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SOME DIFFERENCES BETWEEN POST-PALEOZOIC AND OLDER REGIONAL METAMORPHISM

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ABSTRACT

Many regionally metamorphosed rocks found in post-Paleozoic orogenic zones show important mineralogical differences from the corresponding rocks in older orogenic belts. Metamorphism in the glaucophane schist facies, for instance, shows a striking preferential distribution in the post-Paleozoic orogenic belts. Furthermore, it seems that all known lawsonite is of post-Paleozoic age. It is suggested that post-Paleozoic regional metamorphism, when compared with pre-Mesozoic regional metamorphism, is characterized by the predominance of less steep geothermal gradients during the main phase of metamorphism. There may have been a general, though possibly oscillating, decrease in the steepness of the geothermal gradients during the main phases of regional metamorphism from the early pre-Cambrian toward the youngest orogenic epochs, involving certain changes in the character of the metamorphic mineral assemblages produced. Seen in this light, it seems by no means impossible, for instance, that lawsonite will indeed appear to be a guide mineral for post-Paleozoic metamorphism. It is hoped that the results of this study will encourage further investigations in this interesting field of historical mineralogy and petrology.

A comparison between post-Paleozoic and pre-Mesozoic regional metamorphism involves many difficulties. In many cases it is still unknown whether a certain type of metamorphism shown by older rocks in a given orogenic belt was produced during the formation of that belt or during a previous orogenic cycle. Moreover in several regions even the age of the original rocks is unknown. Therefore a comparison of post-Paleozoic and older regional metamorphism can only be based on data gathered in comparatively well-known regions, the age relations in adjacent parts of the same orogenic belt being inferred by analogy.

A further difficulty is that the most detailed classification of the different types of metamorphism, the classification according to Eskola's ingenious facies principle, has not yet been generally accepted as one of our most important aids in the study of polymetamorphic rocks [2]. Classification according to the facies principle is particularly useful when the different types of metamorphism shown by polymetamorphic rocks are of an approximately similar grade; this is illustrated by the results of recent investigations of rocks from Celebes (de Roever, 1947, 1950, 1953) and in Corsica (Brouwer and Egeler, 1952; Egeler, 1956; further references are given in the last-named paper). Particularly in the description of rocks from the Alps, Eskola's classification has only seldom been used. Hence a comparison of post-Paleozoic and older regional metamorphism cannot be adequately based on facies studies. It is to be welcomed, therefore, that the use of the facies classification was recently recommended by the well-known Swiss petrologist Bearth (1952).

A general comparison between post-Paleozoic and pre-Mesozoic regional metamorphism, however, can also be based on the study of those minerals which show a preferential distribution in either the post-Paleozoic or the older orogenic belts. As already recognized by Eskola (1929), one of the most striking differences in this respect is represented by the abundance of glaucophane and crossite in the metamorphic rocks of the post-Paleozoic orogenic zones and their scarcity and local occurrence in the older belts. Glaucophane and crossite are very widely distributed, e.g., in Corsica, along the Franco-Italian border, in Greece, in Celebes and in New Caledonia, where these minerals may occur in extensive regions. On the other hand, the older areas with glaucophane or crossite are small, e.g. those of Ayrshire, Anglesey, Ile de Groix, Queensland (Schürmann, 1951, 1953), and northern Portugal (Cotelo Neiva, 1948, p. 122-125). Of all blue metamorphic amphiboles known, more than 95 percent, perhaps even con-

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[2] The reluctance of many authors to use the facies classification may have been caused partly by the unsatisfactory character of the definitions of a metamorphic facies given in several important textbooks. This question was recently discussed by Ramberg (1952, p. 136), who gave the following more appropriate definition: "Rocks formed or recrystallized within a certain P,T-field, limited by the stability of certain critical minerals of defined composition, belong to the same mineral facies." Again, some authors may have rejected the facies classification for polymetamorphic rocks because the mineral assemblages of such rocks do not closely approximate equilibrium conditions. If, however, the existence of a number of given metamorphic facies has been definitely established, and if the corresponding critical minerals or associations are sufficiently known, it is also warranted to use these data for the disentangling of the history of polymetamorphic rocks.

siderably more, seems to be of post-Paleozoic age.

A still more striking preferential distribution is shown by the mineral lawsonite. This mineral is of plentiful occurrence in many parts of the post-Paleozoic orogenic belts, where it is confined to regions with glaucophane-bearing rocks. On the other hand, no lawsonite seems ever to have been found in Anglesey or Ayrshire (personal communication by Professor Tilley), in Ile de Groix (unpublished investigations by the present author) and in the other older occurrences of glaucophane and crossite. Indeed, it seems that all lawsonite known is of post-Paleozoic age. It may be that some exceptions to this rule will be found, or have already been found, but the fact remains that there are empirical indications that if not all, virtually all lawsonite was produced by post-Paleozoic metamorphism.

On the other hand, there are at least several minerals that seem to be less wide-spread as post-Paleozoic than as older metamorphic products. Staub (1948) assumes that biotite, hornblende, and several other minerals show a preferential distribution in the oldest rocks of the Alps. In several other parts of the post-Paleozoic orogenic belts large quantities of metamorphic biotite [3] seem to be confined to pre-Mesozoic units incorporated in these belts. This is considered to hold true for large parts of Corsica (Egeler, 1956, and references given by this author) and similarly for eastern Celebes and the adjacent island of Kabaena. Biotite may be plentiful, however, in regions showing post-Paleozoic thermal or plutonic metamorphism. Non-fibrous green hornblende seems to show an even more pronounced preferential distribution as a product of older metamorphism; in Corsica and eastern Celebes this mineral was also found to be of pre-Mesozoic age.

The above instances may suffice to illustrate that many regionally metamorphosed rocks found in post-Paleozoic orogenic zones show striking mineralogical differences from the corresponding rocks in older orogenic belts.

The significance of the preferential distribution of the minerals mentioned above can best be discussed in terms of the facies principle. Glaucophane, crossite and lawsonite are all three critical minerals of the glaucophane schist facies, in which biotite and non-fibrous green hornblende are not known as stable constituents [4].

Hence we may conclude that metamorphism in the glaucophane schist facies shows a striking preferential distribution in the post-Paleozoic orogenic belts. Further, those subfacies of this facies which are characterized by the stability of lawsonite, the lawsonite-glaucophanite subfacies and the garnet-lawsonite-glaucophane schist subfacies, seem to be exclusively confined to these belts. In several parts of these post-Paleozoic belts the metamorphism in the glaucophane schist facies is followed by a subordinate late phase of metamorphism in the green schist facies.

Now the question arises to which cause this preferential distribution of rocks of the glaucophane schist facies in younger orogenic zones is to be ascribed. Almost complete erosion of such rocks in the older belts is apparently to be dismissed, since in these belts rocks of the green schist and epidote-amphibolite facies — i.e. of facies that are considered as temperature equivalents of the glaucophane schist facies — are of wide-spread occurrence. Further, almost all glaucophane, crossite and lawsonite that have escaped alteration during later phases of metamorphism, show a remarkably fresh appearance. Hence the scarcity or absence of these minerals in older belts is apparently neither due to their being preferentially altered in the course of the geological history. Evidently we are dealing here with some special characteristics of the orogenic periods in question.

In this respect attention may be drawn to the comparatively high specific gravity of the critical minerals of the glaucophane schist facies (Eskola, 1929) and to the range of temperatures during their formation, which appears to correspond essentially to that of the green schist and epidote-amphibolite facies. As already concluded in a former paper (de Roever, 1955), the conditions giving rise to metamorphism in the glaucophane schist facies are apparently characterized by slightly higher pressures, or, in other words, by a slightly different geothermal gradient during the metamorphism. This gradient is considered to have been lower, i.e. less steep, during metamorphism in the glaucophane schist facies than during metamorphism in the other facies mentioned.

[3] The biotite-like mineral stilpnomelane, which is often of post-Paleozoic age, should not be mistaken for biotite.

[4] It may be remarked here that the existence of a separate glaucophane schist facies has not been generally accepted but, in the opinion of the author, has now been definitely established. Main arguments are (1) the intimate association of lawsonite and glaucophane in numerous metamorphic rocks of very different character, the occurrence of lawsonite being confined to regions with glaucophane-bearing rocks; and (2) the chemical equivalence of many of the natural assemblages with glaucophane and lawsonite and many assemblages containing albite, chlorite, tremolite-actinolite and clinozoisite-epidote (de Roever, 1950, 1955).

It is suggested, therefore, that post-Paleozoic regional metamorphism, when compared with pre-Mesozoic regional metamorphism, is characterized by the predominance of less steep geothermal gradients during the main phase of metamorphism.

On other grounds some authors have assumed the existence of analogous differences in geothermal gradient between different orogenic epochs. According to Daly (1917), Bucher (1933), and Turner (1948, p. 288) the temperature gradients were apparently steeper in early pre-Cambrian times than afterwards, so that conditions permitting regional metamorphism were reached much closer to the surface than was the case in later geological periods. Bucher goes even farther and assumes a regressive change toward the post-Paleozoic belts.

Therefore there may have been a general, though possibly oscillating, decrease in the steepness of the geothermal gradients during the main phases of regional metamorphism from the early pre-Cambrian toward the youngest orogenic epochs.

Seen in this light, the apparent absence of lawsonite and the scarcity of glaucophane and crossite among the products of pre-Mesozoic regional metamorphism gain in importance. There is apparently not only an evolution of life during the history of the earth, but also some change in the character of the metamorphic mineral assemblages produced during the main phases of regional metamorphism of the various orogenic epochs[5]. It seems by no means impossible that lawsonite will indeed appear to be a guide mineral for post-Paleozoic metamorphism, and that its occurrence in pebbles in non-metamorphic clastic sediments will appear to indicate that the sediments in question are of post-Paleozoic age. Although glaucophane and crossite are of much less value as indicators of the age of a period of metamorphism, even the occurrence of these minerals in extensive regional distribution may similarly indicate a post-Paleozoic age.

[5] In this respect it may also be mentioned that eclogites, which are rocks of great density, seem to be absent or rare in pre-Cambrian complexes. The origin of at least part of these rocks may be roughly comparable to that of the rocks of the glaucophane schist facies.

In the opinion of the author, a discussion of the origin of the phenomena described above is beyond the scope of the present paper. It is hoped, however, that the above lines will encourage further investigations in this interesting field of historical mineralogy and petrology.

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DISCUSSION

Prof. DE SITTER (Leiden) draws attention to an gradient depends much less on the general geothermal gradient than on the depth of the thermal front, which may be accompanied by intrusive rocks. He cites the conditions near the massif of St. Barthélemy, described by Zwart. Here the succession of the zones of thermal metamorphism is much more rapid where the distance to the contemporaneous earth surface was small, than where this distance was large. Though in the former case the gradient was much steeper than in the latter, there is no difference between the mineral zones developed.

Dr. DE ROEVER points out that the gradients dealt with in his lecture are not world-wide general geothermal gradients but local geothermal gradients in orogenic belts, prevailing during the main phase of regional metamorphism. Such a local geothermal gradient is to be defined as the average thermal gradient above a rock that is being metamorphosed. It is expressed in the ratio between temperature and depth-controlled pressure. A local geothermal gradient thus defined, may indeed be considered as depending not only on a world-wide general geothermal gradient but also on local circumstances, which latter, in fact, may be much more important. Prof. de Sitter's question, however, touches the origin of the phenomena described, for which, at the moment, the speaker is not able to give an adequate explanation, As to the second part of Prof. de Sitter's remark: if there is a thermal front that is distinctly connected with the presence of granitic rocks, as in both St. Barthélemy examples, the local geothermal gradients during metamorphism are steeper than those connected with the formation of glaucophane-bearing rocks; in the large region of rocks of the glaucophane schist facies in central Celebes, for instance, synmetamorphic granitic rocks have not been found. Further, the rather steep gradients of the two St. Barthélemy examples, though greatly different, were apparently of such magnitudes that metamorphism still took place within the P,T-fields of the same mineral assemblages. With regard to the concept of a thermal front, Dr. de Roever judges it by no means impossible that during certain kinds of regional metamorphism there was not a raise but a depression of the isotherms, as contended by Daly. This may have occurred when the effects of downward displacement by folding and geosynclinal subsidence were greater than those of the conduction of heat through the rocks, which is extremely slow.

Dr. KÜNDIG (B.P.M.) remarks that the crust of the earth passes through an evolution, which line is also followed by the orogens. It is difficult, however, to discriminate between factors controlled by the general line and such controlled by phases of orogenesis. Studies of Nantz in the United States and Canada on sediments, hypotheses of changes in the composition of the oceans, etc., lead in the same direction.

Dr. DE ROEVER replies that, in order to avoid the effects of local influences and special phases of orogenesis, he made a comparison in a very general sense, between all exposed parts known of all post-Paleozoic and older orogenic belts. Therefore, the striking preferential distribution of glaucophane, crossite and lawsonite in post-Paleozoic belts, to his opinion, is indeed controlled by the general line of evolution of the earth's crust. Perhaps age-controlled differences shown by some other geological objects are also connected with the steepness of the geothermal gradient.

Dr. SCHÜRMANN remarks that the length of time elapsed after the formation of the metamorphic rocks of the older orogenic belts, must be taken into account. Pre-Cambrian and Paleozoic schists have been metamorphosed during so many different orogenic epochs that original glaucophane may have disappeared.

Dr. DE ROEVER: It is not possible to accept the explanation mentioned by Dr. Schürmann, since there are many parts of older orogenic belts that have not been incorporated in younger belts; this is clearly illustrated by the different geographical position of orogenic belts of different ages. This fact is also of some importance in connection with the views of Daly, Bucher und Turner on the steepness of the geothermal gradients in early pre-Cambrian times, since one of the main arguments of these authors is concerned with the amount of erosion in early pre-Cambrian orogenic belts. In this respect the following may be cited from Bucher (op.cit., p. 296): "It is customary to speak of the structure of the Archean rocks as being the product of processes that have been operative 'at great depths'. But there seems little reason for this assertion. The Epi-Archean peneplain truncates these structures. Why should the structures revealed by Epi-Archean base-levelling differ from those exposed by, say, Epi-Carboniferous erosion to base-level? We are deceived by the subconscious thought of the great sediments that have accumulated on top of the Archeozoic rocks in some parts of the world.

If we are to believe that the Archeozoic structures originated at greater depth than those revealed of later date, we must also assume that greater amounts of rock were removed by erosion during Epi-Archean peneplanation than at any time since. The writer knows of no observation which would support this assumption."

Dr. PANNEKOEK (Geol. Survey) would like to have some additional information on what Dr. de Roever means with a "steep" and what with a "low" geothermal gradient. Do we have to assume that the steep one is many times greater than the low one or is it only slightly greater? Further, Prof. de Sitter mentioned an example of great differences in geothermal gradient without much difference in metamorphism. Other examples show that different minerals may be formed with only small differences in gradient.

Dr. DE ROEVER: This can be illustrated in a P,T-diagram, when we draw a line separating the fields of stability of a group of higher pressure assemblages (e.g. those of the glaucophane schist and eclogite facies) from the fields of stability of a group of lower pressure assemblages (e.g. those of the so-called normal facies series). Within the group of lower pressure fields there may be large differences in P,T-ratio, or, in other words, the group of steeper gradients comprises gradients that may show large differences (e.g. the examples mentioned by Prof. de Sitter). On the other hand, the differences in P,T-ratio between metamorphism on both sides of the separating line may be small, i.e., the differences in gradient between regional metamorphism in the glaucophane schist facies and regional metamorphism in the green schist and albite-epidote-amphibolite facies may be small. The latter differences may be comparable to those between 20° and 25° C per km.

Prof. NIEUWENKAMP (Utrecht) would like to have some information about the importance of the history of a metamorphic rock before metamorphism but after the formation of its original material. Is it important, whether a rock is rapidly or slowly heated, etc.? Further, the mineral assemblage produced need not be an equilibrium assemblage.

Dr. DE ROEVER remarks that, in his opinion, the previous history as meant by Prof. Nieuwenkamp does not influence the character of the mineral assemblages produced as long as there is no previous metamorphism, e.g. by internal movements under conditions favourable for metamorphism. The actual mineral assemblage found often is a non-equilibrium assemblage, as illustrated by the frequent occurrence of unstable relics and hysterogene minerals.

Prof. BROUWER (Amsterdam) asks whether a certain amount of hydrostatic pressure is essential to the formation of glaucophane and lawsonite, and, if so, whether this hydrostatic pressure is only controlled by depth.

Dr. DE ROEVER replies that under the conditions prevailing in nature, i.e., at metamorphic temperatures, a certain amount of pressure is indeed considered to be essential to the formation of the minerals mentioned. This need not hold true, however, for an eventual laboratory synthesis of glaucophane and lawsonite at room temperature. Regional metamorphism in the glaucophane schist facies in considered to be a regional dislocation metamorphism under confining pressures that are slightly higher than those prevailing during regional metamorphism in the green schist and albite-epidote-amphibolite facies. Besides depth-controlled pressure there may be a certain amount of confining pressure originated by the combined effect of unilateral pressure and resistance to deformation. In this respect it may be mentioned that in hardness tests with a Vickers indenter nearly two-thirds of the mean pressure of contact is in the form of a hydrostatic pressure and only one-third remains effective in producing plastic indentation (Tabor, Endeavour, Jan. 1954).

Mr. TOBI (Leiden) asks whether there are any theoretical objections against local genesis of lawsonite and glaucophane by pre-Mesozoic regional metamorphism.

Dr. DE ROEVER: No, there may be local variations in the magnitude of the geothermal gradient during the main phase of regional metamorphism. Since lawsonite, unlike glaucophane, has not been found in pre-Mesozoic orogenic belts, this mineral may require slightly higher pressures for its formation.