies that the rocks of the glaucophane-schist facies are even generally influenced by a younger dynamic metamorphism and therefore are always more or less polymetamorphic. In many cases, however, this younger phase of metamorphism has mainly given rise to a deformation of the glaucophanitic minerals, whereas newly developed minerals are of limited occurrence.

For the reasons already given in a former paper (DE ROEVER 1950), which have been quoted above, the metamorphism in the glaucophane-schist facies is considered to be a characteristic metamorphism of geosynclines of the alpine type, the development of lawsonite and glaucophane being mainly governed by the relatively high confining pressure inherent to the geosynclinal environment, with more subordinate thermal influence and shearing stress. The age of the metamorphism in the glaucophane-schist facies is confined as yet to the period between the oldest phase of folding of the geosynclinal deposits (folded inclusions in lawsonite from South East Celebes) and the paroxysm of the overthrust movements. Further data on the age of this metamorphism may be provided by the occurrence of metamorphic and detrital glaucophane in fossiliferous rocks and formations. The author has the intention to make a survey of all literature on lawsonite- and glaucophane-bearing rocks in order to test and elaborate his conclusions.

Though relatively high confining pressure is considered to be an essential factor in the production of lawsonite and glaucophane, the influence of elevated temperature and shearing stress cannot be denied, the former being implied by the depth of formation, the latter by the schistosity of many glaucophane-bearing rocks. The development of critical minerals of the glaucophane-schist facies in very low grade metamorphic rocks, which grade into non-metamorphic rocks, indicates that only the relative

importance of the confining pressure has been the controlling factor in the production of these minerals, and not its absolute magnitude. Therefore in a diagram like that of ESKOLA (1939, page 345) the glaucophane-schist facies may be placed obliquely below the appropriate other facies, the confining pressure being lower for low grade glaucophanitic metamorphism, and higher for the corresponding high grade metamorphism. The metamorphism that produces blue-green amphiboles may be transitional between the glaucophanitic metamorphism and the "normal" regional metamorphism; here the role of stress may be larger than in the production of glaucophane-bearing rocks, while the confining pressure may have been of less importance. The apparently rare occurrence of glaucophane-bearing rocks in paleozoic orogenes and still older mountain systems may be due to the fact that the folding of their geosynclinal deposits has attained a smaller depth.

Concluding these general remarks the author wishes to state that his conclusions have been given in a rather too precise way for the sake of clearness; it cannot be doubted that complications may exist, and that e.g. the formation of glaucophane must have been at least of slightly different age in different parts of the same orogene.

The metamorphic history of the eastern part of Celebes and of Kabaena may now be briefly summarized. During an older orogenetic cycle paleozoic or older rocks were metamorphosed in the amphibolite and epidote-amphibolite facies. After the origination of the alpine geosyncline the geosynclinal deposits were affected by at least one phase of folding before the metamorphism in the glaucophane-schist facies. This metamorphism is thought to have been preceded, laterally accompanied, and followed by metamorphism in a facies characterized by the occurrence of pumpellyite. The pumpellyitic and the glaucophanitic metamorphism may be considered to represent one prolonged phase of metamorphism, which occurred when the geosynclinal deposits attained their greatest depths. The glaucophanitic metamorphism seems to be distinctly separate from the youngest dynamometamorphism in the greenschist facies that accompanied the paroxysm of the large scale overthrust movements, since blue-green amphiboles of intermediate age have not been found.

At the end of this paper some brief remarks may be made on the comparison of the metamorphism of Celebes with that of other islands of Indonesia. The occurrence of glaucophane-bearing rocks in a small region in Central Java was already described long ago (NIETHAMMER 1909). The regional importance of glaucophane in the underground of this island is illustrated by its detrital occurrence at several other localities (LOOS 1924, VAN BAREN 1928, DRUIF 1930). Furthermore several rocks of Timor have been found to contain crossite, etc., part of which was formerly considered to be of magmatic origin, e.g. the only igneous rocks known from the lowermost tectonic unit of Timor, the Kekneno-series (DE ROEVER 1940), and the alkalitrachytes of the feebly atlantic Permian differentia-

tion-series of the next higher Sonnebait overthrust sheet, which were formed during the embryonal stages in the evolution of the geosyncline (DE ROEVER 1942). These examples, which are far from complete, may suffice to indicate that a metamorphism in the glaucophane-schist facies has also occurred in other Indonesian islands; metamorphic geosynclinal deposits like those of Celebes and comparable to those of the penninic overthrust sheets of the Alps may therefore be hidden below or near other parts of the island arcs of Indonesia.

Amsterdam, Geological Institute, June 1950.

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