WITH THE AUTHOR'S COMPLIMENTS.

To Hofrat Dr. W. Hammer

A Suggested Interpretation of the Scottish Caledonide Structure.

BY

FRANZ E. SUESS, LL.D.,

University of Vienna.

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A Suggested Interpretation of the Scottish Caledonide Structure.[1]

By FRANZ E. SUESS, LL.D. (University of Vienna).

I VENTURE to present before the Section a new interpretation of the Scottish Caledonide structure. This essay is based partly on the impressions that I got on a short visit to the Northern Highlands and on a most instructive excursion to Ballachulish under Mr. E. B. Bailey's inspiring guidance; partly on my own experience of the tectonics of Central European crystalline regions; but of course, above all, on the work of many Scottish geologists.

My discussion may start from the three well-known divisions of the crystalline schists in the Scottish Highlands which have been

[1] Paper read before Section C, Geology, British Association, Johannesburg, 1929.

named the *Lewisian*, the *Moinian*, and the *Dalradian*. These divisions are by no means equivalent to each other, and the junction between the first and the second has a tectonic significance quite different from that between the second and the third. The Moine thrust separates the Lewisian from the Moinian. It is famous as the first well recognized large scale example of transportation of more ancient crystalline schists over fossiliferous sedimentary rocks ; and is still more famous through the work of Lapworth, Peach, and Horne—a world standard of careful, thorough investigation and lucid description.

The Lewisian Gneiss is unconformably covered by the enormously thick sequence of the Precambrian Torridon Sandstone. Great masses of crystalline rocks must have been removed before the Torridon Sandstone was spread over the actual surface of the Lewisian Gneiss, of which the metamorphism is consequently of the highest antiquity and has no relation whatever to the early Paleozoic folding of the Caledonian chain. Likewise, the Torridon Sandstone has not suffered any remarkable folding or metamorphism, except in the immediate neighbourhood of the Moine thrust, where it has been affected by the great shearing movement. The whole Lewisian region remains outside of the Caledonian folding zone. It has been considered as its Foreland.

On the other hand, the Moinian and the Dalradian regions are intricately bound together by very complicated folding and thrusting. The boundary between them is most irregular and the distinction is based on the character of their respective type of metamorphism. Evidently the one region has not merely been thrust over the other, as the Moinian is thrust over the Lewisian ; but both regions have been involved as a whole in one and the same extensive and regional tectonic movement.

To the south-east the Dalradian zone is sharply cut off by the Highland boundary fault. South-east of this fault a broad band of the mountain range has subsided, and most of it is now hidden below the cover of Old Red Sandstone and Carboniferous sediments. However, some narrow outcrops of strongly folded fossiliferous Ordovician rocks almost touch the metamorphic Dalradian and, with exposures of Silurian in the Pentland Hills, show that the metamorphic portion of the Caledonian range has come to an end not far from the boundary line.

Considering its visible extent from Durness as far as Shropshire we can observe a division of the Caledonian orogen proper into three clearly defined zones, which are arranged according to the same plan as the zones in the younger and more complete orogens of Middle Europe, in spite of far-reaching individual variations. The first and outer zone, i.e. the zone of non-metamorphic folds, is traceable under its transgressive cover, from Shropshire to the Highland boundary fault. It corresponds in general to the non-metamorphic zone of the Alps, which includes the Helvetian nappes in Switzerland

and their partly visible continuation in the Sandstone—or Flysch—zone of the Eastern Alps. More fully developed and better exposed, in spite of incomplete preservation, is the equivalent in the Horsts of the Variscan-Hercynian mountain belt. This comprises all the non-metamorphic Devonian of the Rheinisches Schiefergebirge, including the Harz and the Thüringer Forest.

The Caledonian middle zone, i.e. the Dalradian, finds its unmistakable counterpart in the Pennide zone of the Central Alps; both of these show the same kind of intense folding and overthrusting and consequently the same type of metamorphism. In the Variscan arc only a relic of a once equally potent middle zone is represented in the nappes of the Erzgebirge, where moreover its general appearance is modified by a greater share of older gneisses and foliated older intrusions incorporated in the pile of nappes.

Still more liable to individual variations are the regions which we have to consider as the third or innermost zones of the orogens. The range of metamorphism may comprise lowest and highest grades according to local conditions; but their rôle in the orogen is marked by the peculiarity that they contain more or less extensive areas of deep, *post-tectonic crystallization* (corresponding to the undermost zone or zone of katametamorphism in the sense of Becke).

This zone is represented in the Variscan arc by the great so-called Moldanubian Block, south of the Erzgebirge; and in the Alps by the so-called East Alpine nappes (Austrides) and the crystalline base of the Dinarides. The contrast to the second or middle zone is most clearly emphasised in the Moldanubian Block, which consists almost entirely of kata-rocks, the metamorphism of which is post-tectonic and produced by the intrusions of enormous granitic batholiths (Intrusion Tectonics, 10 [1]). The Moldanubian Block has been moved as a whole over the nappes of the Erzgebirge and carries on its back the non-metamorphic older Paleozoic of Middle Bohemia, the so-called Barrandien. In my own experience, most of the rocks that are described as mica-schists and phyllites in this region, are in reality products of retrograde metamorphism by more or less extensive local shearing.

What is the meaning of these three zones? The principle that rules their arrangement is most clearly exposed in a third Central European mountain range. The discovery of this range is of comparatively recent date, and hence it has been generally too little considered and its significance in the older European structure has not been duly appreciated. This so-called *Moravo-Silesian range* accompanies the eastern border of the Bohemian massif through its whole length from the Silesian plain near Troppau almost up to the Danube near Krems. It has been dissected and broken by a great number of faults after the close of the folding period.

The name Moravo-Silesian has been given with special reference

[1] Figures in parentheses refer to Bibliography at end of paper.

to the metamorphic folded zone, that is to the middle zone of the orogen (10). The corresponding outer, non-metamorphic zone is represented by considerable remains in the mainly Devonian and Culm hills of Silesia, to the east of Troppau. What we call the third zone is more clearly defined and its tectonic significance is more obvious than in any of the other named orogens. It belongs to the Moldanubian Block of intrusion-tectonics and post-tectonic crystallization. (Fig. 1.)

The boundary between the Moldanubian and the Moravian is an over-thrust plane on the largest scale. A continuous layer of mica-schists, produced from the Moldanubian gneisses by intense shearing below the thrust-plane, is intercalated between them. The boundary, as it has been exposed by erosion, takes a very sinuous course and surrounds large windows of the Moravian. Obviously, the Moldanubian Block has been shifted as a whole, and without any remarkable folding or corrugation, over the Moravian; and evidently this powerful movement has pushed together the Moravian rocks into a pile of nappes and impressed on them the characteristic features of meso- and epi-metamorphism.

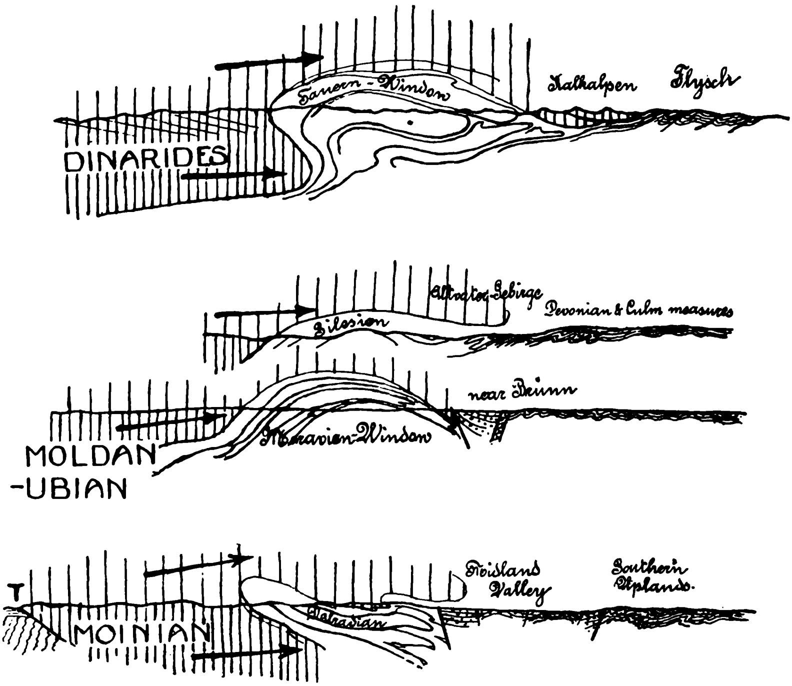
Let us now return to the Scottish mountains. The most conspicuous of the three above-mentioned truly Caledonide zones, the richest in varieties of rocks, the one with the most fascinating and most complicated tectonic features is the *Dalradian*. We owe to Bailey the demonstration of a system of recumbent slides and folds which dominates the south-west part of the Dalradian; and similar structures have been recognized by Bailey, MacGregor, Anderson, Read, and Elles in the middle and northern parts of the Central Highlands.

Bailey's comparison of this region with the Pennine nappes of Switzerland certainly meets the point and, I think, no other region has hitherto been scientifically described that surpasses these in complication, in the degree of stress and consequently of deformation of the rock masses.

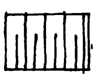
The superposition of several nappes, representing well defined structural divisions, each of which comprises a group of strata in various stages of metamorphism, such as has been demonstrated by Bailey, simulates very closely the sheared series of Grisonide nappes in the West Alpine Bernina district, in which an enormous thrust of the overlying crystalline basement over the East Alpine (Austride) nappes has occurred.

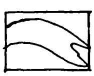
Of course the character of the Scottish nappes is somewhat different from that of the Central Alpine nappes, on account of the difference in their lithological composition, the lesser amount of the calcareous element, the prevalence of arenaceous and quartzose schists, and perhaps also a more thorough and uniformly pervading metamorphism have given to the Dalradian a tendency to produce more homogeneous folds with a more supple flow.

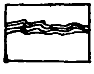
From various studies of Bailey, MacGregor, Anderson, Elles,

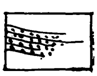


T = Moine thrust.


Creative blocks
(prevalent post-tectonic crystallization).


Regions of Pennide type
(prevalent nappe-structure and syntectonic crystallization).


Zone of folded non-metamorphic rocks.


Post-tectonic (transgressive) sediments in the Midland-valley
and in the " Boskonitzer-Furche " near Brünn.

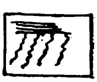

Lewisian with overlapping Torridonian.

FIG. 1.—Types of Mountain Structure.

and others, we can take it for granted that in principle the same structural features dominate the Dalradian to the coast of Banffshire, corresponding to the north-eastern trend of the fold-system as a whole.

The principal members of the sequence can be followed through the whole extent of the Dalradian. The question whether the stratigraphical sequence in some tracts may be normal or reversed, complete or incomplete, is not essential to the interpretation of the Dalradian as a region of Pennine type; i.e. of most complicated sliding and folding.

Further, the tectonic history of any rock is *most definitely expressed in the characters of its metamorphism*, and accordingly many varieties and gradations of metamorphism are met with in the Dalradian corresponding with the intricacy of the tectonic phenomena of the complex.

Space permits but few remarks on this great topic.

As we learn from various descriptions, the range of mineral constituents comprises the characteristic members of the so-called meso- and epizones (in the sense of Becke and Grubenmann).

Cordierite is only found in the contact aureoles of post-tectonic granitic bosses, and is not referable to the conditions under which the Dalradian rocks proper crystallized. Exactly the same holds good in the second zone, the zone of metamorphic folding, in the three Central European mountain ranges already referred to.

The minerals are in different schists of the Dalradian combined in the characteristic crystalline facies, corresponding to the respective conditions of pressure and temperature at the time of crystallization: biotite, sillimanite, kyanite, staurolite, orthoclase, etc., at one end, and chlorite, zoisite, epidote, albite, at the other.

It is obvious from many descriptions of the region that the rocks of different crystalline facies in the Dalradian are by no means arranged according to any supposed vertical order expressing the physical conditions that might have governed their individual origin.

Tilley (11) has recently pointed out the reversed order of the main zones of metamorphism throughout the south-west half of the Dalradian. A south-eastern chlorite-zone dips north-westward below the biotite-zone and this last is overlain by the garnet-zone. Elles has indicated the same sequence in the more complicated Ben Lawers and Meall Corranaich district in Perthshire. As the general trend of these main zones is not parallel to the Boundary Fault, but approaches it more and more to the north-east, the chlorite and biotite-zones gradually become narrower in this direction. In return the sequence is amplified in this region by the addition of sillimanite, kyanite, and staurolite to the index minerals of the metamorphic zones. Moreover there are many more or less local breaks in the succession of the metamorphic rocks, metamorphic unconformities with sharp lines of demarcation; a fact implying folding subsequent to a first stage of metamorphism.

According to our experience in different crystalline regions of Middle Europe, kyanite and staurolite, as characteristic minerals of mica-schists and micaceous gneisses, belong to the mesozone. I may mention the mica-schists with staurolite at the base of the Austrides that are thrust over the chlorite-schists and phyllites of the Pennide zone on the northern border of the " Window of Tauern " near the Brenner Pass, south-east of Innsbrück.

Putting aside the question to what degree the metamorphism was produced by granitic intrusions before or during the folding, it can be concluded from the descriptions by various authors that metamorphic rocks have been folded and that different facies of metamorphism have been involved in the folding. The metamorphism has been inaugurated during an early stage of the folding movement and it has continued in various gradations to its final stage.

Here I think is a large field for investigation: *polymetamorphism* is revealed, I venture to say, both megascopically and microscopically, constructive or destructive, or in combination, in almost every specimen of Dalradian rocks. That is the reason why non-equilibrium rocks prevail.

We may appeal to elevation of temperature, to water as a promoter of migration of molecules and of collective crystallization, or to any other theoretical explanation we please, but at any rate we have structural details, such as the spiral and S-shaped groups of inclosures in garnets, the development of the so-called chequer-albite by crushing and the eye-shaped porphyroblasts in augen-gneiss, which give evidence of *continuous crystallization* during movement. The rock mass has adapted itself to new conditions of shape and volume by mechanical, as well as by molecular, rearrangement of its particles.

It is a matter of field experience that rock deformation is accompanied by a set of characteristic minerals. For instance, albite-schists exactly like those of the Dalradian are found, in many places among the Pennide and Grisonide nappes of the Alps, in association with a drawing out of the rocks, so thorough that almost every hand specimen presents evidence of far-reaching deformation.

Many references to these subjects are found in the literature but only a few can be mentioned. Bailey has referred to the continual growth of quartz and felspar between bent and broken mica, chlorite and tourmaline. Figures and descriptions in Barrow's paper on the intrusion of muscovite-biotite-gneisses in the East Central Highlands show the decomposition of staurolite into " shimmer aggregate " (muscovite or sillimanite). From the descriptions given by Miss Elles, Barrow, and others, the different behaviour of the two micas can be observed: the biotite mostly is clearly the older member, and was sometimes already in course of destruction or transformation into chlorite during the development of fresh muscovite; the muscovite is often in contact with and surrounding felspar which obviously has supplied material for its growth.

All rocks of suitable chemical composition show the phenomenon that we call *Deformationsverglimmerung*, i.e. the appearance of mica, especially white mica, as an indicator of deformation.

An extensive treatise would be necessary even to sketch the chemico-mineralogical processes that characterize this tectonic structure, and reappear with very close similarity in almost the same varieties of rocks in the Alps as well as in the Moravian range.

From these facts the conclusion is justified that the Dalradian rocks have not only been folded and sheared in the highest degree, but that their tectonic structure and metamorphic facies have been *impressed on them by the load and movement of a superimposed mountain mass.*

This conception finds its strongest support in the analogy with the other mountain ranges named, where the overlying block, the *traîneau écraseur*, to use Termier's expression, is still seen, and its influence on the zone of metamorphic folds is clearly demonstrable. If the Dalradian folds had developed by sliding near the surface, they would show tectonic features comparable to the Swiss Helvetian folds without any noticeable trace of metamorphism.

It is obvious that the *Creative Block*, as we may call it, in Scotland could not have come from the south-east, where the non-metamorphic folds exist; moreover the Dalradian movement is itself directed to the south-east. Only the Moinian can have played the part of the *traîneau écraseur*, and indeed, it shows the type of metamorphism that is to be expected in such a mass.

The difference between the Dalradian and the Moinian metamorphism is not a matter of degree. It concerns the very process of transformation and expresses the difference between the geological history of the two regions.

The metamorphism of the Dalradian is syntectonic; it cannot be separated from the tectonic deformation of the rocks. On the contrary, the most significant rocks of the Moinian, the quartzose granulites and the gneissose flagstones, that monotonously cover large tracts, show post-tectonic crystallization at high temperature.

I refer only to Sir John Flett's excellent descriptions, in which he pointed out the typical granoblastic and homoeoblastic structure in these rocks, the equidimensionality of the constituents, the lack of clastic or porphyritic structure, and the disappearance of all mortar structure. There is no tendency to elongation in the constituents. The parallel arrangement of biotite may have been derived from a former original parallel texture of any origin (sedimentary or tectonic, i.e. by foliation or cleavage) by mimetic crystallization (*Abbildungskristallisation*, Sander).

The contrast between the Moinian and the Dalradian is not destroyed by the fact that the Moinian itself did not behave entirely rigidly, but also suffered some deformation during its transportation, which has led to retrograde "polymetamorphism". This may be marked in some tracts by the appearance of grains of zoisite or epidote, or of flakes of muscovite throughout even compact rocks. In other parts it is more closely restricted to rather thick layers with rich development of mica, garnet, etc. Some of the so-called pelitic gneisses belong to the latter.

The three zones of the Scottish Caledonides constitute a *dynamic unit*. By analogy with the better preserved orogens, we can assume that the Moinian represents the "Creative Block" in the Scottish Caledonides and that it has been thrust over the Dalradian region. The breadth of the region of the Dalradian syntectonic metamorphism probably indicates the former contour of the "Creative Block". Beyond these limits only the tangential push was operative and not the weight of the mass. The sediments were bent and folded with contraction of area, but without metamorphism.

We have, however, still to meet some apparent difficulties. It is a fact that the Moinian and its equivalents, the Eilde Flags and the Struan Flags, dip generally below the Dalradian at a rather low angle and do not overlap it, as they should, to fit the proposed explanation. But this difficulty is by no means insurmountable. The plane of contact between the Moinian and the Dalradian is to be interpreted not as a surface of sedimentation but as a tectonic unconformity.

A backward movement of the Dalradian over the Moinian has been suggested. Anderson, in regard to the Schichallion district, has put forward the hypothesis that a normal fault of large dimensions has been subjected to intense shear that came from the east or from the south and has brought all original structures, including the fault and the bedding, into approximate parallelism.

In the Alps the region of the roots at the boundary between the third and the second zone, that is between the Dinaride and the Pennide nappes, has suffered a back movement on account of the excessive and continuous push to the north during the so-called Insubrian phase (Argand).

After the compression of the orogen to its highest pitch in the Caledonides, the pressure of the continuous tangential push had more time to act, and resulted first in a greater exaggeration of the forward movement and then in more retrograde movement forming a complicated structure combining normal faulting and backward thrusting.

Therefore if we look for a backward movement comparable to that of the Lombard plain in the Alps, it will not be found in the Moine thrust, but rather in the boundary region between the Moinian and the Dalradian, the elements corresponding to the Dinarides and the Alps proper.

But what explanation have we for the Moine thrust itself? Bailey has suggested its continuation in the Loch Skerrols thrust in Islay. There it cuts not through the Moinian but through the Dalradian, and has shifted it on to the Torridon Sandstone. It crosses obliquely the different zones of the Caledonian dynamic unit; therefore it must be younger than the Caledonian movement, and, in my opinion, the great thrust has no immediate relation to the Caledonian structure proper. Very likely it indicates an enormous movement far exceeding the extent of the visible breadth of superposition.

Further elucidation of this great question may be expected from the study of its supposed continuation in North America ; that is the great Champlain fault according to Bailey's suggestion (12).

Another difficulty concerns the exposures, mostly of comparatively small extent, of more highly crystalline rocks, which outcrop at numerous points below the Moinian, and are generally considered as belonging to the Lewisian. The regional geological correlations seem to me to contradict this interpretation. The Lewisian, with its cover, is obviously much older than the Caledonian movement, and it is difficult to understand how it could have preserved its original position below the Moinian, since the latter has been metamorphosed under different conditions, and was transported to the south-east in Caledonian time, as is shown by its intricate connection with the folds of the Dalradian.

Many authors have called attention to the original unconformity between the Moinian and the inliers, and to the fact that the two series appear to be separated by a surface of movement or crushing. Indeed, the interstratification of highly micaceous gneisses, mica-schists, and limestone with tremolite, and various other facts, indicate that the Moinian has been shifted over its more highly crystalline basement for an indeterminable, but probably considerable distance.

Only two explanations of these relations seem to me acceptable. Either the inliers represent a deeper facies of the Dalradian rocks which was overwhelmed by the thrust of the Moinian to the south-east during the Caledonian mountain building, or the Moinian has been moved to the south-east over an older crystalline basement together with the whole mass of the Dalradian.

Conclusion.

I venture the following statements :—

(1) The Scottish part of the Caledonides has moved as a whole and complete orogen to the south-east. In this it exactly corresponds with its much larger continuation in Scandinavia.

(2) The superposition of the Dalradian on the Moinian is to be considered as a back movement due to continuous push to the south-east. Such back movement is analogous to that which has affected the so-called Alpine roots on the boundary of the Dinarides.

(3) The Moine thrust of the North-west Highlands cuts obliquely through the Caledonian structure. It is independent of and younger than the Caledonian mountain building. By no means can it be considered a symmetrical equivalent of the south-easterly Dalradian movement in Scotland and in Scandinavia.

(4) The Caledonian orogen shows no symmetrical structure and corresponds in this respect to other large orogens, as the Alps, the Variscan range, etc.

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