OROGENESIS AND METAMORPHIC FACIES SERIES IN EUROPE

by

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Abstract

The Hercynian (Variscan) orogenic belt of Europe is characterized by the widespread occurrence of low pressure metamorphism in its crystalline rocks. Metamorphic rocks of the Alpine mountain chain were formed under high pressures. In addition to this difference, both belts contrast by their extent, structure, amount of uplift, granites, and basic and ultrabasic rocks. The Caledonian belt has an intermediate character, whereas the Svecofennian-Karelian Orogen of the Baltic shield is more of the Hercynian type. Different from the European belts is the circumpacific region with its paired metamorphic belts.

INTRODUCTION

On the occasion of a meeting at the University of Aarhus, where the mapping of metamorphic regions of the world is being discussed, it is appropriate to talk about the metamorphism in European orogenic belts. When the distribution of certain metamorphic minerals and mineral assemblages in Europe are plotted on maps, it appears that a certain group of minerals follows the pattern of one orogenic belt, and another group follows another orogenic belt. Other characteristics of these belts also differ remarkably. Together with the mineralogical differences this leads to the recognition of two extreme types of orogenies with intermediate types in between. Diagnostic minerals and mineral assemblages have lead MIYASHIRO (1961) to the concept of facies series, in which the formation of a number of progressive metamorphic facies is dependent on the pressures in the rocks during metamorphism. For the distinction of these facies series pelitic rocks with aluminium-silicates can be used in the amphibolite facies, and basic rocks in the greenschist and glaucophane-schist facies.

THE HERCYNIAN (VARISCAN) OROGENIC BELT

The Hercynian foldbelt is of very large extent in Europe. Although it is partly covered by epicontinental sediments like in the Paris, Aquitanian and Ebro Basins, etc., and partly involved in the Alpine orogeny, the present outcrops show that this belt covers an almost uninterrupted region in the middle and south of Europe with a surface area of approximately 1500 × 2000 km. Besides covering such a large area, the vast amount of crystalline schists is remarkable. These rocks occur for instance in the Bohemian massif, in the Black Forest, Vosges, and Central Massif (France). They also occur in Brittany, the Iberic peninsula, Corsica, Sardinia, Calabria and in the Alpine central massifs (Fig. 1). In most of these areas pelitic rocks of medium to high grade are characterized by the occurrence of andalusite, cordierite, sillimanite, often with staurolite and sometimes with garnet.

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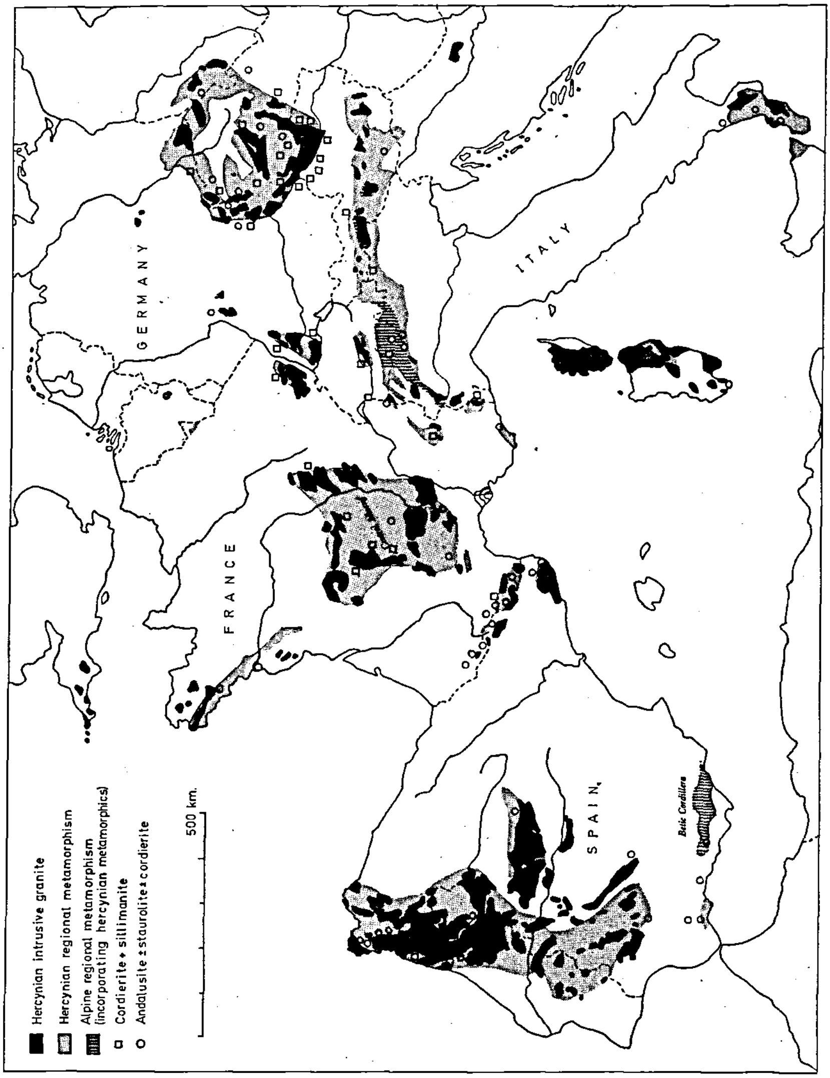

Fig. 1. Map of Western Europe, showing distribution of Hercynian metamorphic rocks, granites and low pressure minerals.

Kyanite, on the other hand is absent in most of these regions, although some minor occurrences have been found. The presence of andalusite, cordierite and sillimanite indicates that these rocks belong to the andalusite-sillimanite type facies series of MYASHIRO (1961). The Hercynian age of the metamorphism in this facies series has been demonstrated in a number of areas, either by stratigraphic or radiometric dating. Stratigraphic dating has been done in the Bohemian massif (BEDERKE, 1935, and SCHREYER, 1966), Montagne Noire (SCHUILING, 1960), Pyrenees (ZWART, 1963), Portugal (PRIEM, 1962), and the Sierra Morena, Spain, (FABRIÈS, 1963). Radiometric dating has been carried out in the Bohemian Massif (DAVIS & SCHREYER, 1962; SMEJKAL, 1965), Black Forest (MEHNERT, 1958), Central Massif (CHEVENOY, 1958), Pyrenees (ROUBAULT et al., 1963), and Galicia (CAPDEVILA & VIALETTE, 1965, PRIEM et al., 1966). The apparent ages fall within the range 260–360 m.y., that is Upper Devonian or Carboniferous.

In most of the other areas mentioned the Hercynian age of the metamorphism has not been demonstrated beyond doubt, but most workers in the areas concerned are convinced of such an age. Consequently the presence of the low pressure facies series appears to be a fundamental characteristic of the Hercynian belt.

Although metamorphism occurred under low pressure, the grade of metamorphism is often rather high. In many of the above mentioned regions the rocks contain cordierite, sillimanite and potassium feldspar which indicate the high temperature part of the amphibolite facies. Many of these rocks are migmatitic and often grade into granitic rocks. They are the result of partial anatexis. Such rocks have been described from almost regions within the Hercynian orogenic belt. Grades higher than the amphibolitic facies are seldom reached, and large outcrops of Hercynian granulite facies are either unknown, or their age assignment is uncertain.

Another peculiarity of many of these regions is that the transition from low grade to high grade may take place within a relatively short distance. This has already been described by BEDERKE (1947) from the Altvatergebirge (E. part of Bohemian Mass), later by PALM (1957) and SCHUILING (1960) from the southern part of the Central Massif and the Montagne Noire, and by ZWART (1962) from the Pyrenees. The shallow position of the metamorphism in the Pyrenees and the related low pressures have been emphasized by the present author (1956, 1963). He arrived at a depth of 3000–4000 m for the upper part of the andalusite bearing rocks and 4500 m for the cordierite-sillimanite bearing schists and migmatites. This corresponds to pressures of approximately 1 and 1,3 kb respectively, if it is assumed that pressures are directly dependent upon the thickness of the cover. This involves quite high geothermal gradients, estimated for some areas in the Pyrenees at 150° C/km, which probably represent an extreme figure for regional metamorphic rocks. Even higher estimates have been made by BEDERKE (1947) and SCHUILING (1960) but their figures have not the same accuracy as the Pyrenean ones, and tend to be exaggerated. However, the order of magnitude is comparable with the Pyrenean dates. It is obvious that high geothermal gradients, shallow low pressure metamorphism and the rapid transition from low to high grade, indicating the thinness of the metamorphic zones, are features which are interrelated.

A point which merits some discussion is the maximum depth at which the same low pressure metamorphism can still take place. In the Pyrenees the maximum thickness of the metamorphic sequence is about 10 km, which, together with the unmetamorphosed or low grade overburden of 4–5 km, gives a maximum depth of 15 km. Elsewhere, for example, in the Central Massif and the Bohemian Massif, where there is a much more widespread occurrence of crystalline schists in the low pressure facies series, the depth of exposure is probably somewhat greater and may be estimated at up to 20 km. These depths lead us to another feature; the amount and rate of uplift. These have apparently been rather small. In some areas post-Carboniferous uplift has amounted to not more than a few kilometres. In other areas it has been greater, but probably rarely exceeds 15 to 20 km.

Another feature of the Hercynian belt is the abundancy of intrusive granitic rocks. They occur in all regions where Hercynian metamorphism has taken place, and often the bodies are of considerable size (Fig. 1). Their age, which has been determined both by stratigraphic and radiometric methods, is almost everywhere Carboniferous, placing them in the final stages of the Hercynian orogeny. This enormous amount of granite has been called the "Hercynian Complex" by FAUL (1962).

It is quite probable that there is a direct relation between the metamorphism and the intrusive granites. We have already seen that in most regions the metamorphism reached a grade high enough to permit migmatization and partial anatexis. From this point to complete anatexis and the formation of granitic magma is only one step further. In this light the abundant granites are a logical consequence of the high grade metamorphism which in its turn is the result of the high geothermal gradient and the great introduction of heat to high levels in the earth crust. The emplacement of the granites in a relatively shallow position is evident not only from their stratigraphic position, but also from the low pressure minerals andalusite and cordierite in the contact aureoles. Examples can be quoted from the Vosges (Barr-Andlau), Saxony, Pyrenees and Spain.

One more feature of the Hercynian orogeny has to be mentioned which does not seem to be directly related to the nature of the regional metamorphism. This feature is the scarcity of ophiolites in the Hercynian geosyncline. Among these initial magmatic rocks ultrabasites are practically absent. Therefore it is rather difficult to divide this geosyncline into a eu- and a miogeosyncline, as should be done according to traditional opinions like that of STILLE (1924) and AUBOUIN (1965). Also the very wide extent of the Hercynian fold belt makes such a division rather difficult.

Summarizing the main features of the Hercynian orogenic belt, it can be stated that, 1) regional metamorphism in the low pressure facies series took place at shallow depth, 2) the individual metamorphic zones are often rather thin, 3) the metamorphism often reaches the high temperature part of the amphibolite facies, 4) migmatization is common, 5) a large amount of granites is present, 6) the whole orogenic belt has a very wide extent, 7) uplift has been moderate to small, and 8) ophiolites, and especially ultrabasic rocks, are scarce.

THE ALPINE OROGENIC BELT

The Alpine orogenic belt in Europe is characterized by its sinuous pattern, which forms several arcs, for example the western Alps and the Betic Cordillera—North African Rif. Although because of its arcuate pattern it

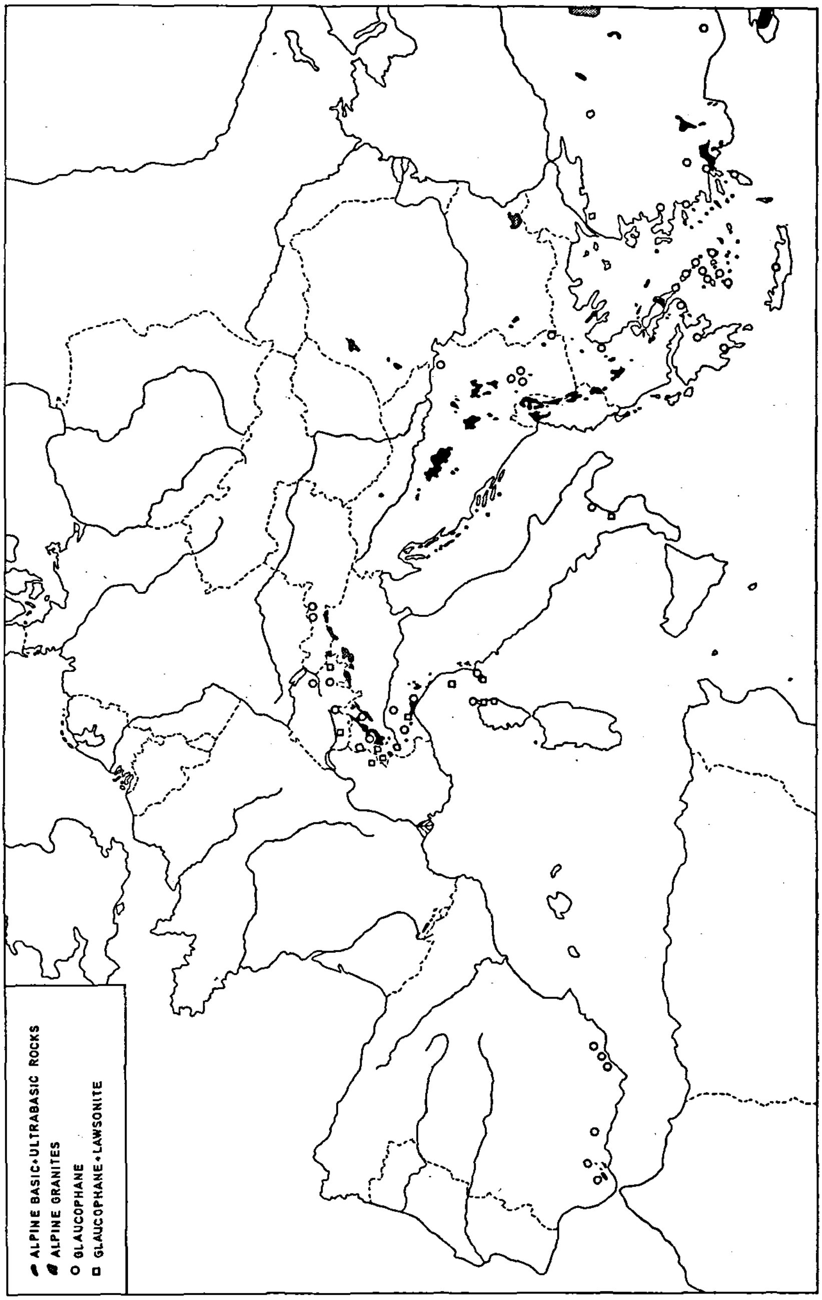

Fig. 2. Map of Europe, showing distribution of Alpine granites and ophiolites, and glaucophane and lawsonite (mineral distribution after VAN DER PLAS 1959).

covers a fairly large region, each individual part of the Alpine belt is relatively narrow, like the Betic Cordillera, the Alps proper, the Carpathians and the Apennines. This stands in contrast to the Hercynides which cover a very large uninterrupted region devoid of such sharp arcuate patterns.

Regional metamorphism in the Alpine belt has taken place in the Western and Penninic Alps, Corsica, Betic Cordillera, and a few other places like southern Italy and Greece. Characteristic minerals are glaucophane, crossite, stilpnomelane, lawsonite, jadeite and other sodium pyroxenes, phengite and kyanite (Fig. 2). Generally the metamorphism in the Alpine chain is of a low grade and belongs to the glaucophane-schist facies. Only at a few places do amphibolite facies rocks occur. The largest region where this facies can be found is in Tessin, where kyanite, staurolite and garnet are common, with locally some sillimanite in the rootzone (NIGGLI & NIGGLI, 1965). Other more localized occurrences of kyanite are in the Tauern window and the Betic Cordillera, where they are often found together with lower grade rocks.

The above mentioned minerals are characteristic of the Jadeite-glaucophane type facies series of MIYASHIRO (1961) and as they are lacking, or at least very scarce in the Hercynian belt, they emphasize the differences between both orogenies. Another characteristic of the Alpine metamorphism is the gradual change from lower to higher grade rocks, or in other words the thickness of the metamorphic zones, which have to be measured in thousands instead of hundreds of metres like in some parts of the Hercynian belt. This is related to the geothermal gradients which must have been much smaller in the Alpine metamorphic rocks, because the distance between successive isograds is so large. This is only possible if the depth of metamorphism and consequently also the pressure, is relatively large, at least considerably larger than in the Hercynides. This supports the opinion that the facies series of the Alps is formed under high pressure. Experimental work on a number of typical Alpine minerals, like kyanite, lawsonite, phengite also agree with this conclusion. Due to the complicated nappe structure in the Alps, in Corsica and in the Betic Cordillera it is unfortunately not possible to give any reliable figures for the depths involved, but from the evidence presented here it is obvious that metamorphism must have taken place at deeper levels than in the Hercynian belt, even taking into account the possible action of tectonic overpressures. As these rocks were formed relatively deep in the earth's crust, uplift and erosion must have been fast and quite large.

Alpine migmatization is almost completely absent. This is probably related to the general low grade of metamorphism. Some Alpine pegmatites occur in the higher grade Tessin region, but it is doubtful that the migmatites there were formed during the Alpine orogeney. They are most probably of Pre-alpine age, as they are overprinted by Alpine structures. Another feature which may be connected with the low grade metamorphism is the scarcity of Alpine intrusive granites. A few occur in the Alps (Bergell, Adamello) and in the Dinarides, but they are absent in the Betic Cordillera and on Corsica (Fig. 3).

Ophiolites, on the contrary, are much more common in the Alpine than in the Hercynian chain, and among these ophiolites ultrabasics are rather common, like in the ophiolite zone of Zermatt, and in the Dinarides. Consequently, a division into a eu- and a miogeosynclinal zone can be made much better in the Alpine chain than in the Hercynian one (Fig. 2).

ANTITHESIS HERCYNIAN – ALPINE OROGENIC BELT

From the previous discussion it is clear that in addition to a difference in facies series, many other differences exist between the two chains. They warrant the distinction into two different types of mountain chains. It is suggested that both types are extreme cases of mountain building. The main characteristic of the "Hercynotype" orogeny are:

1) broad orogenic belt
2) low pressure—high temperature metamorphism
3) thin individual metamorphic zones
4) shallow depth of metamorphism, high temperature gradients
5) relatively small uplift
6) many granites and migmatites
7) few ophiolites and ultrabasites.

The salient features of the "Alpinotype" orogeny are:

1) narrow orogenic belt
2) high pressure, low temperature metamorphism
3) thick individual metamorphic zones
4) deep seated metamorphism, low temperature gradients
5) large and rapid uplift
6) few granites and migmatites
7) many ophiolites and ultrabasites

With regard to the above points two questions require some further discussion. One is the high geothermal gradient in the Hercynotype orogeny, the other the depth of metamorphism in the Alpinotype orogeny.

It is obvious that a large amount of heat has to be introduced in relatively high parts of the earth's crust, in order to arrive at geothermal gradients which are several times larger than present day gradients on continents and in oceans. This heat has to be introduced either by rising magmatic bodies, which in this case can hardly be anything else than granites, or by hot solutions coming from deep levels. With regard to the first mechanism it has to be remarked that the many Hercynian granites cannot have been the cause of the regional metamorphism as they generally postdate this process. These granites are therefore the result of the metamorphism. The heat introducing granites must have been early and in most cases gneissified. Such granites do exist, like for example in the Pyrenees and in some other areas, but it is not at all certain that the volume of these bodies was large enough to cause such large scale, high temperature metamorphism. On the other hand it is difficult to imagine the nature and the source of hot solutions that might have introduced the necessary heat.

For these reasons the origin of the very large quantity of heat required for the Hercynian regional metamorphism remains rather obscure, but there is no doubt that this feature is largely responsible for the Hercynian metamorphism and granitization.

On the other hand the difficulty for the Alpine chain does not lie in its heatflow, as the geothermal gradients were likely not larger, but probably even smaller than present day ones. The difficulty is how the depths necessary for such high pressure metamorphism were achieved. In this respect it has to be stated that in the present author's opinion tectonic overpressures cannot have been the main cause, because the Hercynian metamorphics are also strongly deformed and also have been subjected to large stresses. Nevertheless, high pressure minerals are absent in this orogen. Consequently, high pressure metamorphism has to be sought in deep burial.

It is probably no coincidence that nappe structure are predominant in the Alpine regions. In many of these nappes basement rocks form an integral part, like in the Pennine Alps. Large thicknesses of crustal material can be obtained by the piling up of nappes, and it is not difficult to envisage that in the Alps a thickness of several tens of kilometres was attained, which is sufficient for the formation of glaucophane, lawsonite and kyanite bearing rocks.

The structures in the Hercynian belt are generally less complex, and although nappe structures have been found locally, they generally do not contain basement rocks, so typical of the Pennine nappes.

One feature seems to be connected to these structural differences, that is the narrowness of the Alpine belt vs. the broadness of the Hercynian belt. If crustal material is to be stacked to a thickness of 20–40 km, it can easily occur in a restricted zone, but can hardly be expected in such a very wide belt as the Hercynian orogen. Although thickening of the crust as a result of folding probably occurred also in that orogeny, the amount of thickening was rather small. Consequently the Alpinotype mountain chain, will have a deep root, or down bulge in the mantle, whereas such a root will be only of limited extent in a Hercynotype belt. Isostatic readjustment was therefore a logical consequence in the Alpine chain, but of less importance in the Hercynian one. This explains why rapid and large uplift has occurred in the former chain, but not in the latter type of orogenic belt. In this way the relation between deep seated, high pressure metamorphism, stacking of nappes, narrowness of the chain, downbuckle in the mantle and strong uplift seem to be logically explained for the Alpine chain. Low pressure metamorphism, broadness of the chain, no downbuckle and restricted uplift in the Hercynotype orogeny seem to be likewise related.

Therefore the main cause for the Alpinotype high pressure metamorphism is deep burial by tectonic movements, for the Hercynotype low pressure metamorphism the introduction of heat. Both orogens have in common the characteristic that regional metamorphism and the deformation of rocks occurred simultaneously.

THE CALEDONIAN OROGENIC BELT

If it is true that the Hercynotype and Alpinotype orogenic belts are two extreme types of mountain building, then it is probably that intermediate types also exist. A good example of such an intermediate orogeny is the European Caledonian chain.

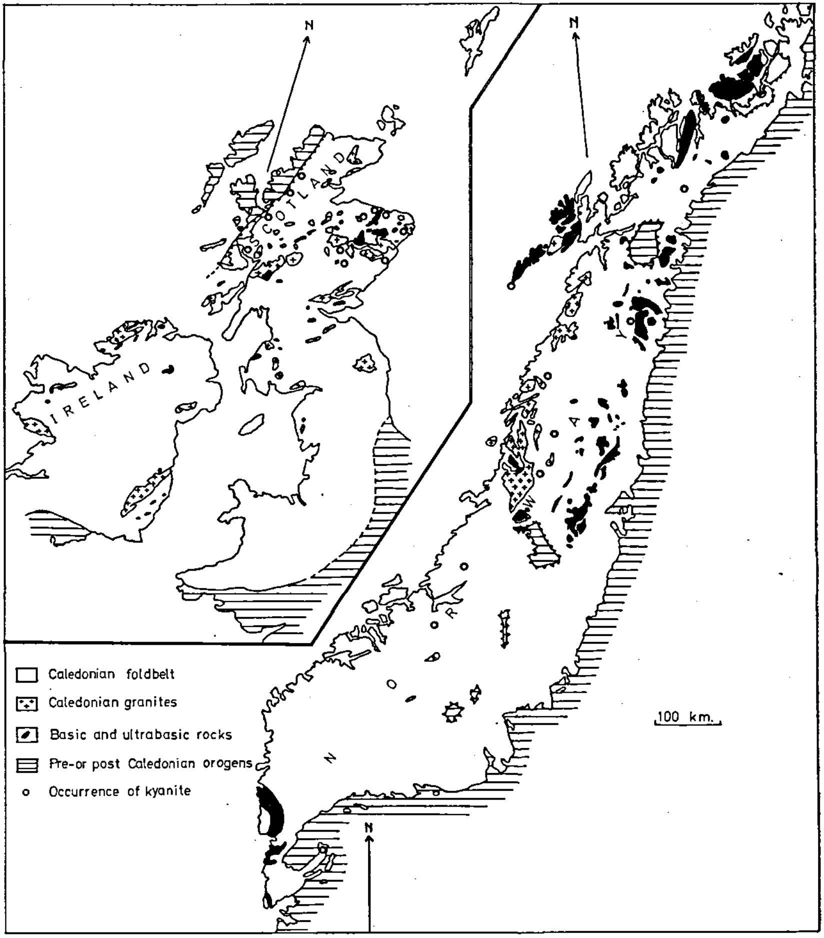

Fig. 3. Map of European Caledonian mountain chain with occurrences of kyanite, granites, and basic and ultrabasic rocks.

The mineral assemblages in this belt belong to MIYASHIRO's kyanite-sillimanite type facies series, with kyanite instead of andalusite in medium grade pelitic rocks, but with greenschists instead of glaucophane schists in the low grade basic rocks. Thus these assemblages have characteristics common and different to both low and high pressure facies series. In both the Scottish and Scandinavian Caledonides kyanite and sillimanite in the higher grades are commonly found. Cordierite is usually lacking in these rocks. Only in one area in eastern Scotland do andalusite-cordierite bearing rocks occur. They probably represent a shallow part of the Caledonian belt, where the phase boundary line between andalusite and kyanite is passed. In contrast to the Alpine belt is the common occurrence of rocks in the amphibolite facies, both in the kyanite and sillimanite zone. Rocks in the latter zone are often migmatitic. They seem not to be so widespread, however, as in the Hercynian chain, but as long as reliable small-scale maps of such features do not exist, the comparison remains somewhat uncertain.

The thickness of individual metamorphic zones is also not known in the Caledonian chain. The pressures during the metamorphism must have been considerable, as indicated by the presence of kyanite and the absence of andalusite. From the depth relations in the Pyrenees one can conclude that kyanite bearing rocks must have formed probably deeper than 20 km, corresponding to a pressure of 5–6 kb. This is in rather good agreement with the new data on the system Al_2SiO_5 published by ALTHAUS (1966) who found a pressure of 6½ kb for the triple point. On the other hand pressure and depth have been smaller than in the Alpine belt, as the glaucophane schist facies is not represented in the Caledonian mountain chain.

Uplift must have been considerable, at least more than in the Hercynian orogenic belt. More than 20 km of overburden must have been removed by erosion.

When the distribution of granites is considered, it appears that these clearly have an intermediate position between those in the Alpine and Hercynian belts (see Fig. 3). They are less abundant than in the latter belt. Ophiolites and ultrabasic rocks, on the contrary, are more common in the Caledonides than in the Hercynides. The structures, with their abundant large nappes in which basement rocks are often involved, are more Alpinotype and probably explain the large thickness of the overlying rocks during the metamorphism. Also the relative narrowness of the chain is more Alpinotype and may again be related to the nappe structures, the down-buckle in the mantle and the large uplift.

Based on its mineral assemblages with their typical intermediate character, it is obvious that in many respects the Caledonian orogenic belt has an intermediate position between the Hercynotype and Alpinotype orogenies. Certain aspects, mainly the structures and ophiolites, have an affinity to the Alpinotype mountain chains.

SVECOFENNIAN AND KARELIAN OROGENIC BELTS

As a last example from the European orogenic belts, one part of the Precambrian Baltic shield will be treated.

The Svecofennian and Karelian orogenies, both of the same age and covering a large part of Finland and Sweden, have all the characteristics of a Hercynotype mountain chain. The facies series of the metamorphic rocks are of the low pressure type with widespread occurrences of andalusite and cordierite. Kyanite is quite rare and glaucophane-schists are absent.

The wide extent of this orogenic belt is striking; it covers an area of approximately 700 × 1500 km, but originally this belt must have been larger because part of it has been reworked in later orogenies, among them the Caledonian orogeny.

The thin metamorphic zones in some areas, like the Tampere schist belt, and the large geothermal gradient connected with these, also remind one of the Hercynian orogen. Moreover the very widespread occurrence of migmatites and granites is typical for the Svecofennian-Karelian belts, as

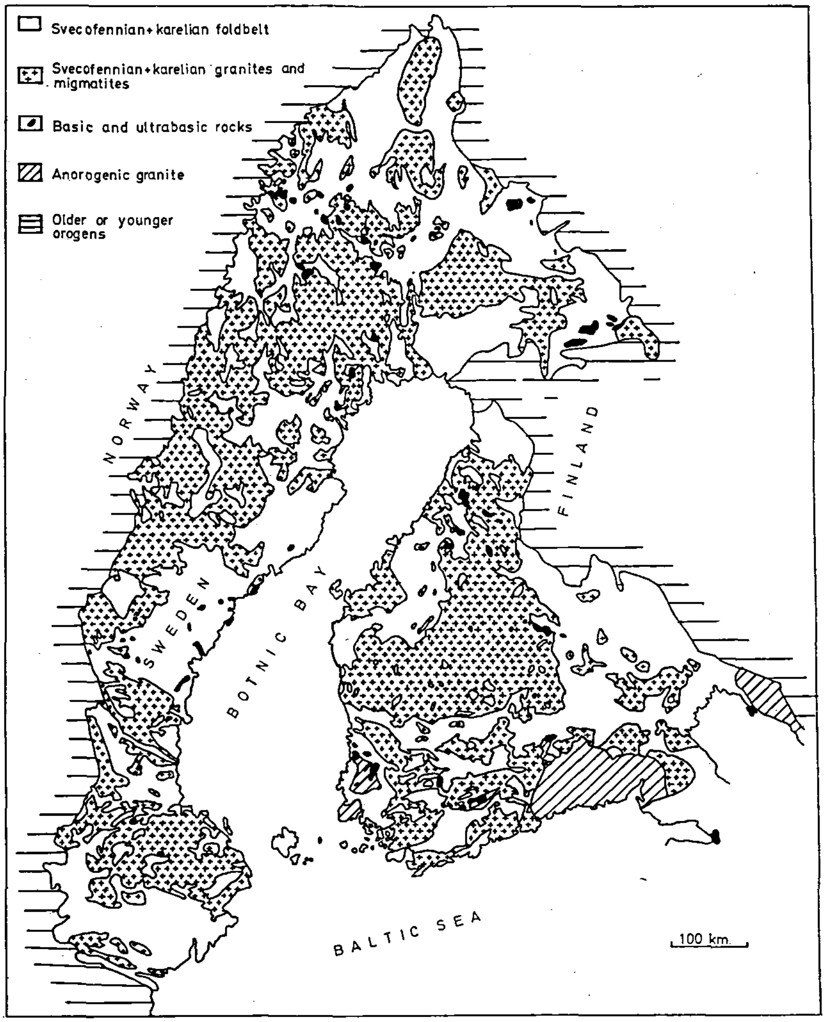

Fig. 4. Map of Svecofennian and Karelian orogeny with granites, migmatites, and basic and ultrabasic rocks.

can be seen on Fig. 4. They are even more abundant than in the Hercynian orogeny. Ophiolites and ultrabasics especially are not very common, although they seem to be somewhat more abundant than in the Hercynides.

The uplift of these rocks must have been moderate. In view of the absence of kyanite the depth of erosion will have been less than 20 km. It probably is somewhat larger than in the Hercynian chain, in view of the greater distribution of granites, migmatites, and ophiolites, and also the local occurrence of granulite facies rocks, like in SW Finland, described by PARRAS (1958).

Therefore, the often heard statement that the Precambrian shields consist of very deeply eroded roots of mountain chains does not apply to a major portion of the Baltic shield. Other, younger orogenic belts like the Caledonian and Alpine belts are much more deeply eroded.

THE CIRCUMPACIFIC BELT

From the description of the European orogenic belts, it becomes clear that large parts of or even whole mountain chains are characterized by the presence of only one facies series in their metamorphic rocks. Many more characteristic features are related in one way or another to these facies series. It can be concluded that such different orogenic belts, having a considerable range in age, are the normal pattern in many parts of the world.

There is at least one important exception to this pattern, however, namely the circumpacific belt, which is characterized by the side by side occurrrence of two belts. In the belt on the ocean side high pressure—low temperature rocks, mainly in the glaucophane-schist facies, are found. In the belt on the continental side low pressure metamorphics up to andelusite-cordierite grade occur. Paired belts of this type have first been described by MIYASHIRO (1961) from Japan, but they are also known from Celebes, New Zealand and the United States.

It is important to remark that several features of the individual belts in the Circumpacific region are similar to the European orogens. The distribution of granites and migmatites is quite characteristic. They are absent or at least scarce in the high pressure belts, but abundant in the low pressure belt. The distribution of ultrabasics is just the reverse, abundant in the high and scarce in the low pressure belts.

A difference with the European orogenic belts is that both belts are rather narrow, and the low pressure belt does not have such a wide distribution. Another difference is that in the high pressure belt the grade of metamorphism is always low and rarely goes beyond the glaucophane-schist facies. In the Alps, high pressure metamorphism occurs not only in the glaucophane-schist facies, but also in the amphibolite facies.

According to MIYASHIRO (1961) and LANDIS & COOMBS (1967), the original geosyncline of the high pressure belt probably had an oceanic substratum. This is certainly not the case in the Alps, where the sialic, Hercynian basement is exposed in all Penninic nappes.

Unfortunately not enough is known about the differences between the structures of both belts, and those in the European orogens. It is also not clear whether the deep burial in the high pressure belt is due to deep geosynclinal subsidence or to the superposition of nappes.

Whatever the explanation of these paired belts may be, there is no doubt that they stand in contrast to the "normal" European orogenic belts, and as no "fossil" paired belts are known thus far, they seem to be a new element in the earth's history. These features underline the peculiar nature of the circumpacific region. Therefore, any explanation of the origin and the history of the Pacific ocean has to take these facts into account.

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