10. *The* SCANDINAVIAN 'MOUNTAIN PROBLEM.' By Prof. OLAF HOLTEDAHL, Ph.D. (Communicated by Sir ARCHIBALD GEIKIE, O.M., K.C.B., F.R.S., For.Sec.G.S. Read June 23rd, 1920.)

A GENERAL feature in the geological structure of the eastern zone of the Caledonian mountain-range of the Scandinavian Peninsula is the existence of highly metamorphic, often gneissose, unfossiliferous rocks above slightly-altered fossiliferous Cambro-Silurian sediments. This feature is met with from the Stavanger district in the south to Finmarken in the north.

It is now more than thirty years since the Swedish geologist A. E. Törnebohm[1] suggested that this remarkable feature, this 'mountain problem' of Scandinavia, might be explained by employing the overthrust theory: by assuming, as had proved to be the fact in Scotland, that the overlying metamorphic rocks originally belonged to the pre-Cambrian System, and by means of an enormous thrust had been brought into their present position above what was left of the Cambro-Silurian sedimentary series.

After further investigations, *inter alia* in the Norwegian mountain-district of Jotunheimen (see map, fig. 1, p. 388), Törnebohm became increasingly convinced of the correctness of this view, of the ancient date of, for instance, those metamorphic stratified rocks of Central and South-Western Southern Norway for which the Norwegian investigator Th. Kjerulf had established the term 'höifjeldskvarts': that is, 'Highland Quartz' (or Highland Quartzite). In 1896 appeared Törnebohm's famous paper[2] on the geological structure of Central Scandinavia, in which, among others, the well-known sections from the Trondhjem district of Norway in the west, into Jemtland in Sweden in the east, showing an immense overthrust from west to east, were published.

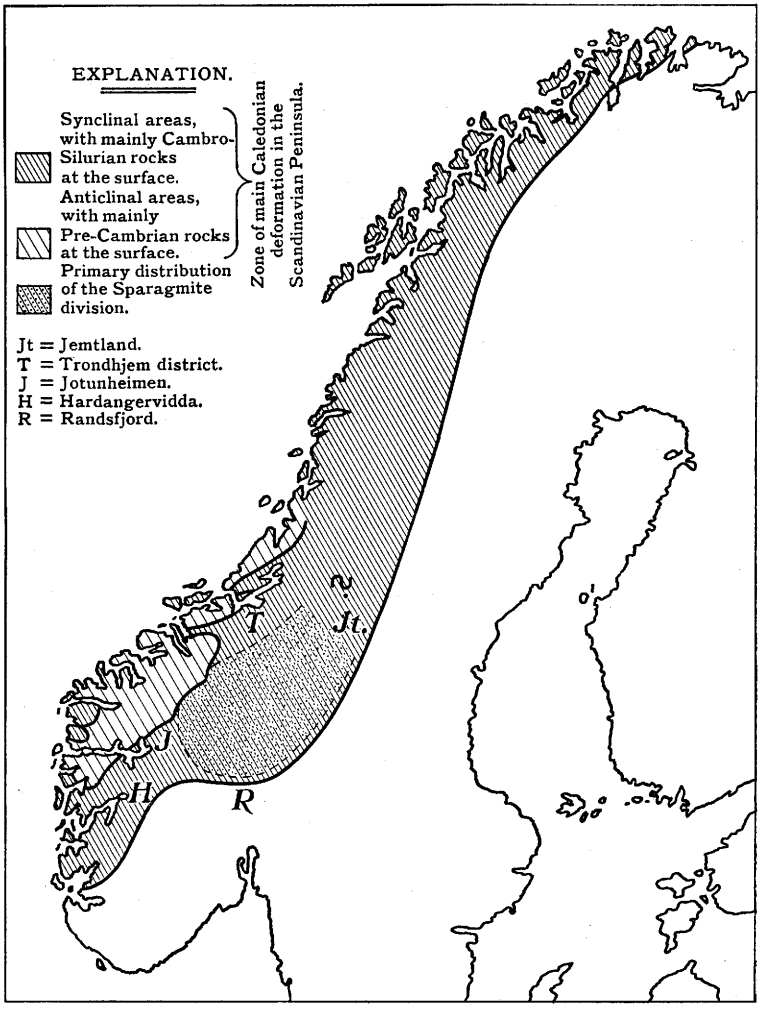
During subsequent years Törnebohm's views were taken up by several other Swedish investigators: thus by A. G. Högbom for the Jemtland district, A. Hamberg for the Sarek district of Northern Sweden, and P. J. Holmquist for the Torneträsk district still farther north. Yet Holmquist did not believe in the very extensive overthrust, but explained the facts by assuming that the roots of the thrust-masses were not very far distant.

When the geologists of various nations met at Stockholm at the International Congress in 1910, the overthrust theory was by far the dominating one in Sweden. It was believed that the metamorphosed rocks of chiefly sedimentary origin—the 'Seve Group' of Törnebohm—lying above the unaltered sedimentary rocks along

[1] Geol. Fören. Stockholm Förhandl. vol. x (1888) p. 334.

[2] 'Grunddragen af det Centrala Skandinaviens Bergbyggnad' Kgl. Svenska Vetensk.-Akad. Handl. vol. xxviii, No. 5.

Fig. 1.—*Sketch-map of the Scandinavian Peninsula, showing the zone of main Caledonian deformation.*



the eastern part of the Scandinavian mountain-belt, were an equivalent of the 'Sparagmite Formation,' a thick series of felspar-bearing sandstones, which in parts of Central Southern Norway lie directly below the *Olenellus* (*Holmia*) Beds, and were regarded as late Pre-Cambrian (Algonkian). It was further held that the igneous masses of the same metamorphic cover (as, for example, the amphibolites, syenites, etc. of northernmost Sweden) were of Archæan age.[1] There was at that time one Swedish geologist only who was in sharp opposition to the theory of the thrust Pre-Cambrian masses, namely, F. Svenonius, who had for a long period made investigations in the mountain-regions, especially of Northern Sweden.

In Norway matters developed otherwise. There the view that the 'Highland Quartz' of Kjerulf, the Norwegian parallel to the Seve Group, was, despite its highly metamorphosed character, geologically younger than the phyllites and shales below, gradually became the predominant hypothesis.

In 1893 W. C. Brögger gave a detailed description of the geology of the district of Hardangervidda[2] (H in the map, fig. 1), where above the Archæan occur phyllites, including alum-shales with *Dictyograptus flabelliformis* at the base. These phyllites pass upwards into highly-metamorphosed stratified rocks (mica-schists, hornblende-schists), sometimes of a typical gneissose character. Brögger came to the conclusion that the latter lay normally on the phyllites, that they consequently represented sediments of later and probably Silurian age. The crystalline character was explained as due to a combined regional and contact-metamorphism which was developed during the time of general deformation under the influence of huge intrusions of igneous masses which had once covered the whole district, and are still preserved in the central zone of deformation, in the coastal districts west and north-west of Hardangervidda.

After 1900 Kaldhol and Rekstad published important papers on the geology of these districts, where they found conditions (intrusive contacts, etc.) that could only be explained by assuming the aforesaid igneous rocks to be younger than the phyllite, intruded into the phyllites during the Caledonian deformation.

This later age of the igneous masses of the South Norwegian mountain-districts was further strongly emphasized by K. O. Björlykke in 1905, in an extensive memoir[3] on the geology of Central Southern Norway. Björlykke had first, after a visit to the North-West Highlands of Scotland, endeavoured, like Törnebohm, to develop the theory of overthrust Archæan masses, but further investigations convinced him that the actual conditions could not be explained in this way. Of great importance for the explanation of

[1] See Törnebohm's article & map in Guide-book No. 1 of the International Geological Congress, XIth Session, Stockholm 1910.

[2] Norges Geologiske Undersökelse, No. 11.

[3] 'Det Centrale Norges Fjeldbygning' Norges Geol. Undersök. No. 39.

the 'mountain problem,' according to Björlykke, is the existence in large areas of Southern Norway of a series of felspar-bearing sandstones, the 'younger Sparagmite of Valdres': these are doubtless younger than the Ordovician phyllites, which they unconformably overlie. Through metamorphism of this Sparagmite have originated rocks like those making up the sedimentary part of the 'Highland Quartz.'

Of Norwegian geologists only one (namely, H. Reusch) had, before 1910, to some extent advocated the view of the Archæan age of the igneous masses in certain districts of the mountain-zone in question.

During the ten years that have elapsed since the Stockholm Congress much work has been done concerning the 'mountain problem,' both in Norway and in Sweden.

For Southern Norway the idea of the later than Pre-Cambrian age of the igneous masses of the mountain-zone has since 1910 been especially emphasized by V. M. Goldschmidt, who has published a series of very important papers on highland geology[1]: on the deformation of the Pre-Cambrian surface, the petrology of the igneous rocks, the metamorphism of the sediments, etc.

In the northernmost part of Norway Th. Vogt and I have made investigations without discovering any facts that indicate a Pre-Cambrian age for the deformed rocks that overlie the unaltered Lower Cambrian sediments (the so-called '*Hyolithus* Zone'), which here, as in Northern Sweden, occur as a narrow belt between the Pre-Cambrian area on the south-east and the metamorphosed masses on the north-west.

In Northern Sweden, in the Ruoutevare district, A. Gavelin[2] found, as a result of detailed study, that the metamorphosed sediments, the 'Seve Group,' probably represent ordinary Cambro-Silurian rocks in a highly-metamorphosed state. As to the igneous masses lying above the '*Hyolithus* Zone' (in this district especially anorthosites and amphibolites) Gavelin came to the conclusion that they were intruded in the Seve rocks during the period of general deformation.

Also P. Quensel[3] has pointed out for a region of Northern Sweden (the Kebnekaise district) that there are strong reasons for assuming that, at any rate, a great part of the Seve Group rocks consists of metamorphosed Cambro-Silurian sediments, and that large masses of the igneous rocks are younger intrusives.

There is no doubt that, at present, the views of the majority of Scandinavian (including the Swedish) geologists, on the 'mountain problem' are vastly different from those expressed in the Swedish guide-books of 1910. While the principle of thrusting, introduced into Scandinavian geology by Törnebohm, is now to a considerable extent accepted, the geological age of the masses moved is, by the

[1] Published in Videnskapsselskapets Skrifter, Kristiania, 1912–16.
[2] Geol. Fören. Stockh. Förhandl. vol. xxxvii (1915) p. 17.
[3] *Ibid.* vol. xli (1919) p. 19.

majority of workers, considered not to be Pre-Cambrian, but later.

As to the igneous rocks of the metamorphic cover, their later (Caledonian) age and intrusive character must now be considered proved in a great many districts. The thrust igneous rocks that must still be regarded as Pre-Cambrian, like the porphyries at the front of the thrust-masses in Jemtland, do not seem to be of more than local importance.

As to the metamorphosed sedimentary rocks lying above the unaltered rocks, the main question has been whether these rocks are to a great extent equivalents of the Sparagmite Division, or whether they are younger. It was stated above that, on Törnebohm's hypothesis, the Sparagmite Formation (which by some has been regarded as a parallel to the Torridonian of Scotland) is referred to the Pre-Cambrian, a fact that made the existence or non-existence of these rocks above the fossiliferous Cambro-Silurian a question of considerable general importance.

Among Norwegian geologists the Sparagmite Formation, or the Sparagmite Division, as it may perhaps better be termed, has not generally been regarded as a true Pre-Cambrian series. In Kjerulf's stratigraphical system the division was classified together with the fossiliferous Cambro-Silurian rocks, as a basal series (stage 1*a*), and Brögger has regarded the Sparagmites as a basal Cambrian division ('Eocambrian'). Recently J. Kiær has emphasized[1] that the division should naturally be placed in the true Lower Cambrian. Seen in this light, the question of the occurrence of the Sparagmite Division in the thrust-complex has no such primary importance, as in general the true Pre-Cambrian has not been thrust. We are, in any case, dealing with rocks which originally belong to horizons above the Pre-Cambrian surface.

Yet the Sparagmite Division, with its huge thickness, several thousand feet, of coarse clastic rocks, is a stratigraphical element of singular importance, and the question of the part which this element plays in Scandinavian mountain geology is therefore naturally one of very great interest. While it must now be considered proved that Törnebohm's Seve Group in many districts is no equivalent of the Sparagmite Series, but of later Cambro-Silurian age, yet it is beyond doubt, as will be stated further below, that in places in Southern Norway the thrust-masses to a large extent primarily belong to the Sparagmite Division, and thus are older than the oldest-known fossiliferous Cambrian sediments in the same districts.

It being thus evident that in different areas different stratigraphical members make up the thrust-masses, what is the reason for this? Does there seem to be any general rule as to the constituents of the thrust-complex in different districts?

The question may be answered thus: In the thrust-masses

[1] 'The Lower Cambrian *Holmia* Fauna at Tömten in Norway' Vidensk. Skrift. Kristiania, 1916.

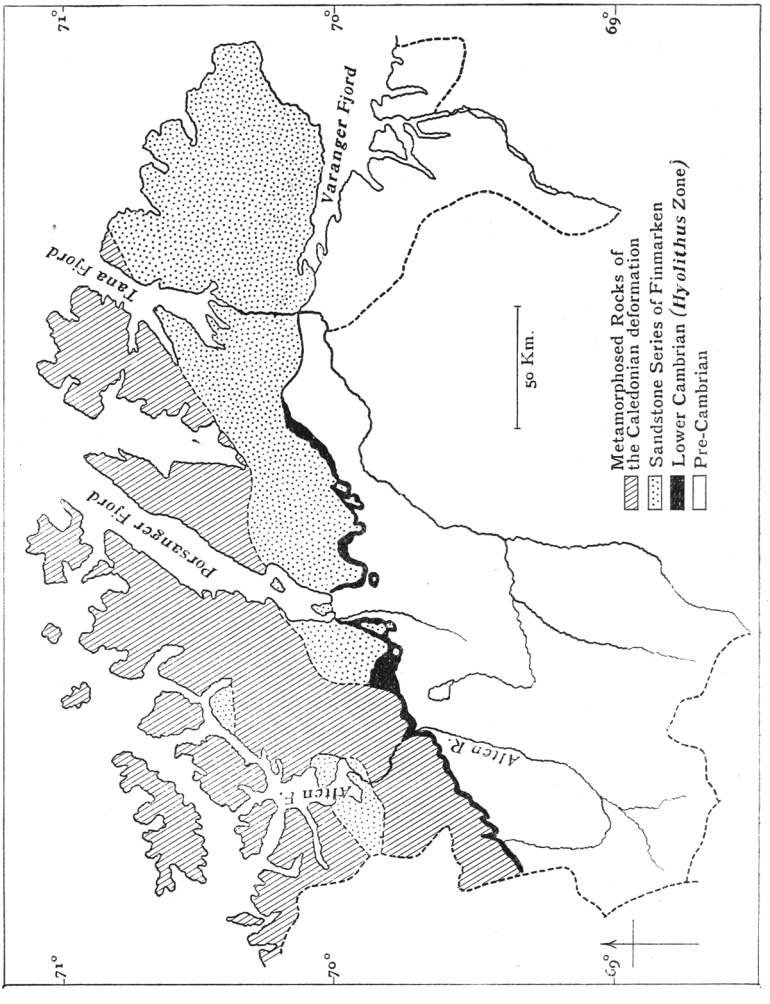



Fig. 2.—*Main geological features of Finmarken in Northern Norway.*

very often, not only one, but several stratigraphical divisions of the Cambro-Silurian formations are present. The age of the thrust sedimentary masses depends on the inclination of the thrust-planes and on the depth which their proximal part has reached. As these planes seem to have reached very far down towards, but generally not below, the Pre-Cambrian surface, the existence or non-existence of thrust-rocks of Sparagmite age may be held to depend upon the primary occurrence or non-occurrence of the Sparagmite Division north-west of the areas where the thrust-masses now occur.

In order to illustrate this statement, we may briefly consider the tectonic features of two widely-separated Norwegian areas where I have made personal investigations.

The first is Finmarken, the northernmost district of Norway. There, in a north-western belt, occur the metamorphic rocks of the mountain-zone, as will be seen from the map (fig. 2, p. 392). In this belt large igneous masses (granites, gabbros, etc.) occur, especially in the north-west, that is, in the central belt of deformation, where the Pre-Cambrian surface must be situated at a very considerable depth. Th. Vogt found these rocks there to be younger intrusive masses, intruded into the mica-schists, quartzites, etc. Also in the south-eastern part of the metamorphic zone corresponding igneous rocks are found, mostly much crushed, often gneissose, granites, also gabbros, here making up a distinct horizon in the huge cover of stratified rocks, which in the far south-east is seen to overlie the unaltered Lower Cambrian shale-sandstone series, the '*Hyolithus* Zone.' The base of this metamorphic cover generally represents a typical thrust-plane, which is seen to have a rather undulating character. This undulation of the bordering plane between metamorphic and non-metamorphic rocks is illustrated in the sections (fig. 4, p. 396), and is also evident from a study of the map (fig. 2). While in the western part of Finmarken only 450 to 500 feet of unaltered sediment come in between the sub-Cambrian peneplane and the metamorphic cover, we find farther north-east, as in the Porsanger Fjord, below this cover about 1500 feet of somewhat folded sandstones, with at the top a thick dolomite-layer. This is what I have called the Porsanger Series (Porsanger Sandstone & Porsanger Dolomite). South and south-east of the above-mentioned fjord this Porsanger Sandstone is seen to overlie, doubtless normally, the Lower Cambrian. At the Alten Fjord appears, in a 'window' in the metamorphic cover, the Raipas Series (sandstone, brownish-weathering dolomite, shale, and greenstone), which must be considered of still later age than the Porsanger Series, all these sedimentary divisions being in my opinion of early Ordovician age and belonging to a huge American-Arctic basin of deposition (as I have stated elsewhere).[1]

[1] See 'Bidrag til Finmarkens Geologi' Norges Geol. Undersök. No. 84, 1918; 'On the Palæozoic Formations of Finmarken in Northern Norway' Amer. Journ. Sci. ser. 4, vol. xlvii (1919) p. 86; and 'On the Palæozoic Series of Bear Island, &c.' Norsk Geol. Tidsskrift, vol. v (1919) p. 141.

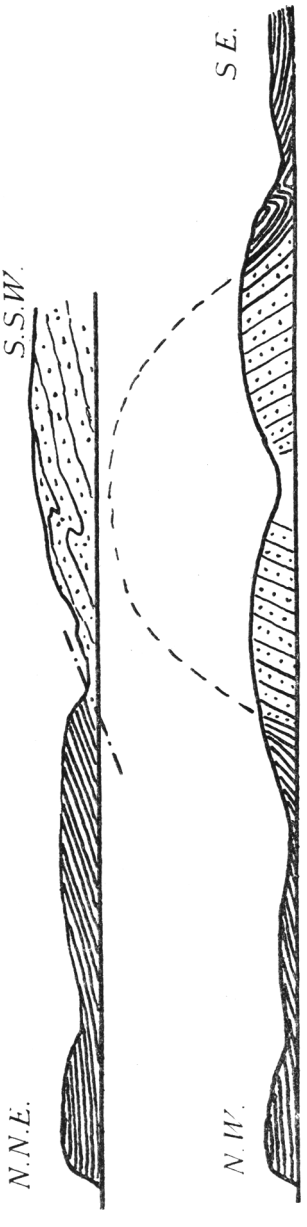



Fig. 3.—*Diagrammatic sections in the north-western part of the Varanger Peninsula, both starting (on the left) at the north-westernmost corner of the peninsula.*

[The upper section is taken at the Tana Fjord, the lower on the northern coast.]

Before describing the typical section from the Alten district I may briefly refer to the features met with in the north-eastern part of Finmarken, in the easternmost area of metamorphic rocks in the Scandinavian mountain-range. There, on the eastern side of the Tana Fjord, are seen to the south folded compact sandstones (as illustrated in fig. 3), while farther north occur sedimentary rocks of quite another character, highly-schistose quartzites together with phyllites, having a regular slight north-westerly dip, as is usual in the metamorphic complex. The metamorphic and non-metamorphic series are here found close one to the other, and a thrust-plane must doubtless be assumed. On the northern coast, east of the Tana Fjord, conditions are different. There the phyllite-quartzite series gradually passes into the compact sandstone just mentioned, and still farther east this sandstone is normally overlain by a complex which no doubt corresponds with that seen at the mouth of the Tana Fjord, but, being situated outside the zone of strongest pressure, shows much less deformation. Thus the metamorphic series to the north-west in this area is, generally speaking, of the same age as the non-

metamorphic series south-east of the bordering line of the thrust-masses. Compared with Western Finmarken, this quartzite-phyllite (or on the south-east, sandstone-shale) horizon seems to correspond with the lower part of the Raipas Series, just mentioned.

As to the section in the Alten district (see fig. 4, p. 396) we find here, above the thrust-plane (marked with vertical striation in the drawings), much-deformed, generally somewhat crystalline stratified rocks that represent felspar-bearing sandstones, and further phyllites, quartzitic bands, and dolomites. It is especially these dolomites that, in my opinion, make it possible to draw conclusions as to the relative age of the thrust-masses and the general tectonic features.

At the south-eastern border of the thrust-complex is observed, at the base of the deformed sandstones, a small irregular mass of grey dolomite with a peculiar oolitic structure, a rock which undoubtedly must belong to the Porsanger Dolomite horizon.

A very coarse-grained dolomite is found in connexion with the igneous rocks midway between this locality and the Alten Fjord. This rock, with its brownish weathering (the Porsanger Dolomite weathers greyish-white), may naturally be regarded as a mass of Raipas Dolomite which has been moved south-eastwards.

On the north-west, at the Alten Fjord, occur in the basal part of the thrust-complex layers of dolomites of highly-varying thickness. On the eastern side of the fjord the lower dolomite-layer is situated a little way up from the base of the metamorphic complex, while on the west the dolomite makes up the very base. The dip is towards the north-west. The rocks above are much-deformed felspar-bearing sandstones, the true character of which, however, is increasingly difficult to identify as we pass towards the north-west: the rocks become gradually more metamorphic and crystalline. We soon find rocks of distinct gneissose character, and still farther north-west we meet with true igneous masses, partly of more acid, partly of gabbroid character, rocks that, as mentioned above, show distinct intrusive characters. The lower, in places non-crystalline, yet much deformed and jointed, dolomitic layer just mentioned, is of peculiar interest, because it is so very like the Porsanger Dolomite that its attribution to that horizon cannot be gainsaid.

It thus seems, from studies in Western Finmarken also, that at any rate the greater part of the metamorphic sedimentary rocks lying above the non-metamorphic must be regarded as being, generally speaking, of the same age as the unaltered rocks occurring below the thrust-plane and south-east of the metamorphic zone. They represent the same dolomite-bearing sandstone series in a more or less metamorphosed state.

In fig. 4 (p. 396) is given a somewhat simplified section from west to east through the Alten district, in the south-eastern part, passing the southern outlier of Porsanger Sandstone south-south-west of

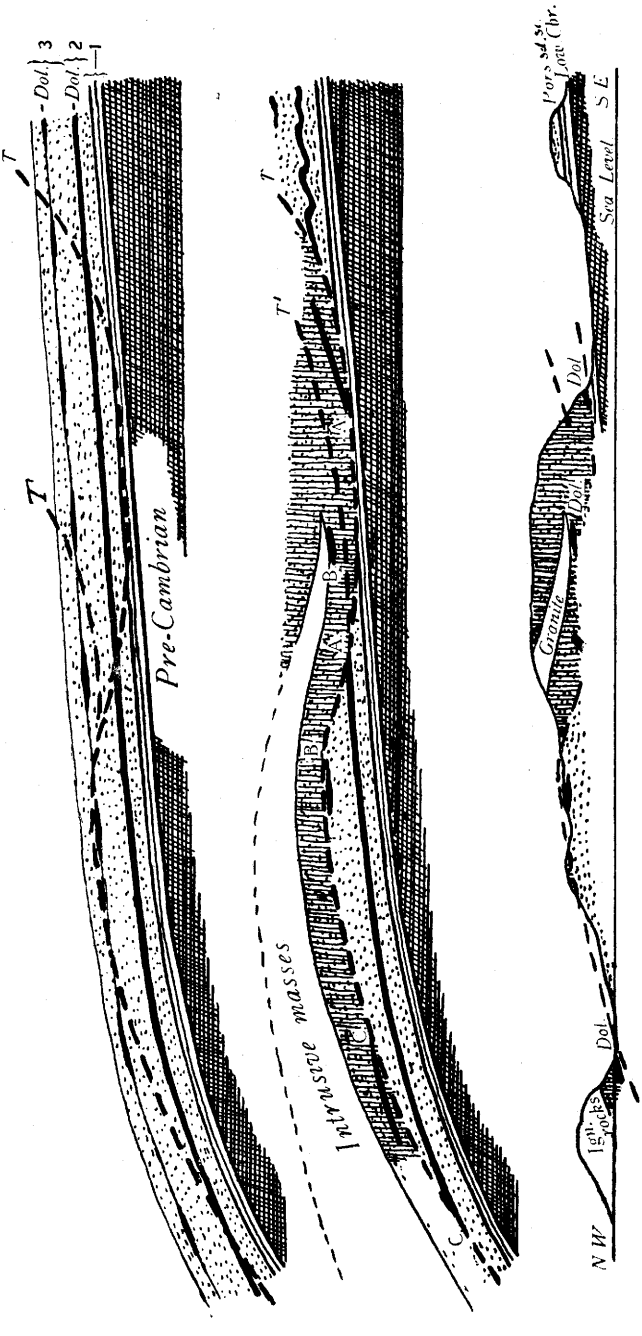



Fig. 4.—*Diagrammatic sections illustrating the geological structure of the Alten district.*

the Porsanger Fjord, and also two sections illustrating how, in my opinion, the present structure may be thought to have developed. The original sequence is, according to what has been stated above:—Pre-Cambrian, followed by the Lower Cambrian shale-sandstone series (1), the Porsanger Series (2), with Porsanger Dolomite on the top, then the Raipas Series, etc. (3). The last-named has in pre-Caledonian time been strongly denuded locally, and the Raipas Dolomite is thus only locally preserved. In (3) is included the relatively thin Bossekop Series (sandstones with shales, and at one horizon a tillite).

The main tectonic feature is a major thrust-plane, T, and other minor thrust-planes, T'. In the drawing there is—for the sake of simplification—indicated only one minor thrust-plane. In fact, because of the enormous general pressure, it is very difficult to identify the thrust-planes in the metamorphic complex itself, but from the arrangement of the rocks we may conclude that they must be present. At the south-eastern border of the metamorphic mass, where the pressure has been somewhat less than in the more central zone of deformation, the existence of thrust-planes of secondary order can, however, be distinctly seen. By the letters AA, BB, CC is indicated in the figure the probable movement of the dolomite masses found in the thrust-complex, according to my view. The igneous horizon, the 'intrusive masses' of the figure, does not show a sharp bordering line against the surrounding rocks, which are of the same general character above and below: in fact, there is a bordering zone with gneissose rocks, the original character of which, whether derived from the granites of the intrusion or from the felspar-bearing sandstones, is generally difficult to decide. This apparent gradual transition from igneous to sedimentary rock in the metamorphic complex, without any distinct thrust-plane here, is natural, if we assume an intrusion causing a metamorphism of the surrounding rock, but very difficult to understand if we should assume the igneous mass to be an overthrust Archæan one.

It is evident, from a study of the Alten section with its strongly undulating thrust-plane, that in detail the relation of age between the underlying, relatively unaltered, rocks and the metamorphic sedimentary rocks above, must be very different at various places. It depends upon the inclination of the thrust-plane. At the eastern border of the Scandinavian mountain-belt, from the Alten district and far south into Northern Sweden, the majority of the thrust-rocks must be considered as of a somewhat later age than the unmetamorphic below, as the latter here consist only of the Lower Cambrian division (the *Hyolithus* Zone).

Where, as for example, farther east in Finmarken, and in Jemtland in Central Sweden, the major-thrust-plane occurs much higher up in the Cambro-Silurian Series, thus corresponding to the conditions seen more to the left in fig. 4, we may expect true overthrusts, with older rocks above younger.

In Jemtland we find in places metamorphosed sedimentary rocks lying above so late a zone as the Silurian *Pentamerus* Limestone. Even if the greater part of the metamorphosed rocks of this region is not of the age of the Sparagmite Division, as Törnebohm assumed, but younger, they may well be considered to be older than the above-mentioned Silurian horizon. Probably, as has recently been held by the Norwegian geologist C. W. Carstens,[1] who has made extensive studies in the Trondhjem district, much of the 'Seve Group' in the Trondhjem-Jemtland region is of Ordovician age.

In fact, it seems to be increasingly evident that the metamorphic sedimentary rocks of the central and northern part of the mountain-belt of Scandinavia are chiefly of Ordovician age. The remarkable likeness between the 'mica-schist–marble group,' making up the sedimentary portion of the solid rock-formations of the western part of Northern Scandinavia, and the 'Hecla hook System' of Spitsbergen, which system must now be considered to cover early and middle Ordovician time,[2] is in this connexion a point of fundamental importance. Just as more and more of the gneiss and granite-masses of Northern Norway during later years have proved to be Caledonian intrusive and not Archæan rocks, the huge mass of gneiss and granite making up the north-western corner of Western Spitsbergen, and previously regarded as Archæan, is now known to represent intrusions of igneous masses during the Caledonian deformation.[3]

In the map of the Scandinavian Peninsula published in Törnebohm's previously-mentioned Guide-Book (No. 1) of the Stockholm International Geological Congress, the greater part of Northern Norway was mapped as Algonkian Seve rocks, and Archæan granites.

Only for a single, yet far from unimportant, part of the Scandinavian region of strong deformation the actual conditions seem to show that the thrust-masses consist mainly of rocks belonging to the Sparagmite Division, and thus are older than the fossiliferous Lower Cambrian. This is the case along the southern, possibly also parts of the eastern, border of the Sparagmite region of Central Southern Scandinavia (see fig. 1, p. 388), the region where the true Sparagmite Division primarily existed, the exact northern border of which, however, is unknown to us. The fact is that some of the 'Sparagmites' (of, for example, Jemtland) probably represent rocks that are younger than the Lower Cambrian, and therefore do not belong to what should be called the 'Sparagmite Division.' This later age of certain widespread Swedish Sparagmites and quartzites has recently been advocated by G. Frödin.[4]

[1] 'Oversigt over Trondhjemsfeltets Bergbygning' Kgl. Norsk. Vidensk. Skrift. 1919, No. 1.

[2] O. Holtedahl, 'On the Palæozoic Series of Bear Island, &c.' Norsk Geol. Tidsskrift, vol. v (1919) pp. 138–41.

[3] O. Holtedahl, 'New Features in the Geology of North-Western Spitsbergen' Amer. Journ. Sci. ser. 4, vol. xxxvii (1914) p. 415.

[4] Sveriges Geol. Undersökn. ser. C, No. 299, 1920.

To illustrate the conditions in the southern part of the Sparagmite area (a district situated outside the typical overthrust regions of Törnebohm) I have drawn the sections shown in fig. 5 (p. 400), reaching from the Randsfjord (see R in fig. 1) and northwards for a distance of about 60 kilometres (say, 37 miles).

Primarily there occurred in the northern part of this district, at a time immediately preceding the deposition of the Lower Cambrian *Holmia* (*Olenellus*) Shale (which, according to our present knowledge of the Cambrian System of the Cordilleran region of North America, took place some way up in what is now known to be the Cambrian Period), a sedimentation of sandstones (Sp. in the upper section), while on the south some denudation must still have taken place. Moreover, the *Holmia* Shale was deposited only in the north. After a thick series of younger, fossiliferous Cambro-Silurian (C–S) had been deposited throughout the whole region, an inclination of the pre-Cambrian floor took place in late Silurian time. Through pressure from the north thrusting began, and originated a typical imbricate structure as shown in the three lower drawings, the lowest of which represents the actual conditions as now observed. We note thick masses of highly-deformed sandstone (mostly quartzite) above the basal remnants of the fossiliferous Cambro-Silurian Series. These remnants mainly consist of highly-fractured Middle Cambrian alum-shales in which are found species of *Agnostus*, *Paradoxides*, etc.[1] Passing northwards, we observe above the quartzites the grey-green *Holmia* Shale, overlain in turn by the Middle and Upper Cambrian alum-shales, and finally by Ordovician strata.

Conditions similar to those observed by me in the Randsfjord district were previously described from a more easterly district of the Sparagmite area in Norway by O. E. Schiötz.[2]

As has already been mentioned, in Southern Norway, for instance, in the eastern part of the Jotunheimen district, a younger, post-Cambrian 'Sparagmite' series exists, which unconformably overlies Ordovician phyllites. This series commonly contains conglomerates, which have recently been studied by V. M. Goldschmidt,[3] who has found much of interest concerning them. In one district the material in the boulders consists to a great extent of a gabbro of the same kind as that seen in a gabbro-mass that overlies the conglomerate. According to Goldschmidt, the material of the conglomerate was originally derived from this gabbro-mass deposited on the south side of it; then, through pressure from the north, the (rest of the) gabbro was thrust over the conglomerate, and covered it. The present conditions are illustrated in the two lower sections in fig. 5, p. 400 (Gb=gabbro, Cgl=conglomerate). In another district a quartz-conglomerate occurs in a similar relation to a mass of granite.

It is evident that, from this point of view, the above-mentioned

[1] Norges Geol. Undersök. No. 75, 1915.
[2] *Ibid.* No. 35, 1903.
[3] *Ibid.* No. 77, 1916.

gabbro and the granite at the time when the conglomerates were formed, were cooled, solid masses, exposed at the surface. There are also other features generally met with in different districts of the eastern zone of deformation, which indicate that the igneous masses were to a considerable extent moved as solid masses. So we may find very commonly, at the base of the thrust igneous masses, mylonitic zones implying a dynamical crushing of solid material. This might by some perhaps be taken as a proof that the igneous rocks in question, despite other facts, must be considered as of ancient, probably Archæan, age, and not as Caledonian intrusions; but this is certainly not the case.

There is no doubt whatever that the crust-movements which we call 'the Caledonian deformation' have lasted for a very long time. As to this question, I might refer to my recent paper on 'Palæogeography & Diastrophism in the Atlantic-Arctic Region during Palæozoic Time.'[1] It is, further, only natural to assume that the time during which the igneous masses moved or were moved, under constant pressure, from the central zone of deformation to the border-belt 30 to 40 miles away to the south-east, may have been of considerable length.

We do not, therefore, strain our imagination in assuming that more or less of the sheet-like peripheral part of the igneous body was present as a cooled and solid mass, while in the central synclinal zone of deformation, where the roots of the body have to be sought, magmatic masses still poured forth. As to the relation between the conglomerates of the post-Ordovician Sparagmite Series just mentioned and the overlying gabbro and granite, it is evident, if we assume a considerable lapse of time for the deformation, that an igneous mass, the intrusion of which took place in the earlier part of the period of crust-movement, may very well have been exposed and weathered into conglomeratic material before the deformation, the last effort of which was the thrusting of the gabbro and granite above the conglomerates, was finally at an end. This more or less 'dead' state of the igneous masses when they reached far towards the south-east in many cases explains the fact that veins and dykes cutting the underlying sediments are missing here (while they are found in the more central zone of deformation), a fact previously considered as excluding the hypothesis of the later, Caledonian origin of the granites and gneisses.

An important theoretical question to be taken into consideration by future research is the possibility of the intrusions being more or less a cause of the movement of the bordering sedimentary masses. It seems probable enough that an igneous body, through a combined regional and contact-metamorphism, might physically become very closely attached to the surrounding mass. As has been stated, we find commonly, as in Finmarken, a wholly crystalline contact-zone. When the igneous mass became consolidated and, through the pressure from magmatic masses, still coming forth from the central

[1] Amer. Journ. Sci. ser. 4, vol. xlix (1920), especially pp. 9–10.

part of the zone of deformation, was pushed towards the south-east and thus a thrust-plane had to be developed, this plane might in some cases be developed far below the igneous body, in the less altered sediments, and the whole overlying mass moved as a unit (compare fig. 4, p. 396).

The future study of the detailed mechanics of the igneous masses in the eastern part of the Scandinavian mountain-zone, these masses being considered not as Archæan tracts of rock, but as parts of Caledonian magmatic bodies, will certainly be one of considerable general interest.

## Discussion.

Sir Jethro Teall said that the paper was of great interest to him. It had been his good fortune to be associated with the work of the late Prof. Lapworth in the North-West of Scotland in 1883, and afterwards with that of the Geological Survey. It was obvious that there were resemblances and differences between the two regions. Both Lapworth and the Survey had proved that in certain places undoubted Archæan rocks had been superposed on fossiliferous Lower Palæozoic rocks by powerful earth-movements; but the question of the age and date of the metamorphism of the crystalline schists of sedimentary origin, which occupied the same position in other parts of the North-West, had not as yet been definitely settled, although there was evidence pointing to the conclusion that the metamorphism at least was of post-Cambrian date. Certain igneous rocks of peculiar composition resembling rocks that had been intruded into Cambrian strata—the Canisp porphyrite, for example—had been incorporated as part and parcel of the Moine Schist Series.

The Author maintained that certain crystalline schists overlying the thrusts in Scandinavia were of post-Cambrian age. He (the speaker) would welcome such a conclusion, but would like to study the paper very carefully before expressing an opinion on this point. If clearly established, it would have an important bearing on Scottish geology. He had a perfectly open mind as to the age of the metamorphosed sediments and associated igneous rocks, also metamorphosed, which occupied so large a part of the Scottish Highlands.

Mr. Bernard Smith commented upon the Author's statement that the movements giving rise to thrusts had been from the north and the north-west. In studying phenomena related to Caledonian and later movements in North Wales, the speaker and his colleague (Mr. C. B. Wedd) had been driven to the conclusion that certain structures apparently caused by movements from a northerly or north-westerly direction were really due to deep-seated movements of underlying rocks in the opposite direction. The deep-seated more rigid rocks had moved forward relatively first, while the younger less rigid rock had lagged behind.

He enquired whether it could be shown that the apparent movements from the north and the west, producing the thrusts in Scandinavia, were consequent upon an under-drive of the pre-Cambrian rocks towards the sea, inducing a lagging and piling-up of the overlying Cambro-Silurian strata.

Mr. E. D. NICHOLSON remarked that it had been stated by some writers, more especially the late James Geikie, that the amount of thrust in the Scandinavian ranges is from 70 to 80 miles. He asked what was the Author's opinion as to the extent of the thrust.

Mr. H. W. MONCKTON expressed his great interest in the paper. He had for many years followed the development of the mountain problem in Scandinavia, more especially with regard to the Author's southern district, with which he was personally acquainted. There was a double question as to the peculiar gneiss-like masses which form some of the highest ground—whether their position was due to overthrusts, and what was their original geological age? For some time it was believed that they had been derived from the Archæan; but the Author, while adopting the theory of overthrust, considered the overthrust masses to be newer than the Archæan. The speaker thought that the Author had probably arrived at the true solution.

The AUTHOR strongly emphasized that it was not possible, in a short paper, to go into detail as to all the facts pointing to a younger age of the metamorphosed sedimentary rocks in the various districts that had now been studied. In addition to what was stated in the paper, he would point out that in the Jotunheimen district metamorphosed sedimentary beds lying above less altered ones quite certainly were equivalents of what is called the 'Younger Sparagmite of Valdres,' which was of post-Ordovician but pre-Devonian age. As to the amount of movement, that of the sedimentary masses was probably not, in his opinion, in the southern part of the 'Sparagmite area' (for example) more than 10 to 20 miles; while the movement of the igneous rocks in the mountain-zone commonly might be much greater, corresponding to the distance between the eastern border of the igneous masses of the metamorphic cover and the central zone of deformation where the masses had poured forth.