7. On the Analogies between the Scottish and Scandinavian Portions of the Caledonian Mountain Range.

By

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Contents.

Introduction.

For decades the so-called Scandinavian mountain problem has been the object of persistent investigations, but as yet no generally accepted explanation has been attained. After TÖRNEBOHM in 1896 in his monumental work on the structure of the central Scandinavian mountains (**45**) had developed his well-known overthrust-theory, it seemed as if an explanation, satisfactory in many respects, of the many mysteries of the highlands had been obtained. But only for a time. Continued investigations outside the real central Scandinavian region soon led to difficulties and contradictions in the application of the overthrust-theory — at least as put forward by TÖRNEBOHM — and led to repeated and still continuing controversies among the leading Scandinavian mountain geologists, even with regard to the most fundamental questions.

In Europe the other part of the Caledonian folding region, chiefly situated in Scotland, has also had and still has its mountain problem.[1] It is interesting to note the striking parallellism in the way the different views and ideas on the highland structure have succeeded one another and gradually were developed in Scandinavia and Scotland, without it being possible generally to explain this agreement as the result of direct impulses or direct exchange of experiences. With regard to the great geotectonic problems, such as the geological position of the Highland schists and the extent and nature of the great Caledonian mass-displacements, the position of the questions is also at present in many respects similar in Scandinavia and Scotland, although perhaps certain problems, on account of special external conditions, have become more prominent in one of these regions than in the other.

Therefore it may be said without exaggeration that at present the Caledonian mountain problem is very actual both in Scotland and in Scandinavia. Under these circumstances it may perhaps be convenient to put forward some comparative views, both similarities as well as dissimilarities, of which, however, the former are so predominant both qualitatively and quantitatively, that they fully verify the affinity between the two regions belonging to one and the same tectonic unit. That in general closely related rocks, both sediments and eruptives, as well as a rather uniform folding-structure predominate in two parts of the same folding zone, so nearly situated to each other, is almost to be expected as denoting that common geological factors have been active in both regions. With regard to Scandinavia I will confine myself chiefly to the central Scandinavian part, already classical owing to TÖRNEBOHM's works, or, more precisely, the Trondhjem field and Jämtland, where most of the points of agreement seem to be present.

The comparisons drawn up here are in many respects of a fragmentary character. A complete and exhaustive treatment is impossible simply because my own acquaintance with the Scottish Caledonian geology is limited to a visit last summer, certainly very instructive and productive, thanks to the kindness of my Scottish colleagues, but nevertheless too short with regard to the extent of the subject. Nor I have had an opportunity of sufficiently studying the copious and exhaustive Scottish geological literature. It is also worth mentioning that my experiences of he Scottish Highland geology were obtained after my work on the Jämtand region already was completed.

The two schematic sketch maps that are enclosed (fig. 1) are intended only to give the structural main divisions within the parts of the folding zone dealt with. Measured at right angles to the axis of the

[1] For a brief survey of the structure of the Caledonian mountain range both in Scotland and Scandinavia, see **35**, **36**, **40**, **41**, where some important data with regard to the historical development of the mountain problem are to be seen.

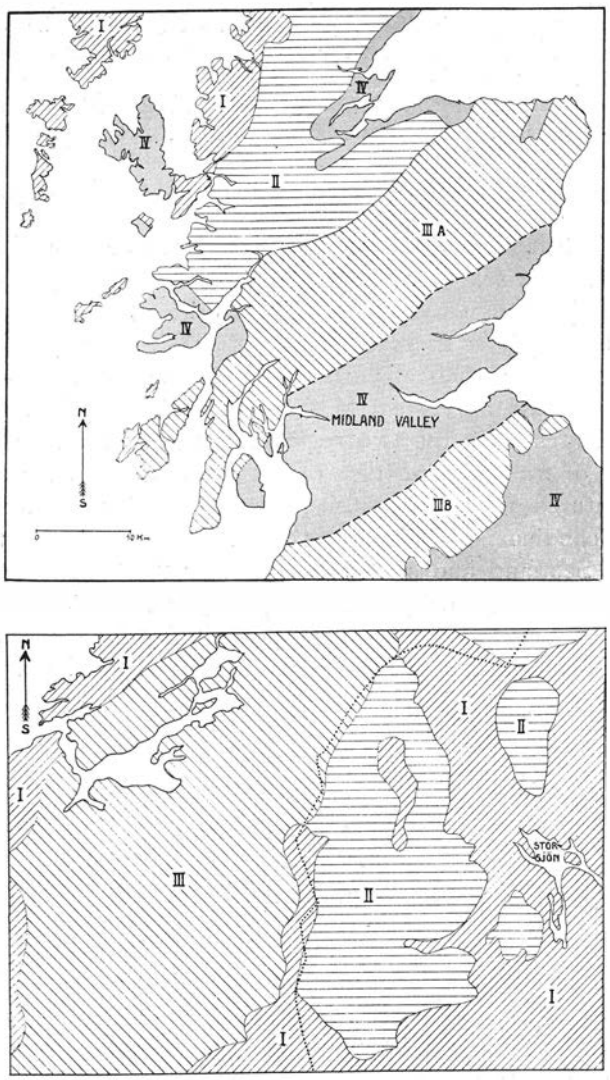

Fig. 1. The structural main divisions of the Scottish and central Scandinavian Caledonian regions. — Scale of both the sketch maps about 1 : 4 000 000. — (The frontier between Sweden and Norway is dotted.)

Main zone I includes in general the autochthonous foundation, visible in Scandinavia, *inter alia,* as windows; moreover the marginal belts of the mountain range, often with strong disturbances (»the imbricate subzone») but where always the Caledonian recrystallization is practically lacking.

Main zone II, or the region of the gently dipping but highly metamorphic Highland schists, characterised by strongest tangential compression and mass-displacements, chiefly consisting of the Scottish Moinian and the Scandinavian Seve group (the Moine- and Seve regions). — To this main zone belong the classic overthrust-belts, in Scotland situated in N. W., in central Scandinavia chiefly in S. E.

Main zone III, or the central folding zone, generally with highly inclined dips and varying metamorphosis, consisting of the Silurian in the central Scandinavian Trondhjem

field (the Köli schists), in Scotland chiefly in part of the Dalradian (the Dalradian region or the subzone III A), in part of the Ordovician-Gothlandian series in the Southern Uplands (the subzone III B).

In Scotland the boundary-line drawn between II and III A is only quite schematic. This restriction also has reference to the boundary-line between the main zones I and III along the western side of the Trondhjem field.

The post-Caledonian deposits in Scotland, IV, are grey-coloured.

folding zone the main divisions corresponding to one another attain nearly the same order of size. That, nevertheless, somewhat smaller dimensions meet in central Scandinavia must certainly be due to the fact that this region is obviously far more denuded, and consequently the formations, especially in the peripherical parts of the Caledonian zone, are more reduced. The striking agreement in the distribution of the structural main divisions indicates that the two regions, as the sketch maps show, have the character of true mirror-copies of each other. The frequently peculiar structural features that distinguish the western or north-western side of the central Scandinavian region are thus to be found along the east and south-east of Scotland and so on. Still further this tectonic equivalence is verified and supplemented by connecting links with regard to the internal structure of the constituent formations, the primary and secondary development of the rocks, etc., all of which will be illustrated by examples given below.

Geological formations and rock groups constituting the structural main zones.

Rock groups of main zone I.

According to the above-mentioned opposite position of the main zones, the autochtonous substratum that appears in Scotland in the N. W. Highlands, outside the overthrust-belt, has its equivalent in a similar rock-complex along the south-eastern margin of the central Scandinavian region.[1] The constituent formations of these two districts are as follows:

In Scotland	In Scandinavia
Cambrian (and *Ordovician*)	*Silurian*[2]
Torridonian	*Jotnian* (Sandstone of Dalecarlia)
pre-Torridonian	*pre-Jotnian*

[1] The main zone I along the western side of the Trondhjem field may here be left out of consideration as being without its equivalent in the still insufficiently denuded districts south-east of Scotland, especially as the boundaries between the Trondhjem field and the Archean foundation are very uncertain.

[2] As the Cambrian, Ordovician and Gothlandian appear in Scandinavia as a geological unit, they will be placed together below, for the sake of brevity, under the term Silurian, unless the contrary is stated.

The pre-Torridonian and the pre-Jotnian complexes of formations, although equivalent, show with regard to their composition no great resemblances to each other and may therefore be treated quite briefly. In Scotland we find more or less schistoze and metamorphic intrusive rocks belonging to the Lewisian formation, together with still older crystalline schists of sedimentary origin, all probably of true Archean age. In central Scandinavia, on the other hand, generally occur young-Archean or still younger formations, such as ser-Archean granites (»Refsundsgranite», etc.) and, somewhat further to the south, post-Jatulian porphyries (»Älfdalsporphyries»). Here the crystalline schists and igneous rocks belonging to the older Archean are less extensive.

On the contrary the Scottish Torridonian and the central Scandinavian sandstone of Dalecarlia are in the main equivalent both from a geological and petrographical point of view. Both consist essentially of red-coloured sandstones, more or less rich in felspar -- according to the Scandinavian terminology »sparagmitic» — and at other times of quartzitic sandstones of considerable thickness and probably of arid or semi-arid origin, deposited on a rugged and uneven land-surface: the sub-Jotnian land-surface. In Scotland this sub-Jotnian relief is specially well marked by height-differences of several hundred metres (**20**) and of course denotes a strong discordance. In both areas there is no pre-Caledonian regional-metamorphosis. A difference consists in the absence of basic lava-flows and basic intrusive sheets in Scotland; on the contrary such igneous rocks are a general phenomenon in the sandstone of Dalecarlia and other Jotnian sandstone districts in Fennoscandia.

Of no less interest are the Cambrian-Silurian systems, because of considerable similarities as well as dissimilarities with regard to their petrographical development and the fossils. Contrary to Jämtland, but in agreement with the conditions, for instance, north of this province, the Cambrian in N. W. Scotland rests on a generally even, peneplane-like land-surface: the sub-Cambrian discordance. The most important and dominating subdivision is the basal quartzite- sandstone-horizon, attaining a thickness of about 200 m. Its lower part, about 100 m. in thickness, may be very rich in felspar and then looks like a pinkish Scandinavian sparagmite, but gradually becomes more rich in quartz towards the top. By this petrographical development — a gradual transition to perfectly weathered sediments (quartzites) — as well as by its stratigraphical position, conformably beneath the fossil-bearing Olenellus beds, this division offers an obvious parallel to the analogous, though often considerably thicker, lower-Cambrian sparagmites in the Scandinavian Highland region. Resting on some thinner horizons of grits, shales, mudstones, etc., comes after that the locally strongly developed Durness limestone and dolomite, the upper part of which probably reaches up in the lower-Ordovician. With reference to the conditions in the Southern Uplands, it ought to be pointed out that no lava-horizon is developed in this Cambrian-Ordovician area.

In the marginal belt of the folding zone in the east the Caledonian movements have resulted, as is well known, in the very intensive imbricate structure, described of old from Scotland, giving rise to a manifold repetition of the Cambrian-Ordovician horizons. Because of the relatively great power of resistance against mechanical rolling out and against destruction in general, the plates of the basal sparagmite-quartzite-horizon, piled up in this way, become predominant in the imbricate subzone.

In the central Scandinavian region, shown in fig. 1, the greater part of the Paleozoic belongs to the Ordovician and the Gothlandian and consequently cannot be directly compared with the Scottish region. In the south as well as to the north as far as to the northern point of the Scandinavian peninsula, there generally occur, on the contrary, lower-Cambrian and old-Ordovician strata, on which the Highland schists are thrust up. Among these are to be mentioned large parts of the so-called sparagmite formation, consisting chiefly of sandstones, rich in felspar, and of quartzites, belonging to the oldest Cambrian.[1] The imbricate subzone, which is extremely developed in Scotland, consisting chiefly of quartzite and sandstone plates, is also present in Scandinavia, though more difficult to reconstruct in detail there, on account of unfavourable external conditions. It is found in the Norwegian sparagmite field[2] — where it is built up of partly the same rock-formations as in Scotland (**38, 44**) — as well as in the central Scandinavian region too, *inter alia*, in the quartzite-masses of the Vemdalsquartzite and Strömsquartzite, which certainly owe their abnormal thickness to this sort of repetition. It is further found in many places in the partly more normally constituted Silurian field in central Jämtland (see, e. g., **12**). Farther to the north, in Finmarken, we get in this marginal belt thick dolomites and limestones, which seem stratigraphically to be quite equivalent to the Durness dolomite, etc. (**39**).

A circumstance that might be of importance for our understanding of the folding-mechanics (p. 219) is that the sub-Cambrian land-surface in Scotland, as in the Scandinavian marginal belt in general, is developed with peneplane-like evenness, but in the central Scandinavian region it has a distinct relief. In connection with this, the sub-Cambrian fossil weathering-zone, characterized by a mechanical and a special kind of chemical decomposition of the rocks, reaches in the former areas a depth of in general only a few cm. or dm., while in the latter district, on the contrary, it is several metres deep. Especially the hills, belonging to the sub-Cambrian broken topography, have in this way been subjected to a far-reaching destruction. This phenomenon ought to be connected with

[1] It is noteworthy that Cambrian quartzites of dark, often dark-blue, colour, called blue-quartz in Scandinavia, where they generally occur in the eastern marginal belt of the mountain range, are also to be seen, though sparsely, in Scotland.

[2] The Norwegian sparagmite field is situated in the continuation to the S. W. (see fig. 1) of the central Scandinavian marginal zone.

the generally more strongly denuding agencies in a district with broken topography, where, *inter alia,* the distance of the subsoil water-surface under the ground-surface is very irregular, at the heights reaching a considerable amount, while, on the other hand, the same agencies are far less effective in an area levelled to a peneplane. — These conditions are seen also in Scotland with regard to the very uneven sub-Jotnian land-surface, with its generally far-reaching fossil weathering-zone and the attached accumulation of coarse-clastic, often sharp-edged, products of weathering in the overlying Torridon sandstone. To the same type we can also assign the sub-Devonian land-surface and its weathering-horizon, mentioned below (p. 236). Strongly contrasted with these is the sub-Cambrian land-surface in Scotland, with its practically almost imperceptible weathering-phenomena and the almost complete absence of superimposed conglomerates.

Rock groups of main zone II.

Along the whole of the classical Scottish overthrust-margin in the North-West Highlands the rocks of the Moinian system are overlying the above-mentioned autochtonous formations in the main zone I. In central Scandinavia the so-called Seve group (among which is included, *inter alia,* the Åre schists) occupies, in relation to the analogous zone there, quite the same position.

Also from a petrographical point of view, the Moinian and the Seve group show such a close connection that most of the common types of rocks, spread over wide areas, cannot be distinguished from each other either micro- or macroscopically. A primary difference lies in the extreme psammitic development of the Moinian, with pelitic schists and limestones only to a subordinate extent. Thus the predominant original composition agrees closely with the general character of the part of the Seve group that derives from genuine sparagmites, e. g. in South Jämtland and Härjedalen, the Offerdal area, etc.

The secondary or regional-metamorphic characters are also strikingly similar in the Moinian and the Seve group. In both regions there takes place a distinct, gradual increase in the degree of metamorphosis towards the centre of the mountain range, thus in Scotland from west to east, in central Scandinavia, on the contrary, in the opposite direction.[1] On the whole, however, a somewhat slighter recrystallization is noticeable in the Moinian, so that relic-clastic structural features are more often found there, even in the central and eastern parts of the region. With regard to the original pelitic sediments, the metamorphosis can be gradually followed, as in

[1] In this connection we leave out of consideration the cataclastic zones, developed by the last, late-Caledonian movements. These zones are both in Scotland and in Scandinavia distinctly later than the crystallinity of the Highland schists.

certain Seve regions, from the chlorite- and sericite-stage to biotite-bearing, finally also to garnet- and amphibole-bearing schists. The lowest metamorphic stage, characterized by chlorite- and sericite-crystallization, attains seldom any great extension, but it is, however, more common in Scotland. On the other hand, the highest metamorphic types of rocks, the lime-silicate gneisses and lime-silicate mica-schists, are more prevalent in the central Scandinavian Seve group.

In Sweden the rock-type of the Seve group has of old, by means of its generally harder, more granular and rougher habitus, been distinguished from the other type of Scandinavian Mountain schists, the Silurian Köli group, with generally more gentle and softer mica-schists, phyllites etc. This difference in character is only a petrographical one and partly primary, inasmuch as the Seve group contains more psammitic, often sparagmitic sediments, rich in quartz and felspar, and these sediments, when typically developed, are seldom or never found in the true Köli group, partly also secondary, and then caused by a more high-crystalline metamorphosis, also of the pelitic sediments, sometimes in the form of a metasomatic felsparization. These general characteristics of the Seve type, a rougher and more gneiss-like habitus, are also found in the Moine schist type, prevalent in Scotland: a well bedded gneiss or granulitic schist, poor in dark minerals but rich in felspar and quartz.

Rock groups of main zone III.

In central Scandinavia the central folding zone of the mountain range is represented by the Trondhjem field, a large geosynclinal formation, squeezed in between blocks of fundamental rocks, and consisting of strongly compressed fossiliferous Silurian sediments. As in other folding zones, these sedimentary rocks are distinguished by an abnormally coarse-clastic development and a considerable thickness, probably several thousand metres.

According to the still incompletely published Norwegian investigations of the last years (**10**), the structure of the Trondhjem field is in the main as follows. — Resting on a basal horizon of typical, light, probably old-Cambrian sparagmite-schists — possibly, however, not present everywhere — there lies at the bottom the so-called Rörås group, which in general has a primary pelitic composition and reaches the oldest Ordovicium. — Conformably above this follows a volcanic series, the so-called Bymark group, consisting of basaltic pillow-lava together with strata of jasper, chert, agglomerates and tuffs, in alternation with normal sediments, quartzites and phyllites, which locally form well stratified layers, bearing magnetite and pyrites. These ore-deposits are probably of pneumatolytic origin, formed in connection with the submarine volcanic outbreaks. This group belongs to the lower Ordovicium.

The Bymark group is superimposed unconformably by the Hovin group, developed in its lower part as a thick conglomerate-horizon with pebbles and boulders of the underlying rock-groups. Further the Hovin group is composed chiefly of sandstones, often in intimate alternation with thin schist-strata and here and there of interformational conglomerate-horizons. Especially the grey-green sandstones have a considerable extension and contain large quantities af acid plagioclases and calcite (»calcite-plagioclase-sparagmites»). In addition, there are impure limestones and possibly a smaller bed of basaltic lava and tuff, belonging to the upper part of the group.[1] By means of rather abundant fossils it is proved that the Hovin group extends from the younger Ordovicium up into the Gothlandium. It seems to be formed during continuing terrestial movements, probably in connection with the beginning folding-process, which caused displacements in the distribution of land and sea.

In the central folding zone (main zone III) the metamorphosis is far more variable than in the region of the Seve schists (main zone II). Thus along the longitudinal axis of the Trondhjem field there passes a broad belt, characterized by extreme recrystallization (»det metamorfiske strög»), while in adjacent parts, especially in the west, the metamorphosis is slight or entirely lacking.

In the N.W. and S.E. the great Highland Boundary faults border the large fault-depression called the »Midland Valley», which is filled by younger formations. Therefore the Ordovician and Gothlandian deposits in the Southern Uplands (subzone III B) are separated from the South-Eastern Highlands (subzone III A) in the north by a wide break. However, there seems to be no doubt that these strata continue under the young-Paleozoic formations in the Midland Valley up to the Highland Boundary fault, especially as in a few places there, a thin strip of fossiliferous upper-Cambrian or old-Ordovician sediments crops up beneath the Dalradian schists, which here dip toward the north-west. In addition, folded layers, belonging to the Gothlandian, are seen in the core of the anticline in the Pentland Hills. In my opinion the Trondhjem field may be put as equivalent to this extensive Ordovician-Gothlandian region, now partly concealed by younger formations just named. But in addition to this, it seems reasonable, from a Scandinavian point of view, also to count to the same large unit extensive parts of the South-Eastern Higlands (III A), especially of the Dalradian formation, present there, which — according to what is mentioned below — shows considerable points of connection from structural as well as petrographical and stratigraphical respects. Both with regard to com-

[1] According to a statement made to me by Dr. CARSTENS, the presence of this upper lava-horizon is not yet fully cleared up.

position and thickness we find in the subzones III A and III B the sedimentary facies characteristic for geosynclinal regions.

In the Southern Uplands, or the southern part of the central folding zone (subzone III B), the denudation has nowhere gone deeper than to the oldest Ordovician (Arenig), so that a comparison with the older Rörås group is impossible. The same restriction also applies to the younger Gothlandian division, which, as far as is known, does not occur in the Trondhjem field. The lithological affinities between the thus remaining divisions are, however, obvious. Oldest is the lava-horizon, which belongs to the Arenig and lies beneath the greater part of the S. Uplands and probably also under the Midland Valley (**19**). This horizon is formed at the same time as that of the Bymark group and constitutes, like that, the main epoch of the volcanic eruptions in old-Paleozoic time. This lava-horizon, best known from the Girvan district, is developed as a submarine pillow-lava of a similar chemico-petrographical composition as in the Trondhjem field (**10, 15, 19, 31**). It is accompanied, as it is there, by agglomerates, tuffs, together with jasper and chert-bearing strata (»Radiolarian cherts»), alternating with more normal fossiliferous sediments. The effusive activity has in both regions also been immediately followed by intrusions — partly in the lava-horizons themselves — in Scotland of gabbros, diorites, granites, etc., in the Trondhjem field of peridotites and gabbroid rocks. The latter, however, are usually more or less completely altered to amphibolites. On the contrary, as far as I know, no equivalent of the pneumatolytic magnetite-pyrite deposits, belonging to the Bymark group (**10**), has been found in Scotland.

At least in certain districts, the lava-horizon is, quite in analogy with the central Scandinavian conditions, unconformably superimposed by a conglomerate, »the Benan conglomerate», containing pebbles from the underlying rock series and even from the above-mentioned intrusive rocks of old-Ordovician age. The succeeding Ordovician and old-Gothlandian series indicate, by their generally coarse-clastic development — chiefly so-called greywackes, sometimes accompanied by interformational conglomerate-layers — a continuing sinking of the sea-bottom and therefore of the sub-Silurian foundation too. Consequently this sub-Silurian foundation obtained the character of deformation-depression.

That already during this period the Scottish sedimentation in its main features was directed by movements in the earth-crust, connected with the formation of the mountain range, is also shown by the fact that in each younger division the psammitic sediments (the greywackes) are advancing more and more towards the S. E., replacing the pelitic ones, and these in their turn encroach upon the limestone sediments. Thus the coarse-clastic deposits become more and more predominant towards the centre of the mountain range, situated in the N. W., a phenomenon that is also found in central Jämtland with on the whole similar manifestations.

In general the dark argillaceous sandstones, described in the Scottish geological literature as greywackes, appear under the microscope rich in felspar and, according to the central Scandinavian terminology, ought to be called dark sparagmites. My observations in the field as well as under the microscope indicate that the rock-type mentioned above from the Trondhjem field as grey-greyishgreen calcite-plagioclase-sparagmite[1] has a considerable extension here. The above-described (p. 207) repeated alternation between thin seams of sandstone and shale is also present, quite typically developed. Very often the sparagmitic material shows the imperfect adaptation, rounding and assorting known from Scandinavia, in the form of sharp-edged grains, flakes and splinters, etc., obviously a result of similar conditions of weathering and sedimentation. — Finally we have to point out the absence of any general regional-metamorphosis, worthy of mention, in spite of the relatively strong compression and the highly dislocated position of the strata. With regard to the metamorphosis, this zone is thus most closely comparable to the most slightly metamorphic parts of the Trondhjem field, especially to the belt situated west of the above-mentioned area, »det metamorfiske strög».

As to the northern subdivision (subzone III A) of the central folding zone, we may first refer to the thin strips of upper-Cambrian and lower-Ordovician sedimentary rocks (»The Highland Border rocks», **7, 9**) that run here farthest to the S. E. The lower part of this belt contains basaltic pillow lava with accompanying agglomerates, tuffs and Radiolarian cherts, alternating with black slates, which by means of their fossils show the above-mentioned age. This lava-horizon is separated by an original unconformity from an upper division, »the Margie series», which, besides a basal conglomerate with pebbles of the underlying lavas, cherts, etc., contains, *inter alia*, a series of green sandstones, rich in calcite and plagioclase. The metamorphosis is partly rather considerable. The lithological and stratigraphical resemblances and the equivalence with corresponding rock-groups in the Southern Uplands and the Trondhjem field seem to be beyond all doubt.

The remaining, main part of the subzone III A, including chiefly the Dalradian formation, is without controversy considered to be a region of powerful compression, in which certain belts are characterized by strong regional metamorphosis and can be considered as equivalent to »det metamorfiske strög» in the Trondhjem field. Apparently the central core of the mountain range may be considered to be situated here. However, the question is whether — except for genuine structural analogies, which will be discussed in more detail below — lithological and stratigraphical similarities can also be put forward in support of such a parallel.

It must then be immediately pointed out that, with regard to the

[1] The greenish-grey colour is due principally to chlorite.

geological position, the Dalradian unfortunately has not been definitely established hitherto (see p. 230 below). It has not even been possible to decide what is the top and what is the bottom of the formation. The difficulties are thus considerable, and we can scarcely expect a definite result of a discussion of the question mentioned above. Although generally by leading Scottish geologists the Dalradian is now considered as an independent pre Cambrian formation, still some views and general considerations — from a Scandinavian point of view — may be briefly set forth.

As a general matter of fact it may then be noted that considerable parts of the Dalradian (without regarding the later igneous rocks and the secondary metamorphosis) seem petrographically to be closely connected with the old-Paleozoic deposits in the S. Uplands, together with which the Dalradian may thus be considered as forming a petrographically quite characteristic, mainly coarse-clastic series of strata of geosynclinal facies (see p. 208). The Dalradian rocks denoted as quartzites often contain, as far as, *inter alia*, my own observations in the field and under the microscope extend, considerable quantities of clastic felspar, especially acid plagioclase, which may even form a principal constituent in the rock (see, e. g., **6**). The original cement seems then to have consisted of argillaceous and calcareous material. Consequently these rocks seem to no slight extent to have had the characteristics of the so-called greywackes and of the calcite-plagioclase-sparagmites, but they have also been of a more normal sandstone-composition. In different parts of the extensive Dalradian region, for instance in the extreme N.W. at Loch Linnhe (see, e. g., **22**, pp. 30—32), or in the main region between Loch Fyne in the S.W. and the coast of Banffshire in the N.E. (see, e. g., **21**, p. 20), there is an intimate and continuous alternation, in the way previously mentioned (p. 209), between thin strata and seams of such greenish grey sparagmitic sandstone and narrow phyllitic stripes. Interformational conglomerate-layers are not rare either. Both in the S.W. part of the region and in Banffshire there also occur so-called epidiorite-beds, which in later times have been shown to be metamorphic pillow-lavas (see, e. g., **3**), with chemico-petrographical characters (**21**) closely agreeing with those in the Arenig in the Southern Uplands. As is the case there, these lava beds are associated with agglomerates and tuffs, interstratified with schists, sometimes also with jasper, etc. Above this rock-group a discordance is to be recognized in certain districts in the usual way (see p. 208), marked, *inter alia*, by a boulder-bed, containing material from the underlying rocks (see, e. g., **21**, p. 32).

The Dalradian rocks can be regarded as on the whole less metamorphosed than the Moinian (see, e. g., **16**, p. 136). Therefore in this respect, the relation between these two rock-complexes is the same as between the Scandinavian Seve schists and Köli schists. Just as we, e. g. in the Trondhjem field, can gradually pass over from slightly recrystallized, typical Köli schists to the highly crystalline schists and gneisses of the

Seve schist type, belonging to »det metamorfiske strög», so we pass over from the peripheric belts of the Dalradian — marked by relatively well preserved primary characters — towards the central zone with highly crystalline rock-types, similar to the above-mentioned ones in the Trondhjem field. Among such more or less highly crystalline rock-types in common, we need only mention here garnet-bearing mica-schists and biotite-oligoclase gneisses, actinolite-schists, corresponding to the Scandinavian »Garbenschists», and the greenish-grey, psammitic phyllites, sometimes developed in considerable thickness in the Dalradian and characterised by porphyroblasts of biotite (see, e. g., **22**). Both macro- and microscopically I have found the last-named schists in composition and structure strikingly similar to the central Scandinavian so-called Stuedalsschists, *inter alia*, inasmuch as in both cases they often seen to represent altered sediments, rich in calcite and plagioclase.

On some leading geotectonic features of the Caledonian folding zone.

In large parts of Scandinavia the chief features of the Caledonian folding-tectonic are not yet known with any certainty, owing to co-operating unfavourable external conditions, chiefly troublesome earth-covering, the lack of fossiliferous or otherwise stratigraphically useful guiding horizons, strong metamorphic alteration of the rocks, etc. In certain districts the knowledge of these questions is certainly less imperfect and more detailed, without, however, approaching the exactness of the admirable works done in the Scottish regions.

In one question, which is fundamental for our understanding of the more far-reaching manifestations of the folding-process, the Scandinavian region seems, however, in many districts to offer more favourable conditions than the Scottish one, because the denudation there has penetrated farther down and often exposed the older autochthonous foundation, lying under the rock-complexes, metamorphosed in the Caledonian time. This foundation now appears as »windows», partly too, as in central Scandinavia, everywhere along the present margins of the folding zone both in the N.W. and S.E. In the south-west of Norway the denudation has even gone so far that now there is scarcely more left than the roots, belonging to the central folding zone or the core of the mountain range, squeezed down in an enormous Caledonian folding- or deformation-depression in the fundamental platform (**28**). There is good reason to suppose that the tangential compression and the consequent decrease in volume of this depression produced the folding, and finally directed toward both sides the mass-displacements or the pressing out — in the form of recumbent folds, thrust-masses, etc. — of the formations that originally rested on the surface of the foundation but then were sunk into this depression.

From a geotectonic point af view Scotland is to be regarded as a less upheaved region than Scandinavia and is therefore less far denuded. Only farthest to the north-west, the undoubtedly marginal zone of the mountain range is exposed, and there the denuation has penetrated down to the deepest Archean foundation, while, on the contrary, on the opposite, south-east, side of the mountain range young-Paleozoic deposits completely conceal the older Caledonian folding-structure in the marginal zone there. In Scotland, because of this, it is impossible on the whole to have any certain opinion about the configuration, etc., of this Archean foundation, situated beneath the folding zone here.

In the south-west of Norway the sub-Cambrian peneplane, with Cambrian basal strata still upon it, has been lifted by Caledonian deformating forces to the exceptional height of 1,000—2,000 metres above sea-level, and then descends abruptly several thousand metres down into the Caledonian deformation-depression in the core of the mountain range. Consequently, the sub-Cambrian peneplane, originally on the whole horizontal, has here in post-Cambrian or, more exactly, in Caledonian time undergone a considerable deformation and now possesses slopes of about 1 : 5 (**28**).

In the region in north-west Highlands, more limited for such observations, and most clearly in the Assynth district, the deformation reaches a corresponding size, as the even sub-Cambrian land-surface — here, as we know, built up of Archean and Torridonian — with a slope not infrequently of 1 : 5—1 : 6, descends steeply towards E.S.E , or towards the centre of the mountain range.[1] Here too the size of the slope seems probably to indicate that we are at the western margin of a marked Caledonian deformation-depression, whose opposite side, on the contrary, is to its position unknown. In analogy with Scandinavia, and with regard to the character of geosynclinal facies that the sedimentary rocks of the Scottish folding zone show, and still further by means of examining the superficial folding-structures in this region, dealt with in more detail below, it seems moreover probable that the Caledonian deformation of the foundation, lying

[1] It ought perhaps to be added here that another deformation of the earth-crust, slightly older than the Caledonian one, can be traced along practically the whole marginal zone in N.W. Both the Torridon sandstone and the Cambrian basal horizons dip here about towards the E.S.E., the former, however, generally 5°—10° less than the latter. If we presume the even peneplane restored to its original position, on the whole horizontal, the Torridon sandstone will have a gentle westerly dip, indicating that a relative upheaval took place in the east after the formation of the sandstone, but before that of the Cambrian. Similar conditions may also be seen on the east side of the central Scandinavian folding zone (**13**, p. 40), where, however, as might be expected, the region of upheaval is situated in the west. — It ought, however, to be remembered that the Torridon sandstone, as a coarse clastic, probably fluviatile formation, perhaps during the sedimentation did not obtain complete horizontality, which is to be noted in judging of its stated enormous thickness, 6,000 metres, as also with regard to the unconformity, described between it and the Cambrian.

beneath the folded formations, continues beneath the greater part of the Scottish folding zone. Unfortunately, we cannot directly decide whether this foundation or platform, as in many districts in Scandinavia, was thereby developed as a number of about parallel depressions. The tectonic structure of the folded, more superficially situated formations is, on the contrary, fairly well known, and there seem to be various arguments in favour of the idea that the main synclines and anticlines, dealt with below, correspond to deformation-depressions in the foundation.

Among the parts of the Moine region, so far mapped and described by the Geological Survey of Scotland, Ross and Cromarty especially offer a good insight into the folding-structure. The 40—50 km. wide Moine zone forms at least one huge main-syncline (fig. 2), with on the whole rather highly inclined strata (**27**), which, however, on account of the Z-folding, described below, in reality often appear far more gentle. On the contrary, the western part of the region is to be characterized as an immense, compound anticlinal upheaval of typical fan-structure, in which not only the lowest horizons of the Moinian, but often too its Lewisian substratum also rise to the surface (fig. 3, **25**). — That the Caledonian mass-displacements in the Moine zone have in the main taken place towards W. and N.W. is indicated to some extent by the above-mentioned, gently dipping minor folds (fig. 2), which, on account of the longer limb is oriented towards the west, form inversions, regularly dipping towards E. and S.E., both on the east and west side of the major syncline. This direction of the movements is seen perhaps even more distinctly in fig. 3, with recumbent folds thrown over repeatedly to the west, finishing with the well-known thrust-margin in the west. This is evidently the main direction of the mass-displacements in the Moine region; but besides this, in the eastern part of the fan-anticline also movements, though less extensive, have taken place in a quite opposite direction, or towards the east. This is manifested especially by the folds, e. g., of Lewisian gneiss, present here, and also thrown over in this direction.

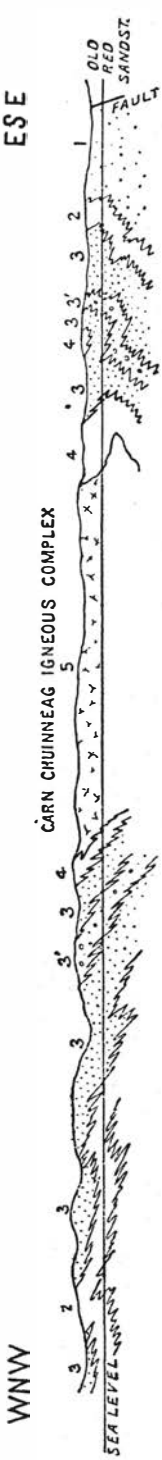

Fig. 2. Diagrammatic section across the central part of the Moine region E.S.E. of Ullapool (reproduced from **27**, fig. 1). — Length of the section about 30 km. 1, 2, 3, 4 subdivisions of the Moinian in ascending order; 5 intrusive rocks.

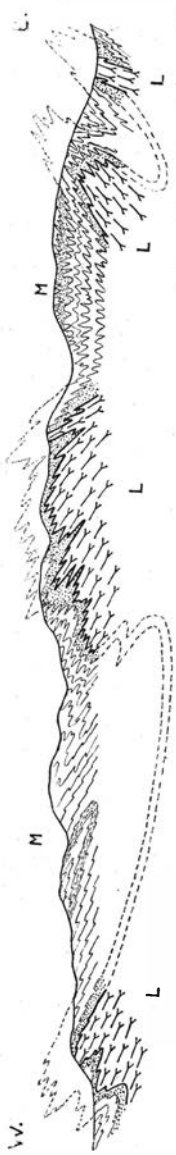

Fig. 3. Diagrammatic section across the western part of the Moine region S.W. of fig. 2 (reproduced from **25**, fig. 7, but a little simplified). — Length of the section about 21 km. L upfolded Lewisian gneiss, M Moinian.

From other parts of the Moine region too, there are equally obvious instances of two-sided movements, caused by a fan-structure and running in entirely opposite directions.

The Dalradian area (III A) can also be described as being in the main a huge synclinal region, with the considerable width of 60–70 km. (fig. 4). In this structural division there also occur, however, typical Moine schists, *inter alia* as a peripherical belt of varying width along the north-western side of the region, and, on the whole, here dipping inwards, i. e. towards the S.E. Just as, in my opinion, the equivalent Trondhjem field rests on a substratum of Seve schists, produced by metamorphosis of the sparagmitic bottom-horizons of the Rörås group, etc., so the Moine schists — eventually, *inter alia,* metamorphic Torridonian, see p. 232— probably form in many districts the basement of the Dalradian syncline. On the contrary, N.W. of this main syncline we find northerly or north-westerly dips (see, e. g., **8**), thus marking an anticline, existing between the main zone II and III A (fig. 1) and probably also developed in the autochthonous foundation. Just as the Moine zone disappears under post-Caledonian deposits in the east, so the original south-eastern part of the Dalradian main-synclinal region probably lies hidden under the Midland Valley fault depression. Among the marginal parts of this structural region we may perhaps count the folded Gothlandian strata, overturned towards the S.E., that come to the surface, e. g., at the North Esk Reservoir in the Pentland Hills, as also farther to the S.W. (**19**).

Although not prominent in fig. 4, the central part of this huge main syncline, which in its turn is arranged in a series of large subfolds of higher and lower order with the axes running in the general Caledonian direction S.W.—N.E., is anticlinally upheaved into a typical fan-structure with dips falling inwards (see, e. g., **21**, fig. 6; **43**). As has been stated by different investigators[1], and as is also clearly seen in fig. 4, with the folds overturned in both directions, the Caledonian mass-displacements and movements in this main region also must have gone in two quite opposite directions, or out towards both sides from the fan-axis or the central axis, i. e , partly to the N.W. towards the main zone II

[1] Cf., e. g., **23**, p. 88; **1**; **7**; **9**.

(fig. I), where, however, the direction of the movements has also been partly quite opposite (see above), partly towards the S. E. against the present Midland Valley. In Forfarshire and Kincardineshire distinct thrust-movements towards the S.E. are thus established along the south-eastern margin of the subzone III A. As in the analogously constructed Trondhjem field, which seems to be compressed to about the same extent, these mass-movements of the subzone III A, forced in opposite directions, will scarcely have reached any considerable dimensions.

The Southern Uplands (III B) represent, according to my opinion, the most southerly part, now accessible, of the central folding zone. The principal structural features, present here, show a close agreement with those in the main zones II and III A. The middle belt forms, in other words, a central compound anticline with individual folds, the axis of which dip towards the centre, where the strata are vertical, but obtain towards the sides a more and more gentle dip inwards. In other words, here lies before us a typical Alpine fan-structure (fig. 5). In this compound anticline the oldest divisions of the formation, among others the lava-platform situated under the Southern Uplands, come to the surface again. The minor folds of this anticline form overfolds and inversions, directed to the N. and N.W. on the north side of the longitudinal axis, to the S. and S.E. on the south side, i. e. once more showing the same noteworthy mass-displacements, although relatively insignificant, in two opposite directions.

The peripheric parts of this huge fold-system are hidden beneath younger deposits both in the N.W. and the S.E. However, there is much supporting the idea, that this subzone has, as a whole, the character of a main syncline, whose northern marginal parts are perhaps to be sought in the anticline that emerges in the Pentland Hills with its core of old-Paleozoic strata, folded together in Caledonian time and dipping towards the S.E. on the eastern side (see, e. g. **17**, section II).

Fig. 4. Section across the central part of the Dalradian region from river Garry to river Tay, N.W. of Perth (reproduced from **23**, fig 4). — Length of the section about 17 km.

We now come to the principal structural features in central Scandinavia. Quite early TÖRNEBOHM came to the conclusion that the strongly compressed Trondhjem field, constructed as an immense syncline, formed in its central region an anticlinal upheaval. In that the lower divisions of the Silurian for-

mation are brought to light and, by inversions of major and minor size, overlie younger horizons (**45**, Pl. 4). This leading idea of TÖRNEBOHM in the interpretation of the architecture of the field, so difficult to explain, the correctness of which has been denied earlier, has during the Norwegian detailed investigations of recent years been confirmed (**10**). Consequently we have here a single fan-shaped anticline of considerable dimensions, with overfolds and accompanying mass-displacements, which, however, probably are of less considerable size, directed towards each side out from the core-axis (fig. 6). This upheaval would thus correspond to at least the two smaller fan-shaped anticlines of — in my opinion — the equivalent Scottish subzones III A and III B. In the eastern part of the Trondhjem field, S.S.W. of Storlien, there is, however, in the neighbourhood of Öiefjeld

Fig. 5. Sketch section across the northern part of the Southern Uplands, S. of Edinburgh (reproduced from **19**, section 1, but a little simplified). — Length of the section about 45 km. — The lower-Ordovician subdivision is shown by a thick black line. — F the Boundary Fault.

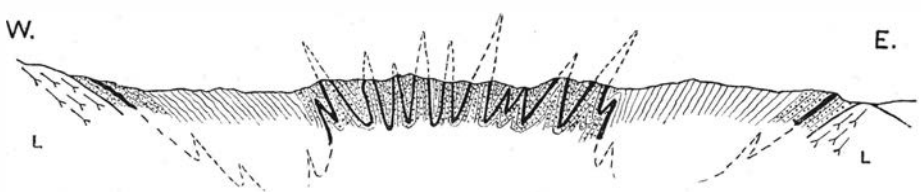

Fig. 6. Diagrammatic section across the Trondhjem field. — Length of the section about 120 km. L Archean foundation, the rest is the Silurian.

a smaller anticline, striking from north to south, which, if one so wishes, may be looked upon as the beginning of another fan-anticline (**45**, map; **14**, p. 177).

Eastward the Trondhjem field is bordered by a large anticline, which over a length of about 200 km forms the political frontier between Sweden and Norway, and in whose southern part the porphyries and granites of the Archean are exposed in the core. With regard to its middle or central Jämtlandian part (fig. 7), the Mountain-schist region, continuing immediately to the east, is in its turn by an anticline — placed about parallel to the above-mentioned one and analogous in structure — the Mullfjäll anticline, divided into two large synclinal regions, the Tännfors field, about 40 km in width (M_1), and the complex of Åreskutan, about 20 km in width (M).

As I have shown in another paper (**14**), there are strong reasons against the interpretation of the geological structure, given by TÖRNEBOHM,

according to which these two Mountain-schist regions belong to a single thrust-mass of enormous dimensions, which, from a root-line west of the political frontier, was forced as much as 140 km out over the autochtonous Silurian substratum in the east. For it has appeared that the bottom-beds of these central Jämtlandian Mountain-schist complexes, M and M_1 (fig. 7), along both their east and west sides, consist to a great extent of the metamorphosed rocks of the substratum, in the form of anticlinally upfolded portions of the Archean rocks together with the basal horizons of the Silurian. Upwards these rocks gradually assume the typical habitus of the Mountain schists. The upfolded anticlines in the margins usually form moderately inclined inversions, with their axial planes always dipping towards the centre of the complex. These overfolded anticlines indicate — like the late-Caledonian cataclastic zones, connected with the same bottom-horizons — mass-displacements, directed out from the centre of the complex, partly in the form of overthrusts. Consequently in the adjacent parts of two contiguous complexes the movements ought to be more or less opposite in direction, quite in agreement with the Scottish conditions pointed out above.

In Scotland the horizontal displacements, proved with certainty, attain their maximum amount, 16 km., in the classical Scottish overthrust-region (**20**, p. 469). The values of up to about 22 km, reported from the south-western Highlands (**22**), seem to be subject of more controversy. It is also difficult to fix certain amounts for the central Scandinavian horizontal displacements. Of course the explanation, put forward by me, implies, in any case, that the enormous amounts, 100–140 km, previously given, are considerably to be reduced, perhaps to about a tenth of these amounts, or sometimes still less.

In a preceding treatise I have tried to explain the tectonics in the just mentioned central Jämtlandian Mountain-schist complexes, which rest upon fossiliferous Gothlandian and partly

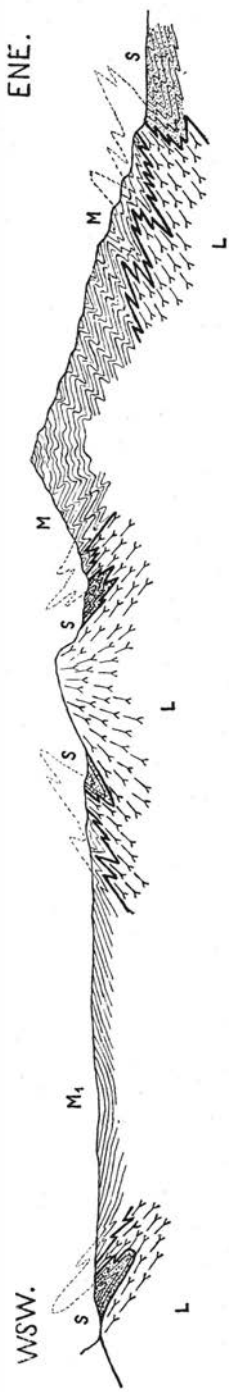

Fig. 7. Diagrammatic section across central Jämtland. — Length of the section about 80 km. (The section is an easterly continuation of fig. 6.) L Archean foundation, S Silurian, M complex of Åreskutan (Seve schists), M_1 Tännfors field (Köli schists).

reach a striking thickness, as controlled by imbricate-structure or a series of individual inversions and folds, piled up on one another, schematically shown in fig. 7, in which sometimes the bottom-layers of the Silurian and possibly pressed-up Archean porphyries and granites also take part (**14**, p. 170). Evidently such an architecture must be considered as implying that in each synclinal region there has taken place a general upheaval or pressing-up of considerable parts of the originally deepest situated basal rock-complexes, among others the Archean substratum. Furthermore, as I have pointed out above, we can look at this geotectonics as possessing a kind of fan-structure, comparable in a certain degree to the central anticlinal upheaval in the Trondhjem field (**14**, p. 187), where, however, the anticlinal fan occupies a considerably smaller part of the large synclinal complex. Obviously the compression has in the latter field been considerably slighter, so that the dips towards the fan-axis have not — even in the margins — become as gently inclined as in the Seve-schist region in central Jämtland.

It is noteworthy, that the fan-anticlines reach about the same order of size in Scotland and central Scandinavia. However, perhaps the Jämtlandian ones give the impression of being somewhat depressed in the centre, but similar examples are also to be seen in Scotland, e. g. in the Dalradian region (fig. 4). However the basal upheaval in the central Jämtlandian Mountain-schist complexes does not need — more than in the Trondhjem field — to have brought to light the Archean substratum in general. The visible upheaval may in the first place have been restricted to the most denuded marginal zones, while the Archean substratum, as the Scottish conditions show (fig. 3), can be hidden nearer the centre under a covering of metamorphic sediments of varying thickness.

Thus the above considerations seem to indicate that the Scottish and central Scandinavian parts of the folding zone have in their main features a similar tectonic structure. However, the question as to the exact configuration of the foundation of the folded rock-complexes must be left open, as far as Scotland is concerned. There still remain some general comparisons between the folding-structure of the two regions.

According to TÖRNEBOHM's description of the geological structure in central Scandinavia, clean-cut thrusts are quite predominant in the eastern region (II, fig. 1), while in the Trondhjem field in the west there prevail, on the contrary, more normally developed folds, *inter alia* of the recumbent Alpine type, in which the thinning out of the lower limb of the upfolded anticline has not advanced as far as to complete breaking and disappearance (**45**, pl. 4). The more or less normal recumbent folds, nevertheless recently recognized from the above-mentioned eastern region (**14**), do not seem to be able to reverse this general state of things. The Scottish investigations have also shown that clean-cut thrusts are the

characteristic tectonic feature in the equivalent Moine zone (II, fig. 1) in the north-west Highlands (**20**), that recumbent folds certainly also occur there (see, e. g., **25**), but that these, like normal folds, belong mainly to the Dalradian zone III A (see, e. g., **2**, **3**, **4**, **5**, **22**) and the Southern Uplands (zone III B). Intimately associated with this matter of fact is that the central folding zones (III, III A together with III B) are characterized, *inter alia,* by varying, but in most cases more or less steep dips and relatively slight horizontal mass-displacements, usually only in the form of overfoldings, while the Moine and Seve regions (II) give the impression, on the whole, of more uniform and gently inclined positions of the strata, associated with horizontal displacements of more important dimensions. Evidently the extent of the compression is decisive in such cases and higher in the last-named zones.

However, this persistent gentle dip seems partly to be only apparent and due to the fact that in reality the often highly inclined strata have been put in a continual series of sharply bent minor folds of compressed Z-shape, often consisting of a longer limb, usually gently dipping, and a shorter and more steep one.[1] Because in strongly compressed Z-folds, with more or less parallel limbs, the curve itself easily escapes notice, while at the same time the longer limb attracts the attention at the expense of the shorter one, we easily get the incorrect impression of a constant gentle dip over wide areas. Such a persistent gentle dip also easily causes us to estimate quite too high the thickness of the folded formations. A folding structure of this type has been described not only from Scotland (see, e. g., **8**, **23**, **27**) but also from Sweden (see, e. g., **37**), where, however, it seems not to have attracted attention enough. With regard to the circumstances, now mentioned, this apparently gentle dip of the strata may of course by no means be taken as contradictory to the given explanation of, e. g., the complex of Åreskutan (fig. 7, M) as essentially metamorphic Silurian sediments, interwoven by Caledonian igneous rocks, and belonging to a strongly compressed Caledonian deformation-depression in the Archean substratum (**14**, p. 180).

Of course the structural peculiarities, now mentioned, in the special tectonic main divisions of the folding zone are only an expression for the different degree of tangential compression in the fan-shaped anticlinal upheavals. The Z-folding, appearing especially in the Moine and Seve regions, shows, by its whole structure, and by the accompanying strong schistosity and metamorphosis in the rock-mass, a more intense stress and stronger differential movements, and is caused by a more powerful compression of the fan-anticlines. In this way the structure that otherwise — regarding the central folding zone — only prevails in the margins of the anticlinorium and consists of individual folds, towards the sides overturned and recumbent, (see, e. g., fig. 5, 6) will occupy also the interior

[1] This condition may be schematically recognized in fig. 7 (M) and, e. g., in fig. 2, 3 (to the left).

of the fan-region (see, e. g., fig. 7, M), where otherwise as a rule more or less vertically placed axial planes dominate. It is of course obvious, that the classification of these fan-regions in one or other of the two principal types is often almost a matter of taste, as only a difference of degree, not one of kind, can be proved between them at present.

Besides the above-mentioned reflections upon the inclination of the strata in the fan-upheavals, another point of view deserves to be discussed. It is noteworthy that the fan-structure, e. g. of the Tännfors field (fig. 7, M_1), is obviously very reduced and only recognizable along the margins, possibly also within a narrow belt in the north-western part of the field (**46**, p. 11, section; **14**, p. 176). In other words, this fan-structure seems not to have influenced to any great extent the position of the strata in the now accessible central parts of the field. The whole structure of this, however, seems to indicate a slighter compression than, e. g., that in the Åreskutan complex (**14**, p. 174). But apart from that, these uniform, gently inclined dips, predominating in the Tännfors field, also recur elsewhere, e. g. in the continuation of the Trondhjem field within Northern Norway. But these regions are on the whole considerably less denuded than the Trondhjem field itself with its highly inclined strata, and consequently it is possible, that in part the above-mentioned gentle dips belong to more superficial sections of the folding zone, while the fan-shaped position of the strata belongs to greater depths. As a rule a gradual increase of the dips will take place in the same degree as we approach the Archean substratum in the geosynclinal depressions. Such a levelling is indicated at the top of the centre in fig. 5 and fig. 7 (M).

It is furthermore of interest to observe the frequently strongly unsymmetrical structure of the fan-anticlines (see, e. g., fig. 3), due to a dominating direction of the mass-movements out from the central axis of the mountain range (see p. 213 above). In central Scandinavia this condition is supposed to be dependent on a corresponding unsymmetrical construction of the underlying deformation-depressions (**14**, p. 182). In the Swedish part these chief movements were going to E. or E.S.E., in the Trondhjem field in the opposite direction, judging from TÖRNEBOHM's sections (**45**, pl. 4).[1] On the contrary, the Scottish folding-region only shows one movement-direction of predominant character, namely to the N.W. However, in the Southern Uplands no chief direction at all will be certainly recognized. This condition is of interest as perhaps indicating, that the subzone III B really may be included in the central folding-zone, and that the south-eastern parts of the original mountain range were situated under the covering young-Paleozoic formations further to the S E.

Finally it is noteworthy, that the geotectonics of the central Scandinavian main zone II — *inter alia,* the generally gentler inclined position of the strata — seems to indicate a stronger compression than in the cor-

[1] Here the great thrust-masses to the east, mentioned above, and in TÖRNEBOHM's opinion deriving from the Tännfors field, ought not to be taken into consideration.

responding Scottish one, and this fact is associated with a greater abundance of contemporary intrusions and stronger rock-metamorphosis in the former region (see below).

Another structural feature may be touched upon here, as being of special interest for Scandinavian geology. In the classical Scottish thrust-region of the north-west Highlands there generally occur patches of Lewisian rocks among the Moine schists, not infrequently whole series, one after the other (see, e. g., **24**, **25**). These patches have been torn up from below and seized by the overthrusts. That there can be no question here of Caledonian igneous intrusions — as in Scandinavia is generally taken for granted — is proved, *inter alia,* by the extremely complex nature of the constituent rocks, which closely agree petrographically with the autochthonous Lewisian rocks and contain, among other things, the pre-Torridonian dike-systems, so characteristic of the Lewisian complex. These patches of Archean rocks have their tectonic equivalents in central Scandinavia (**14**), but are on the contrary generally not mentioned from other parts of the Scandinavian region. Their common appearance, e. g. in Jämtland, seems possibly to be due to the fact, that the sub Cambrian land surface has not had here its otherwise usual peneplane-character (see p. 204 above). Therefore the hills of Archean rocks, originally arising in the Silurian, were easily seized by the Caledonian movements of the sediment-cover and were forced into this at the same time as the metamorphosis. In regions with an even, more peneplane like surface of the foundation the conditions of this process must, on the contrary, have been considerably less favourable.

However, the question is, whether this explanation is also applicable without reservation to Scotland. Here it must be observed, that the Archean is extremely complex in its primary composition, but can — from the dynamic point of view, dealt with here — on account of metamorphosis and crystallinity, against the younger sediment-formations be considered as a uniformly amalgamated rock-mass, in which possibly existing unconformities etc. no longer so easily react as zones of weakness. Consequently the critical junction of the two dynamically heterogeneous formation-groups appears here between the Torridonian and the Lewisian or — in the less extensive regions where the Torridonian is absent — between the Cambrian and the Lewisian, while on the contrary, the Torridonian and the Cambrian, which are largely clastic and psammitic, are dynamically of more equal value. The sub-Torridonian land-surface is, however, considerably more uneven than the sub-Cambrian in Jämtland (see p. 203 above), and the Lewisian inliers, folded into the Moinian, are, as consequently also might be expected, usually both more numerous and of greater dimensions than the central Scandinavian ones. But, moreover, such Lewisian inliers occur normally superimposed by the Cambrian basal horizons, while the Torridonian is lacking. I have no possibility of de-

ciding, whether this sign of weakness in the sub-Cambrian Lewisian surface is only to be connected with the fact, that the broken sub Torridonian land-surface was in the vicinity, or possibly that even the sub-Cambrian land-surface was uneven in certain districts, or whether it is due to other circumstances.

On the Caledonian metamorphosis and the Caledonian igneous rocks.

The problem of the origin and metamorphosis of the Scandinavian Highland schists is one of the fundamental questions of the mountain problem. That large parts of these schists, the so-called Köli schists, which build up, *inter alia,* the Trondhjem field, are nothing but more or less metamorphic Silurian sediments, has long ago been completely proved by fossil-discoveries. On the contrary the so-called Seve schists, including the Åre schists, present greater difficulties, on account of extreme metamorphosis, freedom from fossils, and strong tectonic disturbances. To the Seve schists belongs, *inter alia,* the greater part of the Mountain-schist region, situated to the east of the Trondhjem field (main zone II, fig. 1). According to the older interpretation, as put forward chiefly by TÖRNEBOHM, these schists, as well as their metamorphosis, are pre-Cambrian, and constitute a stratigraphically independent rock group (**45**). The investigations of recent years, both in central Scandinavia and elsewhere, have, however, given the result that these schists by no means denote an independent pre-Cambrian group, but are chiefly composed of regional metamorphic sediments, mainly Silurian, injected by intrusive rocks of Caledonian age.

It is this former, sedimentary part of the Seve schists which from more than one point of view is of special interest. According to the view just mentioned, the Köli schists and the sedimentary Seve schists are only two various metamorphic facies of the Silurian. Nor it is often possible to draw distinct boundaries between them in the field. According to what I have stated above, the Seve schist-type occurs in the regions that are most strongly disturbed tectonically, especially in association with strongly overturned and recumbent anticlines, belonging to the fan-zones (**14**), where at the same time an intimate interweaving and permeating by widespread layer like instrusions, mostly hornblende-schists and amphibolites, has taken place. These *lit-par-lit intrusions* seem to have produced an increase in the metamorphosis of the surrounding sediments by pneumatolytic-hydatogenic supply of substances and metasomatic transformation. Therefore in the Seve schists we find a kind of contact-metamorphosis, disturbed by strong stress, and the combination of these two factors seems to be decisive, contrary to the typical Köli schist.

regions, where the intrusions were to a far smaller degree injected under violent pressure. The mechanism of injection is thus a different one here, and consequently the intrusions appear more as concentrated rock-bodies and as normal laccoliths, whose influence on the sediments, if this can be proved, assumes the character of more normal contact-aureoles. Because of these different manners of intrusion and consequent configuration of the injected rock-bodies, the igneous rocks are often far more striking in the Köli schist regions, than in the Seve schist regions, regarding geological maps on a small scale.

Among the igneous rocks in the central Scandinavian Mountain schists, intruded during different phases of the folding-process, the predominent types are, as far as we know now, basic and acid intrusive rocks, the former of which are common especially among the Seve schists, but generally transformed to hornblende schists and amphibolites. They also may not infrequently be identified as gabbros, norites, diabases, serpentine-peridotites etc. of varying composition. The acid rock-types are, as usual, on the whole younger than the basic ones and have — at least with regard to their last, most commonly occurring generation — escaped the strongest regional metamorphosis. Therefore these rocks often show little or no schistosity, due to pressure, and contain inclusions from the already crystalline Highland schists.

It is these acid intrusive rocks, rich in plagioclase and described under the names of white granites, trondhjemites, granodiorites, etc. (**32**), that are above all characteristic for central Scandinavia and in general for the southern part of the Scandinavian folding-region.

The Scottish Caledonian igneous rocks show a considerable affinity, both geologically and chemico-petrographically, with the above-mentioned central Scandinavian ones. This is especially true of the youngest trondhjemite-generation of the Trondhjem field and the rather abundant Scottish occurrences, usually described as »newer igneous rocks» or »the newer granite group», which, concerning the degree of schistosity, the relation to the surrounding crystalline Highland schists and the obviously younger basement-conglomerate of Old Red, etc., show themselves — like the corresponding Norwegian rocks (see above) — to be younger than the former part of the folding-process and the main metamorphosis of the schists, but older than the final phase. A leading feature, however, is a prevailing greater abundance of potash, often resulting in normal granites, which is quite unknown in the Trondhjem field. The group of acid rock-types rich in plagioclase and consisting of granodiorites, tonalites, quartz-diorites, etc., which are so characteristic, as a rule, for the great folding zones on the earth, differ in Scotland, in accordance with the above-mentioned condition, by minor displacements in the proportions of potash-felspar to plagioclase, from the corresponding trondhjemites, which are extremely poor in potash. Such tonalites, etc., closely related to the

Norwegian trondhjemites, seem to be wide-spread in different parts of the Scottish region, both in the Moinian and the Dalradian (see, e. g., **11**, **22**, **23**, **24**, **27**), as well as in the Southern Uplands (»the Galloway granites», **19**). -- For instance from a considerable district in the north-eastern corner of Forfarshire (**6**), there is described under the name of granite a rather typical, strongly foliated trondhjemite, consisting of much quartz, zonal oligoclase, biotite, garnet, apatite, etc., but no visible potash-felspar. It is accompanied by masses of narrow sheets and sills, partly pegmatitic, permeating the Dalradian schists as minute ribbons, threads and veins. In certain Dalradian schists of the Portsoy district I have observed a similar intimate interweaving, typical for central Scandinavian conditions, of a light rock, which under the microscope can be recognized as a trondhjemite, bearing some potash-felspar.

The basic intrusive rocks in the Scottish Highland schists, many of which go under the name »older igneous rocks» or »pre-foliation igneous rocks» — but which nevertheless probably were to a considerable extent injected during the earlier stage of the folding — are, as in Scandinavia, on the whole older than the acid igneous rocks and in general more metamorphic than these. They are represented by hornblende schists, amphibolites and »epidiorites», at other times by slightly altered gabbros, norites, diabases, periodotites, and in exceptional cases also by anorthosite (Portsoy), of which the latter certainly does not occur in the Trondhjem field but south-west of it.

Although not belonging to the real Caledonian eruptives, the so-called augen-gneisses may, however, be briefly mentioned here. They are acid, red, more or less foliated porphyric granites, rich in potash, often passing into uniformly granular granite-gneisses of medium coarseness. Besides the large laccolith in Rosshire (**27**), they are mentioned from some other districts. Their age is distinctly pre-Caledonian, as in the surrounding schists they have produced normal contact-aureoles, which are proved to be older than the Caledonian folding. Also they have themselves, by all accounts, obtained their foliation because of this folding. It is true, that these gneisses, like the surrounding Moine schists, are nowadays usually said probably to be pre-Cambrian (see, e. g., **35**), but a later age seems possible too, at least concerning certain parts of the schists (see p. 230 below). Consequently under this presumption the augen-gneisses may also be Cambrian or Ordovician, and therefore about comparable in age with the eruptions of the Assynth district (**20**) or the lower-Ordovician intrusive and effusive rocks in the Southern Uplands, the Trondhjem field, etc. (see p. 208 above). At any rate it seems scarcely to be possible at present to bring any decisive evidence against such an interpretation.

The boundary between the Silurian Trondhjem field and the Archean

region, beginning to the west, is not yet established with certainty (**10**). To this Archean region has hitherto been counted a series of red granitic gneisses, rich in potash, which, both in their interior and also along the junctions with the Silurian schists, pass into ledges of typical augen-gneiss. According to the result of the last summer's Norwegian investigations, which I had an opportunity of discussing in the field with Dr. CARSTENS, there seems to be no doubt that at least certain of these red granites and gneisses in the so-called »Vestranden» penetrate the Cambrian bottom-division of the Trondhjem field, while, on the contrary, they do not seem to reach the adjacent Ordivician-Gothlandian Hovin group. Consequently, to judge from this, the age of these granites, etc., ought to be Cambrian or early Ordovician, and pre-Caledonian. It is noteworthy, that similar conditions also seem to occur west of the Sulitelma district in northern Norway, where, according to recent observations (VOGT), acid red granites, rich in potash-felspar, are intruded only in the lower part of the old-Paleozoic Mountain-schist complex, while the trondhjemitic igneous rocks also reach the younger divisions. If these data prove to be correct, then both in Scotland and in Scandinavia an intrusion-epoch of normal potash-granites has immediately preceded the real Caledonian intrusions of, *inter alia,* the trondhjemitic type. Like the other igneous phenomena of the folding-region, belonging to about the same period, and likewise too the displacements of the sea-level, reflected in the sedimentation in the form of conglomerates (e. g., the Benan conglomerate), these intrusions of augen-gneisses and associated rocks seem to indicate an already beginning orogenitic activity.

After these summary comparisons between some representative groups of igneous rocks, it is worth investigating to what extent these intrusions can be proved to have a causal connection with the metamorphosis of the sedimentary Scottish Highland schists. The striking concentration of igneous rocks in certain districts, especially in the Dalradian region and in general in the subzone III A, as shown in the geological general-map of Scotland (**17**), belongs chiefly to the latest intrusion stage, younger than the genesis of the crystallinity of the Highland schists (see p. 223 above). Thus this rock-group becomes, from the discussed point of view, of no importance. In the same way we need not consider intrusions, older than the real folding and metamorphic process, e. g., the augen-gneisses and associated rocks.

In the Moine schists, or the main zone II, the remaining igneous rocks are very scanty and in certain districts practically quite missing. As well as in the central Scandinavian Seve schists, though considerably more sparse in frequency, the basic intrusions, however — often in the form of minute sheets and sills, more or less completely transformed to amphibolites — decidedly predominate. From this fact alone it is evident,

that the metamorphosis of the Moinian, which is more uniform and extreme, compared with that of the Dalradian, cannot reasonably be attributed to the igneous rocks, unless we refer to hypothetical ones, situated at greater or less depths beneath the Moine field. Therefore the evidence seems to show, that we have probably to deal with a facies of regional-metamorphic schists, formed, as is, *inter alia,* proved by the Z-folding, at strong pressure, but generally without direct influence of proved igneous rocks. This difference from great parts of the central Scandinavian Seve schists, appearing by the scantiness of the igneous rocks, just mentioned, may possibly be supposed to have a certain causal connection with the higher metamorphic degree of the last schists. There seems also to be various evidence in support of this. In the western, most slightly crystalline belt of the Moine region, nearest to the overthrust-margin in the west, such intrusions are, for instance, exceedingly sparse, but to the east they become considerably more numerous, in connection with a general increase in the metamorphic degree of the schists.[1] In certain cases sills of amphibolite seem only to occur in the anticlinally upheaved bottom-horizons, which at the same time become most dislocated and metamorphosed, but, on the contrary, not in the central parts of the synclinal areas in the same region (see, e. g., **27**, p. 23).

Perhaps the connection between the pressure associated with the fan-structure, the injections and the metamorphic degree appears, however, most clearly in the main zone III. In almost its entire southern main part, the Southern Uplands, III B, the regional-metamorphosis and the schistosity is exceedingly slight, in spite of the strong folding and the highly inclined position of the strata. The absence of interstratified intrusions, really contemporaneous, is, as far as I know, complete.[2] It is noteworthy, however, that — as is the case elsewhere, e. g. in central Scandinavia — the pressure and the metamorphosis are decidedly strongest in certain belts and zones, belonging to the lower, most overturned, peripherical parts of the large central fan-region in these districts (cf. **19**, p. 75). — In the northern, synclinally built main part, III A, comprising chiefly the Dalradian, one passes gradually from belts generally less regional-metamorphic, situated in the south-east and the north west, into a highly crystalline central zone, partly coinciding with the anticlinal fan-shaped central upheaval (see p. 214 above). Here the schists are interwoven and interstratified by large swarms of narrow sheets and sills, contemporaneously injected with the folding and the pressure. In this area the Dalradian is not, as generally otherwise, less metamorphosed than the Moinian.

[1] Cf., e. g., the extension of amphibolites and hornblende-schists in the sheets 82 and 83.

[2] Thus we do not take notice of the Galloway granites, etc., which belong to the final phase of the folding (»the newer granites») and, as such a one, have produced normal contact-aureoles of the type of the Christiania field (**19**, pp. 634, ff).

Both from a structural and petrographical point of view this zone seems quite comparable with the anticlinally upheaved central part of the Trondhjem field, with its masses of intrusions (»det metamorfiske strög»), where in like manner the metamorphosis has transformed the Silurian schists of the Köli type, elsewhere but little altered, into highly crystalline ones of the Seve schist-type (**10**, **30**, **45**).

As instances of such strongly metamorphosed districts in the Dalradian, characterized by cooperating pressure and injection, we may mention Blair Atholl, Pitlochry, where thin interweaving sheets and sills of hornblende-schists appear in the most crystalline, folded and displaced zones (**23**). — In the coast section in the Portsoy district the igneous rocks seem in like manner associated with the most crystalline and by pressure strongest affected schists, especially obvious concerning the highly crystalline biotite-oligoclase-gneisses east of Portsoy, where, *inter alia,* thin sills, veins, threads and lenticles of a trondhjemitic rock occur along the schistosity-planes and produce a rock series, quite identical with certain central Scandinavian Seve schists (see p. 224 above). — In the same way, in extensive districts farther to the south thin layer-intrusions of, *inter alia,* trondhjemitic and pegmatitic composition, often difficult in the field to keep separate from the side rock, are in their distribution strictly connected with the highly metamorphic areas of the Dalradian (**6**).

Nor in this case, however, does it seem evident that the crystallinity of the schists is directly caused by the injections. An extreme metamorphosis of the sediments has only taken place in the districts, where the igneous rocks in view are most strongly gneissified and at the same time most intimately interweaving the schists (»the permeation area»), not, on the contrary, where the same igneous rocks are developed as only slightly foliated granites, without any such phenomena of permeating, worth to be mentioned. Thus the pressure seems also here to have been necessary for the intrusion-mechanism in discussion, with its intimate interweaving-contacts, and is, because of this, a necessary qualification too for the extreme metamorphosis of the sedimentary complex. It is also to be noted, as has been emphasized (**6**), that the large massives of newer granites in the same districts are younger than the special crystallinity of the schists, and consequently not the cause of this, and that these granites were generally little, or not at all, able to affect these schists. I have previously put forward the same views with regard to the importance of the pressure for the genesis of the regonial-metamorphic Seve schists in central Scandinavia (**14**).

Another instance, pointing in the same direction, is presented by the Dalradian series on the west coast S.W. of Loch Awe, where it is but little affected by pressure, and where the crystallinity is unusually slight, although the intrusive basic sheets — so-called epidiorites — are especially common (**3**, **21**). That, however, even in such a case the appearance of the igneous rocks is in causal connection with the rise of relatively

strong zones of disturbances (**14**), is proved by the rapid decrease in number of these intrusions and their final disappearing towards the N.W., or the area that is more slightly affected by pressure.

As I have previously shown, the Highland schists in Scotland do not as a rule attain equally high-crystalline stages as in central Scandinavia. It is true, that the intrusions, contemporaneous with the main phase of the folding, assume not infrequently the arrangement of an intimate interweaving along the schistosity-planes of the schists, as sills and veins parallel or sub-parallel to them, but this mode of injection is in general not predominating. Distinctly cutting dykes are more common. These characters, differing from central Scandinavian conditions, can, in my opinion, be explained by the circumstance, that the Scottish region to a far less extent seems to be influenced by intense tangential pressure. It is, for instance, striking that Caledonian igneous rocks from both earlier and later phases of the folding-period not only show to a great extent such obviously cutting contacts. They have also caused normal contact-aureoles of the type, usually characteristic of the Christiania field, that is, a contact-metamorphosis undisturbed by coexistent stress. Nor later on this pressure has been sufficient to efface these contact-phenomena, not even along certain of the previously mentioned pre-Caledonian igneous rocks (see p. 224 above). Such contact-aureoles are far more uncommon in central Scandinavia, where they are restricted to certain of the youngest Caledonian intrusion-masses and laccoliths, which nevertheless generally send out often foliated apophyses and sills along the schistosity-planes. The same general impression of a less vigorous pressure is given by the epidioritic and amphibolitic Scottish layer-intrusions, which, it is true, in certain cases have been strongly compressed and foliated — then even sometimes transformed to calcareous phyllites, difficult to distinguish from metamorphic sediments — but which as a rule by no means show the same thinning out and rolling out as the central Scandinavian ones.

It is noteworthy, however, in this connection, that just as in certain areas in central Scandinavia — especially those consisting of schists, rich in quartz and felspar, above all the fields of sparagmite-schists (**14**, p. 70) — so in petrographically analogous Scottish districts, e. g., in the Moinian or at the bottom of the thrusted Lewisian inliers, there appear acid pegmatitic veins, lenticles and eyes, generally closely following the planes of schistosity. They seem confined to more prominent pressure- and schistosity-zones and are undoubtedly of a secretionary nature.

The fact that the Scottish Highland schists in general do not attain the same metamorphic stages as the central Scandinavian ones can, however, also be seen from another side. For the Scottish region must, for good reasons, be regarded as a more superficial section through the mountain range, and the differing metamorphic degree of the rocks, as well as the less frequency of the igneous ones, can, like the differing

mechanism of injection, to some extent be influenced by this circumstance (see also **14**, p. 193). Thus in the degree of metamorphosis and with regard to the frequency of igneous rocks, injected along the planes of schistosity, the Moine schists may at deeper sections agree more with the Seve schists. Also certain observations support such a view. In some parts of the south-eastern Highlands there occur swarms of pegmatitic sills, undoubtedly of magmatic origin, but usually without any provable connection with larger visible igneous masses (**6**). As, however, in tectonically more deeply eroded regions these sills have been found to be the peripheric offshoots of the gneisses and granites, mentioned on p. 227 above, *inter alia*, of trondhjemitic character, which appear in the most regional-metamorphic areas, it is perhaps not improbable, that such intrusions, associated with highly crystalline sediments, occur in a considerable extension at greater depths beneath the surface.

The stress-epoch now discussed, contemporaneous both with the real regional-metamorphosis of the Highland schists, with certain groups of the Caledonian intrusions and with the upheaval of the fan-shaped anticlines, etc., must be kept apart from the far younger late-Caledonian cataclastic structures of a mechanical nature, which especially occur along the more prominent thrust-planes and between rock-groups of different power of resistance. The same relative age between the genesis of crystalline schistosity and that of the mylonitization also exists everywhere in Scandinavia. This mylonitic process seems, at least in the localities visited by me in the north-west Highlands, to be in general less extreme in Scotland, even along the thrust-planes most marked there. However, it is scarcely probable, that such things directly correspond to the relative order of size between the great post-Silurian thrust-movements in the two regions.

During the work of recent years in the Scandinavian part of the mountain range the problem has become very actual whether the Caledonian intrusions were accompanied by any supply of materials to the surrounding sedimentary Seve schists, and this to a sufficient extent to explain satisfactorily the partly abnormal chemical composition of these Seve schists, as well as their characteristic hard, sharply crystalline habitus, etc. From the Stavanger district in the south-west of Norway we have got quite recent observations, proving that this sort of contact-alterations may have taken place to a considerable extent close to the acid intrusive rocks (**32**). On the contrary the question as to how far such a metasomatic alteration of material can also be recognized in the vicinity of the basic intrusions, so common in certain regions, e. g., central Jämtland, seems to require further investigation.

From the Scottish region there are some scattered observations, perhaps worth mentioning in this connection. In the above-mentioned strongly regional-metamorphic district S.W. of Stonehaven, penetrated by trondhjemitic sills (see p. 227 above), the sedimentary schists are to a great extent developed as a coarse gneiss, rich in oligoclase, *inter alia*, as lenticles and eyes (**6**), i. e., with a habitus common in the metasomatically altered Mountain schists in Scandinavia. There is, however, no certain evidence of any addition of material, in this case regarding especially the formation of the oligoclase. As in Scandinavia, here too it is often impossible to dismember the highly metamorphic sedimentary gneisses from the igneous ones, so inextricably are the rocks interwoven with one another. — From adjacent districts is mentioned a gradual petrographical passage from the basic intrusive rocks into the altered sedimentary schists (**23**, p. 29) under conditions that seem to indicate, that here an addition, resulting in the formation of hornblende, has taken place in the schists, in the same way as has been observed in several localities in central Scandinavia (**14**). — Another more instructive example is presented by a rather considerable complex of epidioritic injections, occurring in the Moinian W. of Loch Linnhe (**22**). In a zone, 50—100 m wide, closest to the epidiorite, the surrounding, originally pelitic schists are transformed to a banded granulitic gneiss, unusually rich in idiomorphic felspar. The felspathic material is said to have been introduced in the sediments. From a Scandinavian point of view we would most probably have here a felspathisation of metasomatic nature.

On the age and origin of the Scottish Highland schists.

The question of the geological position and the relations of the Moinian and the Dalradian is — like that of the Seve schists in Scandinavia — one of the most discussed and difficult problems in Scottish geology. At present the most general view seems to be, that these Highland schists are probably of pre-Cambrian and most likely of Archean age. Yet it is admitted, that there is no quite conclusive evidence for this. Here, however, space does not permit a detailed account of the different opinions, and the arguments for and against them, that have been put forward with regard to these problems of age.[1] Therefore I am obliged to restrict myself to discuss only some cardinal points.

The relation between the Moinian and the Dalradian has up till now not been decisively solved, and there is as yet no unanimous opinion on this question. In general, however, the Dalradian is considered to be the youngest, *inter alia*, because of the more or less weighty reason, that this formation is situated on the south-eastern, i. e. the down-thrown side of the

[1] For a detailed summary of these problems of age, see **33**.

large Great Glen fault, that traverses Scotland. The original unconformity that, according to certain investigators, is found between the two rock-groups, e. g. at Blair Atholl (**8, 33**), has also been subject to contradictory explanations. According to another view, the Moinian is equivalent to certain parts of the Dalradian and gradually passes into them. What appears evident at present is that, in spite of all the work devoted to this problem, it has been impossible up till now indisputably to keep apart these two rock-groups from one another with regard to distribution and age, just as little as, according to the investigations of recent years, this has been possible with the Scandinavian Seve and Köli schists.

A pre-Cambrian age for both the Moinian and the Dalradian is considered to be indicated by the absence of positive and determinable fossils, a condition that is, however, not surprising in consequence of the petrographical characters, both the original and secondary ones, of the rocks — mostly coarse-clastic and metamorphic sediments. For instance in the corresponding Scandinavian regions deposits free from fossils, but nevertheless certainly Silurian, occupy extensive areas. — A direct and, at first sight, more decisive proof is the occurrence, although very sparse, of pebbles of, *inter alia,* crystalline schists, equivalent petrographically to certain Moinian and Dalradian quartzites, in the conglomerates of the pre-Cambrian Torridonian (**18, 34**). Yet it is to be noted, that these pebbles unfortunately do not represent any specially characteristic rock-types, and therefore it is not impossible that instead of this they are of an unknown origin, quite in the same way as is considered to be probably the case with a large number of the other pebbles, which are more easily recognizable petrographically. But to this it is to be added, that the Moinian and the Dalradian are quite certainly to be regarded as complex formations, whose different divisions cannot always be distinguished from one another on account of the metamorphosis. Thus in the Moinian there often occur »inliers» of the Lewisian formation, seized by the tectonic movements, and this Lewisian, as is known, contains a series of metamorphic sediments, including just quartzites and quartzitic schists (**20**). It is perhaps not impossible too that it is such Lewisian quartzites, hidden in the Moinian and no longer identifiable as to their real geological and tectonic character, with which the pebbles in the Torridonian have been compared. Under these restrictions these pebbles would only indicate the later age of the Torridonian in relation to the sedimentary division of the Lewisian (see below).

As indications of an old-Archean age for the Moinian as a whole, reference has been made by other writers just to petrographical resemblances between certain Moine schists and the Lewisian sedimentary series in question, best known from the district of Loch Maree (**8**). By distinct contact-metamorphosis, etc., these metamorphic sedimentary series, entering into the Lewisian formation, have, however, proved to be decidedly older than the intrusive division, belonging to the same formation (see, e. g., **24**).

In localities where the contact-relations can with certainty be cleared up, the Moinian rests, however, with distinct and original unconformity on »inliers», consisting of the igneous division of the Lewisian (see, e. g., **24**). Consequently, this makes it quite clear that at least large parts of the Moinian cannot be parallelized with the sedimentary division of the Lewisian, but must be considerable younger.

As is known, the Torridonian is the only provably pre-Cambrian formation in Scotland, younger than the Lewisian. Nevertheless, the alternative has been stated that in Scotland there may also occur or have occurred pre-Torridonian but young-Archean sediment-series, comparable with those in Fennoskandia, though now not directly observable, with which the Moinian may be parallelized. Such an assumption can certainly always be made, but scarcely advances the discussion as to the age of the Highland schists.

Leading Scottish geologists have also advanced opinions differing from those cited above, intending an essentially younger age for both the Moinian and the Dalradian. Thus according to PEACH and others, the Moinian is a metamorphic facies of the Torridonian, and this view is supported by the fact that the basal conglomerate of the Moinian towards the Lewisian inliers not infrequently shows certain petrographical peculiarities of a sort that usually belongs to the basement-beds of the Torridonian, where it overlies the autochtonous Lewisian in the west. In addition, the order of sequence, characteristic of the Torridonian, can sometimes be clearly identified in the Moinian (see, e. g., **20**, p. 600). These observations are, as we see, obviously at variance with the above-mentioned statement about pebbles of the Moinian in the Torridonian.

At an early date the idea was put forward by NICOL and MURCHISON that the Dalradian series consists of metamorphic old-Paleozoic sediments, a view that was later modified by GEIKIE, who considered the formation possibly to be complex and containing — besides the predominating old-Paleozoic deposits — also Torridonian ones, all of which are, however, difficult to decipher exactly, on account of folding and metamorphosis (**16**, p. 137). — Moreover it is noteworthy in this connexion that there occur annelid-tubes, pipes and worm-casts in the Dalradian series, but no fossils determinable with certainty. On the other hand in Islay it is considered that pebbles of Torridon sandstone have been found in the Dalradian (**5**, p. 143; **21**), an observation that also seems to contrast sharply with certain facts mentioned above. It may be added, that the metamorphosis of the Dalradian gradually decreases towards the south-east, and becomes rather slight in the vicinity of the Cambrian—Ordovician Highland Border rocks, situated there. No original unconformity can be proved here between the two rock-groups (**33**, p. 15). According to GEIKIE's opinion, contradicted, however, by others, not even a secondary thrust-plane divides them, but there is a complete conformity in every respect (**7**).

An explanation, agreeing in the main with that of the Dalradian, is

given by GEIKIE for the Moinian, which would thus contain rock-series of widely different ages and composition, from the Lewisian and the Torridonian to the Durness limestone and dolomite, possibly also younger lower-Paleozoic divisions (**17**).

Even this quite brief summary thus proves that practically all imaginable explanations and attempts of combinations have already been tried in interpreting the relative age of the Moinian and the Dalradian, and that a hopeless confusion seems at present to prevail with regard to these questions. However, it is noteworthy that, in general, each of these explanations is very restricted, as only referring to some special observations or a certain group of observations among the material, so copious but full of contradictory data. This material of observations can be used with almost equal right to support widely differing interpretations. A solution that satisfies the whole problem and the entire material of observations, and that explains the striking contradictions, must obviously imply a definite abandonment of the view, hitherto generally accepted, that the Moinian and the Dalradian are independent and unitary stratigraphical rock-groups and, instead of this, adhere to the line of thought proposed by GEIKIE. At least to an outsider, and especially from the central Scandinavian point of view, this explanation appears *ex analogia* at present most acceptable. In other words, the Moinian and the Dalradian are to be regarded as complexes of several rock-groups of differing ages, which have obtained their metamorphosis during the Caledonian folding.

In Scandinavia the problem has developed on the whole in a similar way. The principle idea in TÖRNEBOHM's overthrust-theory, namely that the Seve schists represent a stratigraphically independent rock-group, has of late years been abandoned as untenable and leading to contradictory consequences. Instead the Seve schists have been reduced to a petrographical rock-group, chiefly composed of — besides Caledonian igneous rocks — the same sediment series (in this case probably only the Silurian) that, at the beginning of the folding-process, were overlying the Archean surface in these districts, together with — at least regarding central Scandinavia — smaller parts of the up-pressed and in-folded Archean substratum, the whole strongly welded together by the metamorphosis.

If this point of view is transferred to Scotland, we have thus to ask what pre-Caledonian formations can be proved to be present there beneath, as well as, and especially, above the sub-Cambrian denudation-surface. These geological formations ought in the first place to be suspected of constituting the adjoining Highland schists. But of course, the possibility must always be kept open that perhaps all these pre-Caledonian complexes cannot be now firmly established, because of several circumstances. Besides Caledonian intrusions and patches of

Lewisian rocks, we will therefore have to expect in the north-west, in the Moinian, metamorphic derivatives, above all of the Torridonian and the Cambrian, possibly also of somewhat younger Paleozoic sediments. In the Dalradian in the south-east, on the other hand, we have to anticipate especially those of Ordovician and Gothlandian age, besides possibly Cambrian and Torridonian ones. In agreement with the now prevailing view (see p. 230), the Dalradian becomes in this way on the whole younger than the Moinian. That the Moine schists, by their more extreme quartz-felspathic composition, differ petrographically from the more argillaceous Dalradian, will with such a point of view only be in the main an expression of the original facies-development of the sediments in the autochtonous regions, as the Dalradian region in this respect ought to have been chiefly related to the sediment-development in the old-Paleozoic region in the south-east, but the Moinian to the principally psammitic and siliceous region in the north-west.

I have pointed out above (p. 210) the considerable petrographical and stratigraphical analogies that can really be proved between the Dalradian and the undoubtedly old-Paleozoic rocks in the S.E. — the volcanic horizons with their pillow-lavas and cherts, the unconformities towards the overlying divisions, the often marked interstratifications of thin pelitic and psammitic layers, the frequently peculiar sparagmitic composition, etc. — all indicating a genetic connection, which in its turn furthermore emphasizes the affinity with the Scandinavian region, in this case above all with the Trondhjem field. The presence of geosynclinal and deformation-depressions in Scotland, formed in association with the old-Paleozoic sedimentation and folding-process, also seems best to harmonize with such a point of view, but scarcely, on the contrary, with the supposition generally accepted, that almost exclusively pre-Torridonian or Archean rock groups (if this age is assigned to the Moinian and the Dalradian) build up the chief parts of a folding zone, formed in Caledonian time and not yet denuded to the roots. The now prevalent Scottish interpretation implies, that the Dalradian and Moinian regions, like their metamorphic transformation to crystalline schists, belong to a powerful pre-Torridonian folding zone (**33**), along which the later occurring Caledonian folding was exactly oriented, but only restricted to more peripherical and superficial displacements and overthrusts, without superinducing other metamorphic alterations than sometimes a cataclastic one, scarcely worth mentioning. Such an explanation is, however, quite incompatible with the experiences gained in Scandinavia, as it would mean that the Scandinavian Mountain schists are pre-Cambrian and chiefly occupy their original position. But because the denudation has here produced in the mountain range a section, stratigraphically considerably deeper, compared with Scotland, it can be said with certainty that there is here no such rock-group of this age and position.

From conglomerates belonging to different horizons of the Caledonian folded Gothlandian in the northern part of the Southern Uplands, as in the similarity folded Downtonian in Pentland Hills and Lanarkshire, the occurrence of pebbles consisting of crystalline schists of different kinds, in all probability originating in the Highland schists, has been long known (**19**, p. 53—68). Possibly it would be tempting to find in this circumstance a proof of a pre-Cambrian age for the Mountain schists as for their metamorphosis. Such a conclusion is, however, not permissible. In spite of opinions in favour of a crystallization of these schists in late-Archean and pre-Torridonian time (see, e. g., **33**), it seems to me, however, that the indissoluble connection with the Caledonian folding zone and its structure, the Caledonian intrusions, etc., indicate too obviously that the main mass of the Highland schists, here as in Scandinavia, has obtained its present metamorphic dress during the post-Cambrian Caledonian epoch of folding. The metamorphosis visible in the mentioned conglomerate-pebbles can, with this point of view, derive from the earlier stage of the Caledonian epoch of folding, but the folding of the Gothlandian strata from the later stage. The abundance of conglomerate-layers in this part of the rock-series records extensive changes of the sea-level, certainly of an orogenetic nature, phenomena that seem to a certain extent to have begun already in lower-Ordovician time (see p. 208). With an old-Paleozoic age, given here as most probable for at least the greater part of the Dalradian, a similar explanation may also perhaps be given for the pebbles with the characteristics of Highland schists, which appear in a thick boulder-bed, entering into the Dalradian (**23**). On this presumption the regional-metamorphosis during the later stage was of a sufficiently radical kind to superinduce a considerable metamorphosis upon the younger part of the sediment series too. — It ought also to be noted that the so-called Banff series, at the coast in the north-east, is considerably less metamorphic than the underlying part of the Dalradian group.

Contrary to the generally accepted Scottish idea, according to which the Caledonian folding zone is chiefly to be dated from pre-Cambrian time (see p. 234), it has been considered possibly hitherto in Scandinavia to fix the beginning of the Caledonian folding to younger-Ordovician (**42**). In central Scandinavia only a few phenomena of about a similar nature to the Scottish ones, referable to different phases of the folding-epoch, have up till now been observed, to any extent worth mentioning. I have previously pointed out that basement-beds of the Hovin series in the Trondhjem field, with an especially continuous unconformity, probably testifying to orogenetic movements, rest upon the old-Ordovician Bymark series, in analogy with the equivalent Benan conglomerate in Scotland, etc. We may also mention that the basal series of the Trondhjem field seems to be in general more metamorphic than the overlying younger divisions, e. g., the Hovin series (**10**, **14**, p. 130). On the Swedish side there has been

found a conglomerate with a matrix, highly crystallized in Caledonian time, and containing pebbles, partly of Caledonian igneous rocks, foliated already in earlier time, partly too of sedimentary crystalline schists, formed during the former part of the folding-epoch (**14**, p. 122). That formations of this nature are so rare in Scandinavia seems to be explainable chiefly by the lack of younger-Gothlandian deposits.

This absence of stratigraphically determinable young-Gothlandian and old-Devonian sediments also makes it impossible in Scandinavia to define the Caledonian folding-process upwards in the time-scale so exactly as in Scotland. — However, a common feature with regard to the unconformities from the rocks of the Caledonian folding zone seems to be, that they often represent a very uneven land-surface, dissected by marked valley-systems (see, e. g., **16**, pp. 312 ff.). Like, for instance, in the case of the sub-Torridonian land-surface, we may regard, as a consequence of this uneven topography, the frequently considerable thickness of the fossil sub-Devonian weathering-zone — compared, for instance, with the sub-Cambrian one — as well as the thick basal breccias overlying it, consisting of an unstratified and unsorted mighty mass of gravels and sharp-edged boulders, jumbled together. Moreover, the profound sub-Devonian weathering-zone is distinguished, as it is locally in Scandinavia too (**29**), by an extensive drenching of red substances, which, together with the decomposition in general, often causes difficulty in keeping the weathering-zone separate from the overlying sediments.

Bibliographical List.

1. Abstracts of the Proceedings of the Geological Society of London, N:o 1069 (1921).
2. Bailey, E. B. Recumbent folds in the schists of the Scottish Highlands. — Quart. Journ. Geol. Soc. vol. 66 (1910).
3. —— The Loch Awe syncline, Argyllshire. — Quart. Journ. Geol. Soc. vol. 69 (1913).
4. —— The Glen-Orchy anticline, Argyllshire. — Quart. Journ. Geol. Soc. vol. 68 (1912).
5. —— The Islay Anticline, Inner Hebrides. — Quart. Journ. Geol. Soc. vol. 72 (1916).
6. Barrow, G. On an intrusion of muskovite-biotite gneiss in the south-eastern Highlands of Scotland, and its accompanying metamorphism. — Quart. Journ. Geol. Soc. vol. 49 (1893).
7. —— On the occurrence of Silurian(?) rocks in Forfarshire and Kincardineshire along the eastern border of the Highlands. — Quart. Journ. Geol. Soc. vol. 57 (1901).
8. —— On the Moine gneisses of the East-Central Highlands and their position in the Highland sequence. — Quart. Journ. Geol. Soc. vol. 60 (1904).

9. CAMPBELL, R. The geology of south-eastern Kincardineshire. — Trans. Roy. Soc. Edinb. vol. 48 (1913).
10. CARSTENS, C. W. Oversigt over Trondhjemsfeltets bergbygning. — Vidensk. selsk. skrifter 1919. N:r 1. Trondhjem 1920.
11. DARKYNS, J. R. and TEALL, J. J. H. On the plutonic rocks of Garabal Hill and Meall Breac. — Quart. Journ. Geol. Soc. Vol. 48 (1892).
12. FRÖDIN, G. Einige Beobachtungen über den Oldengranit und die subkambrische Denudationsfläche innerhalb der kaledonischen Faltenzone in Jämtland. — Bull. Geol. Inst. Upsala. Vol. XIII: 2 (1916).
13. —— Om de s. k. prekambriska kvartsit-sparagmitformationerna i Sveriges sydliga fjälltrakter. — Sveriges Geol. Undersökning Ser. C. N:o 299 (1920).
14. —— Über die Geologie der zentralschwedischen Hochgebirge. — Bull. Geol. Inst. Upsala. Vol. XVIII (1921).
15. GEIKIE, A. The ancient volcanoes of Great Britain. — London 1897.
16. —— The scenery of Scotland. — London 1901.
17. —— Geological map of Scotland (with explanatory notes). — Edinburgh 1910.
18. *Geol. Surv. of Great Britain.* Summary of progress 1907, p. 72 (1908).
19. —— The Silurian rocks of Britain. Vol. I Scotland (1899).
20. —— The geological structure of the North-West Highlands of Scotland (1907).
21. *Geol. Surv. of Scotland.* The geology of the seaboard of Mid Argyll. Explanation of sheet 36 (1909).
22. —— The geology of Ben Nevis and Glen Coe. — Explanation of sheet 53 (1916).
23. —— The geology of the country round Blair Atholl, Pitlochry, and Aberfeldy. — Explanation of sheet 55 (1905).
24. —— The geology of Glenelg, Lochalsh and South-East part of Skye. — Explanation of sheet 71 (1910).
25. —— The geology of Central Ross-shire. — Explanation of sheet 82 (1913).
26. —— The geology of Southern Ross-shire. — Explanation of sheet 83 (1918).
27. —— The geology of Ben Wyves etc. — Explanation of sheet 93 (1912).
28. GOLDSCHMIDT, V. M. Die kaledonische Deformation der sydnorwegischen Urgebirgstafel. — Vidensk. selsk. skrifter. Kristiania 1912.
29. —— Das Devongebiet am Röragen bei Rörås. — Vidensk. selsk. skrifter. Kristiania 1913.
30. —— Die Kalksilikatgneise und Kalksilikatglimmerschiefer des Trondhjem-Gebiets. — Vidensk. selsk. skrifter. Kristiania 1915.
31. —— Übersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger und Trondhjem. — Vidensk. selsk. skrifter. Kristiania 1916.
32. —— Die Injektionsmetamorphose im Stavanger-Gebiete. — Vidensk. selsk. skrifter. Kristiania 1920.
33. GREGORY, J. W. Work for Glasgow geologists. — The problems of the South-Western Highlands. — Trans. Geol. Soc. Glasgow. Vol. 14 (1910).
34. —— Moine pebbles in Torridonian conglomerates. — Geol. Mag. 1915.
35. *Handbuch der Regionalen Geologie:* The British Isles. — Heidelberg 1912.
36. —— Fennoskandia. — Heidelberg 1913.
37. HOLMQUIST, P. J. Die Hochgebirgsbildungen am Torneträsk in Lappland. — Geol. Fören. Förh. Bd. 32 (1910).
38. HOLTEDAHL, O. Iakttagelser over fjeldbygningen omkring Randsfjordens nordende. — Norges Geol. Undersökelse Nr. 75 (1915).

39. HOLTEDAHL, O. Bidrag til Finmarkens geologi. — Norges Geol. Undersökelse Nr. 84 (1918).
40. —— The Scandinavian »mountain problem». — Quart. Journ. Geol. Soc. vol. 77 (1921).
41. HÖGBOM, A. G. Studies in the post-Silurian thrust-region of Jämtland. — Geol. Fören. Förh. Bd. 31 (1909).
42. KIÆR, J. Etage 5 i Asker. — Norges Geol. Undersökelse Nr. 34 (1902).
43. MACNAIR, P. The geology and scenery of the Grampians and the valley of Strathmore. — Glasgow 1909.
44. SCHIØTZ, O. E. Den sydøstlige del af sparagmit-kvarts-fjeldet i Norge. — Norges Geol. Undersökelse Nr. 35 (1903).
45. TÖRNEBOHM, A. E. Grunddragen af Centrala Skandinaviens bergbyggnad. — Svenska Vetensk. Akad. Handl. Bd. 28 (1896).
46. —— En geologisk profil över den skandinaviska fjällryggen mellan Östersund och Levanger. — Sveriges Geol. Undersökning Ser. C. N:o 6 (1872).

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