Studies in the post-Silurian thrust region of Jämtland

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Studies in the post-Silurian thrust region of Jämtland.

By

A. G. HÖGBOM.

(With Pls. 6—9).

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Introductory remarks.

The eastern border of the Scandinavian Highlands presents in its architecture a very striking analogy with the western Highlands of Scotland. It repeats on a still larger scale the peculiar overthrust features of that country, as made known by the admirable researches of British geologists. The formations which have taken part in the great displacements also show striking resemblances in many respects. In spite of these analogies, and although the Scottish Highlands can be regarded as a continuation of the great Scandinavian mountain range, yet there are some differences worthy of notice. In Scotland the thrust movements came from the ESE. and forced the eastern rock series over the western Silurian belt. In Sweden, on the contrary, the overthrusts are directed from the WNW. and have covered the eastern Silurian area. In Scotland furthermore the displacements are older than the Old Red Sandstone, from which they are separated by a long period of denudation, while the terrestrial movements in Scandinavia still continued in Devonian time.

The geology of the Swedish overthrust region has, like that of the analogous Scottish region, been a subject of much discussion and controversy. Opinions and interpretations have also changed in a similar manner along with the development of geological exploration.

According to the first extended surveys in the sixties and seventies of the last century, which were summarised in 1873 by TÖRNEBOHM in his memoir »*Über die Geognosie des schwedischen Hochgebirges*» [1], the western quartzites and schists seemed to follow in normal superposition over the underlying Silurian strata. Further investigations could only confirm the existence of a superposition along almost the whole of the eastern border of the highlands, but not until 1888 was the right interpretation of the tectonic structure set forth as a principle by TÖRNEBOHM in a paper on »*Fjällproblemet*» [2]. Already

in 1883 that author had demonstrated the occurrence of thrusts west of Lake Wenern, by which archæan gneisses were driven in anomalous superposition over a younger complex, known as the »Dalformation» [3]. In the eighties the overthrust theory was established in Scotland too, and then also the peculiar rock-structures developed by displacements of this kind were first observed and recognized. The time thus seemed ripe for an application of the overthrust theory to the region under consideration. It is, however, not surprising that this theory could gain adherents in Scandinavia but slowly; for its application to this region involved thrust movements many times greater than the Scottish displacements, which at that time were regarded as something quite extraordinary and without parallel in other parts of the world. TÖRNEBOHM was nevertheless bold enough to draw the necessary conclusions. After a review of the whole central part of the Scandinavian Highlands from Jotunheim to the north of Jämtland, this eminent geologist was in 1896 able to publish his important work on »*Grunddragen af det centrala Skandinaviens bergbyggnad*» [4] with an accompanying survey map on which his interpretation was applied to the stratigraphy and geotectonics. The eastern part of this district was represented from the same point of view by myself in 1894 [5] on a map of somewhat greater scale. For the northern part of the highland border also the overthrust theory was subsequently proved, especially by HOLMQUIST [6]. Regarding the southern part of the mountain range which runs through central Norway, from Jotunheim to Hardanger, the opinions of Norwegian geologists do not seem to be unanimous, inasmuch as some of them have accepted the overthrust theory, while others are undecided or maintain a normal superposition of the »highland-quartzites» (schists, gneisses, quartzites) over the Silurian.

Just as in Scotland the overthrust geology is best illustrated in the Assynt district, where denudation has to a great extent removed the superimposed rocks, so in Sweden the Jämt-

Fig. 1. *The Swedish and the Scottish overthrust areas compared.*
Black = Silurian; Shaded = overthrust areas.

land district provides perhaps the best field of excursion for geologists who wish to become acquainted in a short time with the thrust-tectonics of the Scandinavian mountain range. In Jämtland, as far as is yet known, the overthrusts reach their greatest development; there the overthrust complexes are divided up and dissected by denudation in such a manner as to reveal the extent of the dominant thrusts. There also the fossiliferous Silurian strata help one to trace the stratigraphy. Furthermore Jämtland is the district where the overthrusts were first proved and mapped, as well as the district most conveniently situated as regards communications. Several of the most interesting classic localities and sections are situated in the immediate vicinity of the railway between Östersund and Trondhjem or can be visited by steamers plying on the great Jämtland lakes.

Another suitable opportunity to take cognizance of the thrust-tectonics is afforded along the railway between Kiruna and Narvik, which traverses the northernmost part of the Scandinavian highland range. In this paper, however, the Jämtland district only is taken into consideration.

Referring for further details to previous literature on the subject, I have on this occasion only to give such an account of the geological features of the district as may elucidate the excursions which will be made to its most accessible parts.

General account of the main rock-groups.

The main rocks of the district under consideration belong in age to four different groups: The *Archean* or the *fundamental rocks*, the *Jotnian*, the *Seve group* and the *Silurian*. To these groups a fifth might be added, comprising some *post-Silurian igneous rocks*, which, however, play a more insignificant part quantitatively. Owing to their varying facies and the varying

influence of the metamorphic forces these rock-groups are petrographically very varied. From a petrographical and tectonic point of view the overthrust masses might be regarded as a special group and might be separated from the others. This group then, which might be called the »western schists», is for the most part composed of metamorphic and schistose rocks, derived from the four groups above mentioned. For the present purpose it will be most suitable, first to give a general characterization of the rock-groups according to their age, and then to consider in some detail the tectonic features of the overthrust areas.

The fundamental rocks.

Under this name are comprised all the pre-Jotnian rocks which form the substratum for the Jotnian and the Silurian. As pointed out by the author in another paper [8] these rocks cannot be regarded as Archean in the proper sense, inasmuch as they are younger than the typical Archean formations. The granite described below, to which reference is made in that paper, has been classed as »Serarchean» (= late archean).

The mountainous ground east of the great Silurian area of Jämtland is composed mainly of a coarse porphyritic granite which, after the lake Refsunden in the east of Jämtland, has been called the »Refsund granite». As has been demonstrated by the author in the paper just cited, this granite is essentially younger than all sedimentary Archean rocks of Sweden. Close to the Silurian area one finds the granite intrusive in the young Archean schists in the vicinity of the Lockne and Ismund lakes. A little further to the east, the pre-Jotnian (»sub-Jotnian») igneous rocks of Ragunda, on the other hand, is intruded into the Refsund granite, thus showing that there exists a great hiatus between the granite and the Jotnian. The Refsund granite having in earlier literature been referred to the Archean, it is for the present best to keep to this terminology.

The Refsund granite, together with the above-mentioned Lockne schists, forms the immediate substratum of the easternmost part of the Silurian area. West of the Lockne lake the Silurian strata rest directly on a breccia of the granite which is coarsely weathered, and boulders of the granite are also present in the bottom beds of the Silurian *Orthoceras* limestone.

From the occurrence of isolated exposures of the rocks underlying the Silurian further to the west it can certainly be concluded that the Refsund granite does not extend far beneath this formation. Already in the surroundings of the lake Storsjö the granite is replaced by *felsitic porphyries* and granitic rocks associated with them, probably belonging to the same group as the *Dala-porphyries* that occur further to the south [8]. In many localities these porphyries and granites have been exposed by the denudation in the interior of the Silurian area, and in some places they are also laid bare underneath the overthrust area, always forming the immediate substratum for the Silurian. Generally the porphyries have been much crushed and sheared by the tectonic movements, but occasionally their primary structures (spherulites, micropegmatite, lithophysen, fluidal structure, etc.) are well preserved. In the overthrust schists one can find these rocks present and then they mostly are extremely crushed and often mylonised so as to be hardly recognizable. Those patches which have been seized by the overthrusts occur generally close to the bottom of the great thrust-masses immediately over the 'sole' or plane of movement, as will be illustrated later on by some examples.

The Jotnian.

This group has been treated at some length in another paper by the author [8], and to it the reader is referred for further information. In the district now in question the Jotnian sandstones nowhere occur in their undisturbed position, but further to the north and still more to the south of Jämtland,

especially in the provinces of Härjedalen and Dalecarlia, this sandstone formation occupies large areas east of the overthrust border. In its geological position and petrography, the Jotnian sandstone in essential respects is wholly comparable with the Torridonian of Scotland.

The sandstone is separated from the underlying fundamental rocks by a great hiatus, and a vast period of denudation also intervened between the sandstone and the younger formations, as is substantiated by the fact that the latter generally rest immediately on the fundamental porphyries and granites, in tracts over which the sandstone undoubtedly once extended.

The Seve group.

This group comprises a clastic facies, generally known as the *Sparagmite formation*, and a crystalline facies, often called the *Åre schists* after the mountain Åreskutan.

The Sparagmite formation is chiefly built up of felspathic grits and sandstones of quite a fresh appearance. Conglomerates, with pebbles of reddish quartzites, porphyries, and granites, play an important part in the lower horizons of the formation. There also a dolomitic limestone often occurs, which in works of reference is known under the name *Hede kalk* (= *Birikalk* in Norway). The sparagmites reach their greatest thickness (some hundred meters) south of the district here under consideration. According to TÖRNEBOHM the sparagmite in Dalecarlia and Härjedalen rests unconformably upon the Jotnian sandstone. As a rule the immediate substratum of the Sparagmite formation really consists of the fundamental granites or porphyries already described. This unconformability is supposed by TÖRNEBOHM to represent a very long intervening time of denudation, but to the present writer it seems probable that the interval is not greater than that between the upper and lower divisions of the Torridonian of Scotland.

The original relations of the Silurian to the Sparagmite formation are on the whole of the same kind as the relations between the Silurian and the Jotnian, inasmuch as the sparagmites were already to a great extent removed by denudation before the Silurian epoch. Thus the Silurian generally is not found resting on the sparagmite, but on the older fundamental rocks. In the valley Råndalen (Härjedalen) the fossiliferous Ordovician indeed occurs in undisturbed position in the bottom of a broad pre-Silurian valley, carved out in the Sparagmite formation. In the district here to be considered the sparagmites are certainly absent in their undisturbed occurrence, except in a somewhat dubious locality south of Storlien. But in the lower and eastern parts of the overthrust masses the sparagmites play an important part, always metamorphosed to cataclastic flagstones and mylonites or to true mica-schists. In this case they fall together with the Åre schists from which they cannot easily be separated (see below).

The *Åre schists* are mainly light mica-schists, quartzitic gneisses, amphibolites, and brown garnetiferous sillimannite gneisses. They constitute the mountains of the western highlands and are the dominant rocks in the overthrust areas. Petrographically and tectonically the Åre schists very much resemble the »Moine schists» of Scotland, but the latter also seem to enclose other members, to be paralleled with the Silurian schists (»Köli schists») of Jämtland, described below.

The geological relations of the Åre-schists to the eastern sparagmites are somewhat complicated and are not cleared up in all points. Starting from the eastern sparagmites which are but slightly or not at all disturbed, one finds that in the western thrust-areas these rocks become schistose and transformed to mylonites, sericite-schists, and white mica-schists. The conglomerates also become stretched, with the pebbles strongly flattened. Generally the crystallinity increases from east to west. Indeed, it is obvious that the Åre schists owe their petrographically different development to something be-

sides post-Silurian metamorphism; there must also have existed a primary difference between the eastern sparagmites and the western schists, a change of facies characterized partly by the entrance of basic igneous rocks into the western series, partly by the substitution of argillaceous and slaty sediments for the gritty sparagmites and conglomerates. The basic rocks, just mentioned, which probably are to a great extent tufaceous, repeatedly alternate with these argillaceous beds. Generally speaking, one can say that this change of facies goes slowly on from the east or southeast to the west or northwest. According to TÖRNEBOHM the amphibolitic and gneissose rocks occupy in the Åre-schist series a somewhat higher position than the white mica-schists. The latter, according to the same author, are the real equivalents of the sparagmites, which consequently correspond to the lower divisions of the Åre schists.

It is noticeable that the metamorphic characters of the Åre schists cannot be referred to the post-Silurian displacements only, but that these rocks must already have become metamorphic schists before the Silurian time. This theory is substantiated by the occurrence on the western side of the Scandinavian mountain range (Trondhjem firth) of these Åre schists typically developed and in their normal position underneath the Silurian. In western Jämtland (Dufed) the same conclusion can be drawn from the occurrence of pebbles from the Åre schists in the bottom layers of the overlying Silurian schists, which will be described later on. The interpretation of this pre-Silurian metamorphism cannot be discussed in this connection. It may, however, be suggested that the metamorphism of the upper, gneissose members of the Åre schists must have been caused to a large extent by the contact of intruded basic igneous rocks, which often are still recognizable as gabbros and cognate plutonic rocks. Although these intrusions in Jämtland are, at least in the main, of pre-Silurian age, it may be mentioned that in the northern-

most part of the mountain-range, as well as in the southern, or Norwegian part, post-Silurian intrusions of gabbros and other plutonic rocks also play a significant part.

The Silurian.

In the district under consideration the Silurian occurs with two different facies: an *eastern* facies, generally fossiliferous and not at all or only slightly metamorphic, and a *western* metamorphic facies (the so-called »Köli schists») in which fossils have been only found locally. As is to be seen on the maps, the former occupies a great area, bounded mainly by the thrust-schists in the west and the archean fundamental rocks in the east; the latter is confined to the overthrust areas, on the schists of which it is superimposed. This facies has its greatest development on the Norwegian side, but between Storlien and Dufed and in the North of Jämtland it also reaches into the westernmost parts of Sweden.

Within each of these areas or facies, as is shown in the following pages, there is also a change of facies. Here the former area will be considered first.

The eastern Silurian area.

This area occupies the central part of Jämtland, comprising the surroundings of the great lake Storsjön. By its fertility and gently undulating surface this area contrasts with the mountainous woodland in the east, as well as with the highlands in the west. From the southern and northern ends of this large area small strips branch out and, with some interruptions, follow the highland border closely along its whole extent; some smaller Silurian areas of the same type are also exposed farther to the west (Äre, Kall) inside the great thrust-area. The enlargement of the eastern Silurian belt in Jämtland is a peculiarity caused by uncovering through denudation. A great part of the Silurian area was once covered by the overthrust western schists, as is proved

by the still preserved remains of these schists, which at the present time form conspicuous table mountains, rising above the Silurian surroundings (Alsen, Offerdal, Undersåker).

The geotectonic structure of the Silurian in this area shows that the foldings of the highland range have not extended further to the east than the Silurian now reaches. At the eastern boundary of the Silurian area the strata are undisturbed by foldings, but at some localities it can be proved that they have been displaced by faults and small thrust movements (Lookne, Brunflo) which may represent the distal feeble manifestations of the great western displacements.

Referring for detailed information on the stratigraphy of the Silurian area to other publications [5, 9, 10, 11], I will here only give a tabular statement of the palaeontological subdivisions *)

Gothlandian	{	Upper <i>Graptolite</i> shales.
		<i>Pentamerus</i> limestone.
		Quartzite with <i>Phacops elliptifrons</i> .
Ordovician	{	<i>Brachiopod</i> shales.
		<i>Trinucleus</i> shales.
		[<i>Chasmops</i> limestone (partly represented by »middle» <i>Graptolite</i> shales)]
		<i>Ogygia</i> shales (mainly a facies of the upper part of the <i>Orthoceras</i> limestone).
		<i>Orthoceras</i> limestone.
		<i>Phyllograptus</i> shales.
		[<i>Ceratopyge</i> limestone].
		[<i>Dictyonema</i> shale].
Cambrian	{	<i>Olenid</i> beds.
		<i>Paradoxides</i> beds.
		[<i>Olenellus</i> beds].

As to the geographical distribution of the different divisions of the Silurian, it may be mentioned that the *Cambrian*

*) The horizons which are put in [] are only locally developed or known.

and *Ordovician* prevail in the eastern part, and that going towards the west, especially to the north-west from the lake Storsjön, one finds the *Gothlandian* developed and predominant over the lower divisions, which, however, are exposed in many places where denudation has removed the upper divisions.

The total thickness of the Silurian is generally not great. In the eastern part of the area the two lower divisions are palæontologically and petrographically quite similar to the corresponding areas of middle Sweden, and their total thickness does not much exceed 100 meters, of which the greater part is furnished by the *Orthoceras* limestone, and the rest mainly consists of black bituminous Cambrian shales. The total thickness of the Silurian further to the west cannot be estimated, because of the uniform character and the intricate folding of the predominant shales. The *Phacops* quartzite and the *Pentamerus* limestone, so important to the stratigrapher, generally have an insignificant thickness, seldom exceeding twenty meters and usually much less. Indeed these beds often thin out and vanish, and in this case the stratigraphical orientation is difficult or impossible, since the shales are very uniform in character and poor in fossils.

Besides the differences already mentioned between the eastern and western parts of the area, another feature deserves to be specially emphasized. This is an entire change of facies, by which the different palæontological horizons change in their petrographical characters from east to west. Further to the west the eastern *Orthoceras* limestone thus becomes gradually replaced by dark shales with bands and ellipsoids of limestone (*Ogygia* shales), and the shales in their turn grade westwards into sandy or gritty shales with beds of sandstone and quartzite which may swell out to a great thickness and wholly take the place of the shales. The imposing mountain system of Oviksfjällen, west of lake Storsjön, is such a quartzitic facies of the lower divisions of the Silurian

(Fig. 2). Also in the northern part of the district (Ström) similar quartzites reach a great development. The Silurian age of these quartzites, the thickness of which in the Öviksfjällen may be computed at several hundred meters, is substantiated by the finding of fossils in some small shale intercalations.

In my opinion the much disputed *Wemdal-quartzite*, further south, is also such a facies of the Silurian [12]. This quartzite forms a conspicuous range of high mountains, or rather

Fig. 2. Sällsjön. The mountain in the background consists of Silurian quartzite [15].

a wall, dissected by erosion and extending to a length of 150 kilometers, from the south end of the lake Storsjön to the well-known mountain Städjan in Dalecarlia. The Wemdal-quartzite rests unconformably on the underlying formations, which are partly the Jotnian Dala-sandstone, partly the sparagmites, partly the Silurian, and partly the fundamental porphyries and granites. The Silurian generally occurs as small terraces of *Orthoceras* limestone or Cambrian shales at the eastern fronts of the huge quartzite-mountains. The whole quartzite wall is driven by overthrusts to the ESE. and is

thereby brought into an abnormal superposition over the Silurian, which is only a little or not at all disturbed. This overthrust, although probably reaching some twenty kilometers, is to be considered as a minor thrust and an outpost of the great Jämtland thrust. (See below p. 313 and Plate 7, fig. 11).

It may be supposed that the quartzites of Wemdalén and Oviken partly owe their great thickness to an imbricate thrust tectonic structure. Their petrographical uniformity, however, makes it impossible to follow the tectonic details. The subordinate thrust-planes within the quartzite itself, especially in the Wemdal-quartzite, are none the less often well marked by numerous shearing or crush zones dipping WNW.

The Wemdal-quartzite is generally bluish white or yellowish and reminds one much of some varieties of the Cambrian quartzites in Scotland (Inchnadamph). There also exists a striking resemblance between the overthrusts of the quartzite over the limestone in Scotland and the overthrusts of the Wemdal-quartzite over the *Orthoceras* limestone.

Returning from this digression on the Wemdal-quartzite to the large Silurian area and to the upper divisions of the same, it is noticeable that, on the whole, the change of facies of these divisions is less pronounced than in the lower divisions. The most observable members of the Upper Silurian (the Gothlandian), the *Phacops* quartzite and the *Pentamerus* limestone, show almost the same development in the neighbourhood of Alsen and Offerdal as in the Silurian areas of Åre and Kall about 50 kilometers further to the west. Although the component elements vary greatly in thickness, and, as already mentioned, often thin out or disappear, these horizons as a whole are wide-spread and persistent. The *Pentamerus* limestone is often rich in fossils (*Favosites*, *Halysites*, Crinoid-stems, Brachiopods) and reminds one sometimes of coral-reefs; but often fossils are wanting or scarcely present. Bedding or banking is generally to be seen, but is less distinct than in the *Orthoceras* limestone. The tectonic movements

have, more or less, affected the structure of the *Pentamerus* limestone. Occasionally it becomes strongly schistose and stretched, but generally the tectonic forces have only produced a crush-structure, characterized by a net-work of slaty matter winding around lenticular nodules of the unaltered limestone. Especially on the weathered rock-surfaces this peculiar structure is very conspicuous. Interstratified layers in the *Phacops* quartzite ally it petrographically and palæontologically to the underlying Brachiopod shale as well as to the overlying limestone. A transition from the quartzite to the latter also often takes place in this wise, that the quartzite becomes calcareous or that the limestone becomes siliciferous and encloses irregular bodies of chert. In the western parts of the area the quartzite is much crushed and interwoven with small veins of white quartz. The quartzite itself is of various colours, from white or yellowish to bluish and black. As there often are no fossils and as even the *Pentamerus* limestone is not always present as a leading horizon, the *Phacops* quartzite cannot in every case be distinguished from other quartzites of the same district which belong to the lower divisions of the Silurian.

In obtaining information as to the tectonic structure beneath the great western overthrusts the quartzite and limestone horizons just described are a great help. As will further on be illustrated by some examples, the Silurian underneath the thrust masses is generally strongly folded, and sometimes the overturned folds are replaced by a repeated imbricate structure. These tectonic features are most readily seen where the quartzite and the limestone are present as leading horizons.

The western metamorphic Silurian (the »Köli schists«).

When the Silurian occurs in its normal superposition over the Åre schists of the overthrust areas, it consists of rocks but slightly resembling the eastern Silurian already treated. Not only by their more or less thorough metamorphism but also by their original composition the western

Silurian schists differ from the eastern Silurian. The absence or scarcity of fossils in the former is another difference worthy of note. In Jämtland there occur three greater areas of these Silurian schists. The northernmost area stretches along the Norwegian boundary, overlying the eastern Åre schists. Another, a comparatively small area, covers the interior of the overthrust plateau at Offerdal and forms on this plateau a considerable mountain, Ansätten. This area is especially interesting because of its situation to the extreme east, right inside the normal Silurian, thus giving striking evidence of the great dimensions of the thrust movements. The third area lies between Dufed and Storlien and stretches in the south close to the foot of the great mountains Snasahögen and Bunnerfjällen, in the north to the mountain Anjeskutan, close to the lake Anjan. From the famous waterfall, Tännforsen, this area has been called the *Tännfors area*. Topographically the area, by its flatness and its low gently sloping mountains, offers a conspicuous contrast to the surrounding areas with their large mountains. Extensive swampy grounds and shallow lakes are also characteristic of this area. On the whole, the same features are also found in the first-mentioned area in northern Jämtland.

The predominant rocks of the Tännfors area are *phyllites* and *mica-schists*, the former prevailing in the east, the latter in the west. The phyllites often become somewhat gritty, and their bottom layers grade into schistose grits with still recognisable clastic constituents. In the bottom-layers, for example close to the railway bridge at Dufed, scattered pebbles also occur in this rock. The pebbles partly consist of quartzitic schists and amphibolites, which petrographically may be compared to some varieties of the underlying Åre schists. There are also other circumstances which prove that the Tännfors schists rest unconformably on the Åre schists. Especially on the southern boundary of the Tännfors area, where the two schist groups are wholly independent of each other with regard

to their dip and strike, the unconformability is obvious. At the western boundary conglomeratic layers also occur at the base of the Tännfors schists. Characteristic of the lowest horizons of these schists is another rock group, viz. *peridotites*, of very varying composition and often transformed to talc-schists, more or less rich in magnesite. Chromite also is constantly present. Sometimes these rocks are accompanied by banded impure carbonaceous rocks, or by amphibolites and chlorite schists with bands rich in carbonates. South of the lake Ånn, these magnesia rocks form a continuous belt of some kilometers in length and of varying thickness, immediately in contact with the underlying Åre schists. At Handöl, south of Ånn, quarries which are opened in the talc-schists afford a good opportunity for studying the magnesia rocks. In the schistose rock there, great lumps and balls of unaltered peridotite occur, which have been preserved from metamorphism probably because of their having slid away under pressure in the greasy talc matter. Smaller bands of cognate magnesia rocks also occur at some other localities, on the western as well as on the eastern border of the Tännfors area (Storlien, Nordhallen). In the area in the north of Jämtland, and yet more on the Norwegian side, peridotite rocks are very common and they occur there, not at the bottom only, but also in higher divisions of the schists.

The mica-schists prevailing in the western part of the area in question are of various kinds. White mica-schists, often with small rhombohedra of siderite, with rhombdodecahedral garnets and with needles or prisms of amphibole and with small flakes of brown mica, are the most common. By the varying amount and development of these accessory minerals great variation is produced. Two peculiar varieties which are especially characteristic may be mentioned. The one is a splendid »garben»-schist with great sheaves of amphibole (fig. 3), the other a somewhat porphyritic schist or phyllite with flakes of brown mica scattered in the rock, independently

of its schistosity. As a rule, these schists very much remind one of the »Tremola schists», south of St. Gotthard. The uppermost member of this schist group is an amphibolite with

Fig. 3. «Garben-schist», Medstugan, Jämtland. Natural size [15].

accessory siderite. Because of its greater resistance to denudation, this rock forms mountains rising above the adjacent softer schists.

In the Tännfors area, and in the Ansätten area (north of Offerdal) which, broadly speaking, have the same petrographi-

cal characters, no fossils have been found. From the area in the north of Jämtland, however, fossils are known, occurring in a limestone which is interstratified in the schists. These fossils are stems of crinoids, resembling the crinoids of the *Pentamerus* limestone in the eastern Silurian area. On the Norwegian side also, where these schists reach a great development and are represented by higher divisions than on the Swedish one, fossils have been found, by the help of which these rocks can be referred to the middle and upper divisions of the Silurian. The Tännfors schists, as shown by their position relative to these fossiliferous rocks, may thus belong to the lower divisions of the Silurian (i. e. the Cambrian).

In the upper horizons of the schist series, especially on the Norwegian side of the boundary, basic igneous rocks and their tuffs play an important part in the composition of the complexes. On the Swedish side it is only the magnesia rocks at the bottom, and the amphibolites in the uppermost part of the schist series, that can be regarded as of igneous origin.

Younger igneous rocks.

Igneous rocks, contemporaneous with the tectonic movements, occur mainly on the Norwegian side. On the Swedish side, the porphyritic *Ottfjäll diabase*, which at many localities forms numerous dikes in the overthrust region, may be referred to this group. As an example of the mode of occurrence of these dikes the mountain Ottfjället, south of Åreskutan, may be cited [13]. It is worthy of note, that similar dikes are also met with in the overthrust masses south of Offerdal, and that these dikes do not occur in the underlying Silurian.

The great post-Silurian movements.

As the leading features of the thrust tectonics are presumably known and are moreover delineated on the maps,

I may proceed directly to a description of some illustrative localities, selecting and dwelling chiefly upon localities situated in the vicinity of the railroad. In passing, short remarks will also be given on more distant tracts which contribute to the understanding of the geotectonic structure.

Brunflo.

Going by train from Ånge, one passes along the lake Refsunden through the mountainous granite area of eastern Jämtland, and reaches the Silurian area of middle Jämtland between the stations Pilgrimsta and Brunflo. The landscape at once changes in character, and soon a wide perspective opens over the south-eastern arm of the lake Storsjö and its smooth shore slopes, with their leafy woods and small estates. *Brunflo* is well situated for a starting point for the study of the lower divisions of the Silurian area. Close to the station a section is cut through the fossiliferous Cambrian, and in the immediate vicinity a number of quarries are opened in the *Orthoceras* limestone. The great flat hill east of Brunflo (Lunne) is also built up of this limestone. From the top of the hill there is a splendid view over the lake Storsjö and the Silurian surroundings of the same, with the snowy mountains on the western horizon. To the east the mountainous granitic area forms a natural boundary. Some small, but conspicuous hills next to the Silurian (in the SE.) do not consist of granite, but of diabase.

From this point of view an important feature of the Silurian is to be observed. East of Brunflo, as well as along the whole eastern border of the Silurian, one can see that this formation, topographically, lies lower than the adjacent eastern granite area. While the hill summits belonging to the latter, as in the surroundings of the lake Refsunden, rise to an average height of 400—500 meters above the sea (100—200 meters above the lake), the granitic substratum of the Silurian in this tract lies only about 300 meters above the sea or even

lower, as is proved by the occurrence of the *Orthoceras* limestone on the shore-line of Storsjön (292 m.) near Brunflo. The Silurian consequently lies in a depression relatively to the eastern Archean [14, 15]. As no signs of the development of a shore-facies in this direction occur in the Silurian,

Fig. 4. *Orthoceras* limestone, Lanne, Brunflo [15].

it is obvious that this depression is not original, but has arisen from various tectonic movements, which have taken place in postsilurian time. Faults and vertical displacements are also known; they mark the eastern boundary of the Silurian, especially a little further south, in the vici-

nity of the lake Locknesjön¹. It seems, however, that the existing eastern boundary of the Silurian lies, as a rule, a little to the west of the belt of dislocations, inasmuch as the flat sub-Silurian land-surface is generally exposed to some extent between the Silurian and the eastern mountainous granite area.

Apart from these dislocations the Silurian strata in the vicinity of Brunflo have apparently preserved their original position. In the quarries and in the railway sections north of the station the distinctly bedded *Orthoceras* limestone shows either a perfect horizontality or an almost inappreciable dip. On a closer examination, however, one finds that the tectonic forces of the western thrust region are appreciable even here. As first noted by WIMAN [10], the limestone is cut by small joints or fault-planes, gently dipping to the NW., and thrusts on a small scale have taken place along these joints. Thereby a differential movement of the various beds of the limestone in the same direction is often met with, marked by slicken-sides and striation in the slaty layers, by which the limestone bands are generally separated from each other. Although the differential movements on both sides of the joints and bedding-planes may be insignificant, they may occasionally sum up to considerable amounts. As a manifestation of the same forces, it is to be noted that in the vicinity of Brunflo, where the strata, as already mentioned, apparently lie in undisturbed order, the *Orthoceras* limestone has nevertheless been found, in a well-sinking, underlying the Cambrian shales. From these observations it may be concluded that the western thrust forces have reached to this tract and have there produced a, so to speak, embryonal imbricate structure

¹) From Brunflo an excursion to the west side of the lake Locknesjön can be recommended. Besides the dislocations, the petrographical development of the Silurian, with conglomeratic facies of the *Orthoceras* limestone and the well-exposed weathering breccias at the base, afford plenty of interest. The Archean Lockne schists and their relation to the Refsund granite further contribute to the interest of this excursion [11].

in the Silurian strata, without shifting them much from their original horizontality.

On the relations between these tectonic features and the vertical displacements described above no direct observations have been made, but it may be suggested that the former are previous to the latter.

Östersund and Frösö.

Departing from Brunflo for Östersund, the train at first passes over horizontal strata of the *Orthoceras* limestone, which is at intervals visible close to the railroad-bed. Later on the rock becomes covered, but at Thorvalla and on the opposite side of the lake, at Fugelsta, quarries are opened in it which show that the strata continue to lie more or less horizontally towards Östersund.

Opposite this town, on the island *Frösö*, the steep mountain *Östberget* (Plate 7, fig. 1) attracts attention by its rough topography, sharply contrasting with the gentle surface forms of the Silurian rock. Here the first more pronounced manifestations of the western foldings and overthrusts occur. The main part of this mountain consists of a strongly crushed porphyry, which is hardly recognizable without microscopic examination. This porphyry is of the same kind as the subsequently described porphyries which form the substratum for the Silurian further west. In the eastern precipice of the mountain, as, for example, close to the steps leading to the belvedere, the crush-structure can easily be seen. On some points of the steep face, patches of rubbed Silurian shales also still adhere. The western side of the mountain is more gently sloping, and there the porphyry is covered by the Silurian. By following the shore to the NW. from the north end of the mountain, one finds the Silurian limestones and shales well exposed, forming folds turned over to the SE. From these and other observations in the surroundings of Östberget it may be concluded that the porphyry is a part of

the substratum of the Silurian driven up by the folding and that the steep eastern face of the mountain represents either a fault, or an overturned fold of which the interior has been laid bare by denudation. Continuing from Östberget to the south, there lies a small hill, Öhnet, which mostly consists of a white Silurian quartzite of the same kind as the quartzites of Sunne, a little further to the west. It will be obvious from the above observations that these mountains of the island Frösö cannot be interpreted as remnants of any greater covering thrust-masses, but that they only represent a local prominence or cropping up of the substratum of the Silurian.

In clear weather the belvedere on the top of the mountain Östberget offers a splendid panorama, so that the relations of the topography to the geological structure can be readily studied. The area overlooked from this point is comparable with the area of Würtemberg and Baden together.

For information on the interesting Quaternary deposits of Frösön reference may be made to another paper by the author [16].

Berg.

From Östersund an interesting, but somewhat time-absorbing excursion (3 days) can be made by steamer to Berg at the south end of the lake Storsjön. There the tectonic displacements already reach considerable dimensions. The conspicuous mountain *Hofvæberget*, near to Berg, is a remnant of a western thrust-mass isolated by denudation. Of the same kind is a mountain plateau some miles farther to the SE. The situation of these mountains in relation to the western thrusts appears from the section, plate 7, fig. 11. They form the eastern outposts of the same thrust which has driven the previously described Wemdal-quartzite over the Silurian. The *minimum* amount of this thrust may be estimated as at least twenty kilometers in the neighbourhood of Berg. On the western side

of the lake this thrust-plate is overlapped by the great Jämtland thrust, the schists of which form the Fuda plate (»Fudascholle», TÖRNEBOHM), as will also be seen on the same fig. 11. In the description of the Plate the former thrust has been called the »Hofverberg-thrust».

Offerdal and Alsen.

The railway route from Östersund to Näliden on the north-east side of the Storsjö does not offer much of geological interest. The train, however, passes some sections, revealing that the strata (limestone and shales) generally dip to the NW. or WNW. This dip is moreover characteristic of the whole western part of the Silurian area and is caused by a complete overturning of the folds to the SE. or ESE. Further to the west the shales become phyllitic and schistose, and then the cleavage-planes show the same dips, while the strata, when they are marked by interstratifications of quartzite or limestone or are otherwise appreciable, occasionally can be proved to undulate independently of the cleavage, with its constant dip of 30—50° to the NW. Leaving the railway at the station Näliden, one embarks on the steamer plying on the lake of the same name and reaches Änge in Offerdal, at the north-western end of the lake, in an hour and a half.

Änge is the starting point for excursions in this district, so important for the understanding of the thrust architecture.

Viewed from the lake the great mountain plateaus which border the broad Offerdal valley fascinate the geologist with their mighty precipices. They are the eastern outposts of the great western thrust-mass, from which they have been separated by denudation through an intervening belt of about 30 kilometers, where the underlying Silurian is exposed. The unconformability in the superimposition of these plateau rocks on the Silurian is illustrated by the sketch map and by the section, Plate 7, fig. 6, drawn along the upper border of this

map. The excursions here proposed are intended to give a fuller idea of the tectonic features of this tract.

In the Silurian of Offerdal the following horizons can be paleontologically stated [5, 10]:

Gothlandian	{	Upper <i>Graptolite</i> shales.
		<i>Pentamerus</i> limestone.
		<i>Phacops</i> quartzite.
Ordovician	{	<i>Brachiopod</i> shales.
		<i>Trinucleus</i> shales.

Fossils are not always present in these rocks, but they occur frequently enough to make the stratigraphical orientation possible. Referring, with regard to the fossils of the different horizons, to the paper of WIMAN [10], I will here only enumerate some localities in Offerdal which are noticeable for their fossils.

Ede, east of the church, the section, Pl. 7, fig. 3.

Ekeberg, north of the church.

Brännatorpen, north from Änge.

Berge, the section, Pl. 7, fig. 2. Upper *Graptolite* shale.

Änge, at the southern end of the old bridge and at some other points.

Kjönsta, south of Änge.

Thanks to their power of resistance to denudation, the limestone and the quartzite beds generally form prominences and outcrop ridges rising over the softer shales, thus affording good leading lines for a study of the tectonic features. It frequently happens, that these two rocks follow each other in inverted order or that in a section a recurrence of the same horizons in apparently normal superposition is to be seen. As examples of overturned folds and imbricate minor thrusts causing these tectonic features, figures 2, 4, and 7 on Plate 7 may be adduced.

As a rule the dip is to the NW. and W., but when there is only a slight inclination the dip may also turn in other directions. The axes of folding have a strike quite

independent of the thrust plateaus, which, on the whole, are horizontally superimposed.

Having taken cognizance of the Silurian in the neighbourhood of *Edle*, *Änge*, and *Berge*, especially of the sections figg. 2, 3, and 7, one can proceed to a study of the great thrust in the precipices north and east of the locality last mentioned.

From the section at *Berge*, (Pl. 7, fig. 2) one can choose either the way leading in a northerly direction to the isolated mountain *Bergeknätten*, or one can go eastwards and ascend the plateau *Riseberget* along the section, Pl. 7, fig. 5. On the slopes of *Bergeknätten* Silurian shales are exposed, dipping inwards underneath the escarpment of the higher part of the mountain. Probably the shales occur on all sides of the mountain, but on the northeastern side they are covered. On the south-western and eastern sides the shales occasionally can be followed close to the foot of the overlying conglomerate. In the precipices the conglomerate is well exposed. The ascent can best be performed from the south-east through a small glen leading in this direction. On both sides of this cleft the bottom beds of the conglomerate are strongly compressed, but in the higher parts of the mountain the rock appears in a well preserved condition.

The conglomerate is highly variegated and is composed of well-rounded pebbles of different rocks for the most part red and brown porphyries, veinquartz, quartzites, and granites, cemented by a gritty and generally somewhat schistose matrix, usually of a light greenish colour owing to the development of sericite and epidote. This rock also forms the escarpments of the great plateau in the east, showing only insignificant variation in its composition. In the easternmost cliffs, however, (NW. from *Tulleråsen*) it becomes very coarse, with boulders of granite, sometimes more than a meter in diameter. Sometimes the pebbles at the base of the bed are lengthened and crushed by the pressure, but often they have preserved their forms better than might have been expected. Petrogra-

phically the conglomerate reminds one very much of the conglomerates of the Sparagmite formation. The pebbles are of the same kind as the rocks underlying the sparagmite, while no pebbles of the Åre schists or of Silurian rocks have been recognized. The porphyries and granites of the conglomerate show great resemblance to the rocks of the great porphyritic and granitic area in the north-west, but the pebbles also comprise varieties of porphyries and tuffs of which the original source is unknown. From these circumstances — apart from other evidences — it seems probable that the conglomerate is older than the Silurian and consequently lies in an anomalous superimposition. In adjacent parts of Jämtland the conglomerate has, it is true, nowhere been found underneath the Silurian, the substratum of this formation here being porphyries and associated granites¹⁾. Following the section Pl. 7, fig. 5, from Kläppe, one first has, before reaching the conglomerate cliff, to cross a series of slaty shales with interstratified banks of a greyish or dirty green quartzite, with an apparent thickness of about 100 meters. In this series no fossils have been found, and its relation to the fossiliferous Silurian has not been cleared up. Rocks of this kind very often occur immediately underneath the conglomerate and the schists of Alsen and Offerdal, but they are not found in the folded Silurian rocks further down in the valley. They grade into the mylonitic rocks which generally represent the undermost parts of the thrust-masses. North of Offerdal church, west of Ekeberg, rocks of this kind form the tops of some small hills, which lie approximately on the same level as the bottom of the overthrust conglomerate bed.

¹⁾ In the western end of fig. 6, Pl. 7, the underlying porphyry is pressed up in an overturned anticlinal, in the same way as on Östberget (fig. 1). The rock also shows crush structures like those in the porphyry of Östberget, but the original spherulitic structure of the porphyry has here not been wholly destroyed. Together with the porphyry a quartzite (Ordovician) has also been pressed up — a further analogy to Östberget.

Together with the rocks just described, black shales occasionally occur, and in these shales *graptolites* have been found. But whether these shales are interstratified in the former rock-group, or have been squeezed into them by thrusts remains an open question. Indeed, it is curious that the *graptolites* found here have escaped destruction by the powerful thrust movements, which in other respects have left such evident marks in the rocks underneath the conglomerate.

The sections already described may be regarded as typical and ought to be sufficient to convince visitors that the conglomerates are superimposed on the shales and on the folded Silurian of the Offerdal valley. Besides, from the road south of the conglomerate plateau, this superimposition is easily visible, and the contact is exposed for a great length along the inaccessible precipice, the upper part of which is formed by the conglomerate, the lower part by the shales. Even in the eastern and western escarpements of the thrust-plateau of Offerdal the superimposition is evident.

The great Offerdal plateau, the southern border of which has now been considered, extends about 50 kilometers to the north, with an average breadth from east to west of 20 to 30 kilometers, and it is traversed by the valley of Landösjön. The rocks composing this plateau rest for their greater part on the Silurian. The northernmost end, however, lies partly on porphyries and granites without intervening Silurian, as will be seen from the maps. The conglomerates which occur in the vicinity of Änge are limited to the southern border of the plateau, south of the Landösjön, and reach their greatest development, with a thickness of up to 100 meters, in the south-eastern end of the plateau. North-west from the localities already visited the conglomerate thins out and is not continuous. The main mass of the plateau consists of various flagstones and schists overlying the conglomerate or, when this rock is absent, directly covering the Silurian (cf. Pl. 7, fig. 6).

Going from the southern border of the Offerdal-plateau to the interior, one finds the schists superimposed and forming the great Almåsa mountain, which rises to about 200 meters above the edge of the conglomerate precipices. The schists in this mountain are nearly horizontal or dip gently towards the interior of the mountain. Some of the schists have very pronounced cataclastic characters and may be classed as sparagmite schists or gritty schists containing as metamorphic constituents sericitic mica and epidote; others are thoroughly crystalline white mica-schists. The former are more common at the base, the latter in the upper and northern parts of the overthrust mass. North of Ekeberg, where the conglomerate is wanting, these schists lie directly on the mylonite rocks and slates, already described as often occurring below the conglomerate; and then they cannot easily be distinguished from these slates, into which they grade by intermediate forms. The Almåsa schists, because of their splitting into thin flakes of several meters square, are worked in some quarries north of Offerdal. At Änge one has an opportunity of seeing these plates and their use for various purposes. These schists were originally sparagmites and they have probably been in close geological connection with the conglomerates above described. As these schists recur further to the west and as opportunity also will present itself for seeing them there, the excursions in Offerdal are not extended to Almåsa¹⁾. Before leaving the Offerdal thrust-plateau it must be remembered that these schists, as already said, are in their turn overlaid in the north of Landösjön by Silurian schists belonging to the western Silurian (the Köli schists).

¹⁾ Visitors who have time enough may be recommended to follow the border of the thrust plateau from Bergeknätten, pass by Grötom and Ekeberg, and take the way back to Änge over Ede. Thereby an opportunity is given of seeing the thrust-belts and their rocks (sparagmite-schists, conglomerate, and underlying slates) at Grötom and Ekeberg as well as the sections at Ede, figg. 3 and 7, Pl. 7. At Grötom the well-developed ice-shore line (410 m. above sea-level) is furthermore to be noted (see the Excursion N:o A 6).

After seeing the above-described localities in Offerdal, the visitor will probably not be convinced of the overthrust theory, but will suppose that the conglomerate and the schists, the superposition of which over the Silurian he will admit, are post-Silurian. By their rigidity the plateau rocks could have resisted the pressure which has caused the folding of the underlying Silurian. The plateau rocks might, in short, have acted as the upper plate or board in the experiment of JAMES HALL. Thus a thrust-plane might have arisen underneath the plateau rocks, without being an overthrust by which older rocks were driven over the Silurian. As the impossibility of such a hypothesis will appear from the observations to be made further to the west, at Halland and Åreskutan, I will not on this occasion enter on a discussion of the reasons which even in Offerdal can be adduced against the hypothesis. Suffice it to say that the following facts can hardly be consistent with the same: 1) the absence in the Offerdal conglomerate of pebbles from the supposed older Silurian, and the occurrence in the conglomerate only of rocks which are proved to be pre-Silurian; 2) the strong metamorphism and crystallinity of the upper schists, which can have been metamorphosed by no other forces; 3) the overlaying of these schists by the Silurian Kōli schists; 4) the occurrence in the northernmost part of the plateau of compressed pre-Silurian porphyries in the thrust-zone, between the Silurian and the superimposed schists. The last feature, which will moreover be demonstrated at the plateau borders further west, ought in itself to be conclusive quite apart from the former arguments.

Offerdal to Nālden. For the way back from Offerdal to the railway different routes can be chosen.

1. To pedestrians who wish to spend a whole day, the path over the mountain Hāllsjöberget from Offerdal to Ål-sen, is to be recommended in clear weather because of the beautiful scenery and views over the western mountain range.

The whole mountain Hällsjöberget is an isolated remnant of the great overthrust mass and is built up of sparagmite schists and mylonites. At Alsen the folded Silurian recurs at the foot of the mountain with the same development as in the Offerdal valley. The solid rock, however, is much covered and the geology less plain than in that valley. Following the road on the north side of lake Alsen to the village of Røde one can nevertheless see some good exposures. At Bräcke, 3 kilom. west of the church of Alsen, the thrust-schists approach the lake level; the underlying rocks are there the same as in the section fig. 5, Pl. 7, from Berge. Above these greenish quartzites and shales there is a very characteristic thrust-rock, a knobbed, lustrous schist or slate, containing much calcite. The rock may have arisen from the crushing and mylonizing of Silurian shales and limestone (probably *Pentamerus* limestone). Similar rocks are often present at the bottom of the great overthrusts, when limestones occur in the underlying Silurian (cf. further on Åre). East of Bräcke, this rock is well exposed close to the small sawmill at Glösa.¹

Further to the east the slopes of *Rødeberget*, which is a southeastern offshoot from Hällsjöberget, deserve to be visited. Following the section, fig. 8, Pl. 7, along the tourist path, leading from Ö. Røde to the top of the mountain, one passes from the Silurian shales across greenish quartzites and mylonites of different kinds up to the uppermost knobbed schists, which are partly identical with the calcareous schists of Glösa, and partly have a somewhat gneissose aspect. The whole section represents a thickness of more than 100 meters, and may, broadly speaking, be considered as a mylonitic thrust zone between the underlying folded Silurian and the overthrust masses, now removed to a great extent by denudation. From Røde one can take a rowing boat to the railway station Ytterå, or one can continue along the carriage road to Näliden.

¹) In the soft rock close to the waterfall and the mill some petroglyphs (birds, reindeers) are carved, which may be ascribed to the Bronze Age.

2. Another route is the new carriage-road from Offerdal to Näliden which, however, does not offer much of interest. More interesting is the old roundabout way over Glösa and Wiken on lake Alsen by which an opportunity is given of visiting the above-described localities of Glösa and Ö. Røde. This way leads over a depression of the overthrust plateau between Offerdal and Alsen. Except for the localities just mentioned, this way is of only little geological interest.

3. The quickest way back is by the steamer from Änge to Näliden. The time spent on the two former routes could with better geological profit be devoted to the study of the neighbourhood of Undersåker and Åreskutan, which will be described later on.

Undersåker, Kall, and Åreskutan.

From Näliden to Hjerpen the railway route is of little geological interest. The solid rock is generally covered and consists of Silurian shales, more or less distinctly transformed to phyllites and slates, the schistosity or cleavage of which dips about 30–50° to the W. and NW. Occasionally, for example in the surroundings of Hjerpen, the stratification is also visible and shows a variable dip, independent of the cleavage. *Pentamerus* limestone is interstratified here and there in the shales, especially in the vicinity of Mattmar, where it reaches a comparatively considerable thickness.

At Hjerpen two different routes can be chosen for the study of the overthrust structure, the one following the railway to Åre, the other going in a northwestern direction to the lake Kallsjön, and then from Huså over the mountain Åreskutan to Åre. In clear and settled weather the latter route, which requires at least two days, is worth taking, but ought to be preceded by the excursion of one day to Hålland, below described. Moreover, both excursions are of great interest with regard to the glacial geology of these parts [16].

Hålland and the Rista falls.

Leaving Hjerpen, the train immediately passes Hjerpströmmen, a tributary of the Indal river and, following the northern side of the river, enters the charming Undersåker valley bordered by wooded mountain-slopes. South of the river these slopes are somewhat steeper and are formed by the escarpments of the great overthrust masses which rest on the Silurian of the valley.

Starting from the first station, Hålland, one can in some few hours study the relations of the Silurian to the thrust rocks. The Silurian is well exposed in the beautiful *Rista falls*, which are best reached by following the ordinary tourist path on the southern side of the river.

The rock precipices of the falls consist of a strongly compressed and slaty *Pentamerus*-limestone which is also stretched in an east to west direction. The slight dip is towards the W. Occasionally the annular segments of the crushed crinoid stems are still recognizable, but all other fossils are destroyed. At the base of the falls (best developed on the north side) there is a thin band of white quartzite underneath the limestone. This quartzite is the *Phacops* quartzite, already described from Offerdal, and underneath the quartzite occur phyllites which may be equivalent to the *Brachiopod* shales.

Following the river further to the east, one passes the same rocks in the reversed order, from which circumstance it may be concluded that the Silurian here forms an isoclinal fold analogous to the Berge fold of Offerdal (Pl. 7, fig. 2). The fold here, however, is more overturned and the rocks are more strongly compressed. Less than ten minutes walk to the east of the falls rises a small hill, which is an isolated remainder of the thrust-rocks once superimposed on the Silurian. The hill consists of a variegated schistose mylonite rock in which (at the top of the hill) a strongly crushed porphyry is still recognizable under the microscope.

In the slopes south of the Rista falls the overthrust rocks occur on a greater scale. Climbing up this slope (best in the direction S. 20° E. from the river-bridge at Hålland) one finds at the foot of the slope, 50 meters above the river, phyllitic slates with bands of white quartzite, belonging to the Silurian. Further up there are mylonitic schists of various kinds, gently dipping S. or SW. Among the rocks building up this thrust-plateau some, principally those in the lower parts, have the cataclastic characters very pronounced; others, principally on the highest parts of the plateau, are more crystalline and gneissose. The former somewhat remind one of the knobbed lustrous schists of Glösa (p. 321), the latter are amphibolitic and chloritic schists with epidote and garnet, dense quartzitic schists, much resembling the thrust-schists of Torneträsk, called »hard-schists», and showing beautiful crumpled structures. Gneiss rocks of the same types as those which occur in the western Åre schists also partake in the building up of this plateau. In the lower levels of the thrust-schists mylonised porphyries have also been noticed at some localities. These rocks are especially noteworthy inasmuch as they are undoubtedly derived from the pre-Silurian porphyries and must have been dragged away by the overthrust from the western porphyritic areas (Mullfjället W. of Åreskutan). Some of the gneissose rocks mentioned above seem to be foliated and crushed granites of the same kind as the compressed pre-Silurian granites in the synclinal of Storlien (see p. 339).

Going over the schist plateau to the east, one comes down to a semicircular bight formed by the Silurian lowland in the bordering thrust plateau. Here good exposures are unfortunately wanting, and therefore no time should be spent in visiting this locality. It is better to make the return to Hålland by the path leading from the thrust plateau NW. by N. to the river-bridge.

From the slopes above the station, on the north side of the river, a topographic feature of the overthrust masses

south of the river is to be seen and is worthy of attention. From this outlook to the south it can clearly be seen that the overthrust mass south of the river, just visited, does not consist of a single great plate, bounded downwards by the great thrust-plane, but that it is composed of subordinate imbricating plates, each plate being shifted to the west over the adjacent eastern plate. These subordinate plates form mountains rising over the great thrust-plane with a steep eastern front and with a gentle slope to the west (cf. Pl. 7, fig. 11). This tectonic feature is developed yet more distinctly and on a greater scale in the mountains further to the south, especially in the high mountain complexes of Anahögen and Lundörren, south of the lake Ottsjö. The thrust masses at Kall described below, also afford good examples of the same feature.

As for the great thrust-plane separating the underlying folded Silurian from the superimposed schistose thrust-masses, it can be proved from the same outlook that the plateau has a general gentle dip to the west and crosses the river-valley about halfway between the stations Hålland and Undersåker. On the north side of the river, its front runs immediately EN. from the village Stamgårde, there forming an escarpment in which sheared gneiss and amphibolites are the main constituents. Besides, it may be inferred from the course of the thrust front in the topography, and from the topography of the neighbouring Silurian, that the bottom of the thrust-plate is gently undulating. Furthermore the dip of the thrust schists prove that this is the case. Generally a gentle folding, with the axes of folding running WNW.-ESE., transversely to the mountain range, can be traced almost everywhere in the great thrust-masses, from Härjedalen in the south to Torne-träsk in the north. Inasmuch as the river-valleys also are generally in a transverse direction to the mountain range and have been carved out in the anticlinals of these folds, the dip of the thrust-schists is generally from the valley on

both sides. This feature is still better illustrated by the thrust-plateaus of Alsen and Offerdal and in Lappland than in the tract now under consideration¹. Here, and in the middle of Jämtland generally, it is somewhat obliterated by another folding of the thrust-masses in the main direction of the mountain range. As a consequence of these crossing folds the dip of the schists in the isolated mountains is often inwards, not only on the southern and northern but also on the eastern and western slopes, of which feature Åreskutan, Renfjället, Snasahögarna and many other mountains offer striking examples.

Lake Kallsjön—Huså.

From Hålland one can either continue directly with the train to Åre (see below) or turn back to Hjerpen and make the tour which will here be described.

From Hjerpen to Bonäset, at the southern end of the lake, along the carriage route (about 15 kilometers) only Silurian phyllites are to be seen, but immediately to the west of Bonäset the escarpment of the great overthrust is reached again. The thrust-schists here are traversed by the Kallsjö valley and appear again at the eastern shore of the lake some kilometers to the north of Bonäset in a small mountainous island, Kroksön, near the village Krok. At ordinary water-level a sandy isthmus joins the island to the mainland. On the eastern and northeastern shores of the island Silurian phyllites are exposed, gently dipping to the SW. Over the phyllites the thrust rocks which form the main mass of the island are superimposed, and the contact is distinctly visible. The thrust-rock is a strongly crushed porphyry, which close to the thrust-plane is mylonised and schistose and hardly recognizable,

¹ Speaking of this subject, one may remember that this feature also has an analogy in the Scottish thrust region, where, moreover, the imbricate structure above the great thrust-plane is in many places even more conspicuous than in Jämtland.

but on the top plateau of the island has not lost all the macroscopic characters of a porphyry. Microscopic examination shows that the rock belongs to the same porphyries as those which normally form the substratum for the Silurian. This occurrence thus is an isolated remnant of the thrust-masses, and, in its relations to the underlying Silurian, the porphyry is wholly analogous to the small hill east of the Rista falls, already described (p. 323).

Moreover, the same porphyry also occurs at the bottom of the thrust-schists west of Bonäset, and exposures of it can be seen in the carriage road between Bonäset and Huså. The porphyry there occupies the same position in relation to the overlying Åre-schists and the underlying Silurian as at Undersåker and in other localities on the eastern front of the great thrust.

From Bonäset to Huså three different routes may be suggested viz: 1) by carriage along the northeastern shore to Kall, and from Kall to Huså by boat; 2) by carriage along the southern shore to Huså; 3) by steamer.

The first route gives an opportunity of seeing the island Kroksön, described above. A little further to the west, having passed over a small stream, one meets the thrust-schists again in the mountain Staberg, which mountain, as well as some others further to the north, shows very strikingly the topographical features caused by the imbricate architecture, already described from Hålland (p. 324). The thrust-schists further towards Kall are chiefly Åre gneiss with amphibolites. Furthermore, a coarse crystalline limestone of considerable thickness is also interstratified in the gneiss (north of Westgård).

The same rocks also occur along *the second route*, but there they are generally more covered. In good weather *the third route* by steamer is to be recommended for geologists who have already taken cognizance of the tectonics at Hålland (p. 323). This route also affords good views of the

tectonic features of the topography, while the interesting terraces and shore-lines dating from the end of the glacial epoch are also to be seen very distinctly [16].

From Huså, geologists who can dispose of half a day may make a tour by rowing boat along the coast to Sikås, a few kilometers to the NW. of Huså. The Silurian area on the west side of the lake, which has been deprived of its covering thrust schists by denudation, comes in contact with these schists between Huså and Sikås in a manner that distinctly proves their superimposition on the Silurian also here, on the western side of Åreskutan. For a considerable distance along the shore line, between Sikås and Huså, the quartzites, *Pentamerus*-limestones, and phyllites have a gentle dip of about 30° SE, and going in this direction one finds, when approaching Huså, these Silurian rocks succeeded by greenish, partly quartzitic, partly micaceous schists and slates, in some varieties very much resembling the rocks of the thrust-zone in Offerdal, Alsen, and Undersåker. At Huså the dip turns gradually from SE. to S., and the rocks become gradually more crystalline upwards [17]. From Huså up towards the old copper-mine Bjelkesgrufvan the schists are first dense amphibolites, but higher up gneiss also begins to alternate with the amphibolites, which finally become more distinctly granular. In a rivulet-bed, to the left of the road, a white marble is interstratified in the schists. The copper-bearing zone of Bjelkesgrufvan consists of a fine granular pyroxene-gneiss or a pyroxene granulite which is more or less distinctly banded and alternates with amphibolitic beds. The copper-ore (mainly chalcopyrite), together with some other sulphides, is dispersed in the rock as *fahlbands* of insignificant thickness.

From the mines up to the top of Åreskutan, granular amphibolites and garnetiferous sillimanite-gneisses alternate in the same manner as described below from the southern side of the mountain (p. 330). As for the ore-bearing zone, it can be followed some kilometers to the east (Gustafs and Fröå mines).

This horizon, which always dips inwards to the higher part of Åreskutan, turns at Fröå to the S. and SW., and reaches the Åre lake a little west of the station Björnänge.

Åre.

From this station there should be made two excursions of importance for the interpretation of the thrusts.

1. *From Åre to the rivulet Ullån* (3 to 5 hours).

In the valley between Åreskutan (E.) and Mullfjället (W.) a strip of Silurian forms the underlying rock. This Silurian belt is a continuation of the Silurian of Sikås at Kallsjön already described (p. 328). From the section, Pl. 7 it is to be seen that the Silurian rocks (Cambrian quartzites, phyllites, *Phacops* quartzite, *Pentamerus* limestone, phyllites) have the porphyry of Mullfjället as their substratum and, with a general dip to the east, are covered by the schists of Åreskutan [Pl. 7, fig. 9]. The stream Ullån has cut its bed in the upper members of the Silurian series, following the strike of the rocks pretty closely. Small waterfalls arise where the stream crosses the strike. So early as 1869 the eminent paleontologist LINNARSSON found Crinoids in the limestone of Ullån, and TÖRNEBOHM proved that the schists and gneisses of Åreskutan overlay the Silurian. Ullån has since been a classic locality in the discussion on the highland geology of Sweden.

In visiting Ullån one takes the road from Åre along the northern shore of the lake. The Åre schists are exposed in some small cuttings. Near Ullån the schists become more mylonitic and grade into the calcareous slaty schists described above from Alsen and other localities, near the bottom of the thrust masses. Reaching the stream, one turns to the right and follows a side-path up to a small sawmill. There the compressed and stretched *Pentamerus*-limestone is exposed in the stream-bed. The rock is of the same appearance as at the Rista falls, already described (p. 323). The Crinoid stems can also be found in the same state of preservation. Follow-

ing the stream bed upwards one also finds the underlying *Phacops* quartzite and the phyllites, the latter probably representing the underlying *Brachiopod* shales as well as the upper *Graptolites* shales, but in these rocks no fossils have been preserved. There can, however, be no doubt about the quartzite- and limestone-beds of Ullån being equivalent to the rocks of Sikås, Rista falls, Alsen, and Offerdal. Coming to a bridge (about 1 kilometer from the sawmill and 200 meters above the Åre lake) one turns to the east. In the vicinity of the bridge the limestone still occurs, with a gentle dip to the east. Going further in this direction one first finds small exposures of the limestone and the Silurian phyllites in the swampy ground, but soon mylonitic thrust-schists appear, dipping ESE., and slowly grading upwards into mica-schists, sheared gneisses, and amphibolites of the same kind as at Åre and in the other slopes of Åreskutan.

Although the immediate superimposition over the Silurian is not as clearly visible here as for example at Sikås, it should, however, be perfectly clear from what is here exposed. About two kilometers further to the north, a small mountain-stream, Tvärån, coming from Åreskutan, falls into Ullån. Following this stream upwards, one finds an opportunity of seeing the immediate contact between the Silurian and the Åre schists, but the walk to this locality is tiring and time-consuming, and therefore it is advisable to return to Åre from the bridge of Ullån already mentioned, in a south-eastern direction, following either the path leading to Bräcke or another path to Berge. The descent offers excellent views over the old ice-lake terraces of the Åre-valley [16].

2. *From Åre to the top of Åreskutan* (4 hours up, 2 hours down).

In the mountain Åreskutan the Åre schists form a synclinal, the eastern outcrop of which lies at Undersåker (cf. Pl. 7), the western outcrop, as has just been described, in the Ullå valley. Moreover, going from Huså or Åre up to the top,

O. Frödin foto.

Fig. 5. *Contorted gneiss with amphibolitic inclusions.* Åreskutan.

O. Frödin foto.

Fig. 6. *Mottled amphibolite.* Åreskutan.

one will also find the schists dipping inwards. Consequently the strike of the schists, broadly speaking, runs around the mountain, a peculiarity which this mountain has in common with many other mountains in western Jämtland (cf. p. 326).

Ascending Åreskutan in any direction one thus always passes from lower to higher horizons of the Åre schists. At Åre the lowest, mylonitic bottom rocks of the thrust-mass, which are exposed nearer to Ullån and at Hålland, lie far below the level of the lake (cf. Pl. 7, fig. 11). The lowest schists visible at Åre are fine granulitic pyroxene-gneisses and quartzitic mica-schists, alternating with fine-grained amphibolites. These rocks continue up to the Mörvik plateau (500 m. above Åre). Following the tourist path further upwards, one finds the fine granulitic rocks succeeded by coarser gneisses, mineralogically characterised by a bronze-brown mica, garnet, cordierite, and sillimanite, in varying amounts. This rock is often very contorted; spots, and irregularly curved patches and inclusions of fine grained amphibolitic rocks are mixed in a coarse gneissose or pegmatitic matrix, in a manner much reminding one of some archæan veined gneisses, to which this Åre gneiss also shows a striking resemblance. The gneiss is succeeded above by amphibolites, which sometimes grade into dioritic and gabbroid rocks of varying structure and composition. A somewhat fluidal structure arises from the distribution of the dark and white components in different bands or strips. In other cases the rock is mottled, as is illustrated by fig. 6. The amphibolitic rocks continue to the top, with a single interruption worth noticing, caused by a bed of gneiss of much the same kind as the lower garnet-gneiss. On the top the amphibolite is a massive, granular black rock, composed essentially of amphibole, diallage, plagioclase, and quartz.

The gneiss, as well as the amphibolites, contains curved strips, streaks, and veins of granitic or pegmatitic composition. Occasionally one also meets with true dikes of aplite

and pegmatite, which are distinctly defined and cut all the other rocks independently of their foldings and schistosity.

Going down from the top in other directions one finds the rocks, broadly speaking, following each other in the same succession as in this section; but, as to the details, it is not possible to prove a regular stratification. In the other mountains, consisting of the Åre-schists, the same great rock-groups also recur in the same order as in Åreskutan.

From the top of Åreskutan in clear weather there is revealed a magnificent panorama over nearly the whole of Jämtland, an area comparable to the whole of Switzerland.

From this point also the relations between the physio-graphical features and the great geological lines are quite manifest.

Concerning the glacial geology of the surroundings and the glacial formations of Åreskutan itself, which have acquired their peculiar characters from the movement of the late land-ice from the east of Jämtland towards the higher districts in west, attention may be called to another paper by the author [16].

Dufed—Storlien.

Dufed. From this station some excursions may be made in order to study the formations and the tectonics on the western side of the mountain Mullfjället. The mountain, with its continuation south of the railway, consists of reddish felsite-porphyrries, bared by denudation of their Silurian covering and of the thrust-schists superimposed thereupon. The somewhat diagrammatic section, fig. 11, Pl. 7 gives some idea of the main tectonic features. Especially noticeable is the mode of occurrence of the Åre schists on the western side of Mullfjället. These schists, which in Åreskutan are developed to a thickness of at least 1,500 meters, here form a thin strip only, between the underlying eastern Silurian and the western Kôli schists. South of Dufed this strip, as well as the eastern

Silurian, disappears, and the Köli schists lie directly on the porphyries. (Pl. 7, fig. 10). At their eastern boundary the Köli schists form a marked escarpment facing east, which, especially in the mountain Forsaberget, south of the Dufed bridge, and at Nordhallen, east of the waterfall Tännforsen, stands out in the topography. At the foot of this escarpment the schists are extremely compressed and folded; therefore it is probable that here occurs an upper thrust plane, along which the schists have been driven eastwards over the underlying rocks.

In the wooded and generally much covered neighbourhood of Dufed it takes a long time to gain an orientation of the tectonics. Hardly less than three days are needed to follow the belt between Nordhallen and Forsaberget, should the geologists wish to prove the correctness of the interpretation given on the maps and in the sections described above. The most important exposures occur near *Nordhallen*. There the conglomeratic bottom layers of the Köli schists, with their pebbles of different Åre schists, are also best developed.

If time is wanting, the geologists can reduce the excursions to the exposures on both sides of the river-bridge, west of Dufed, where phyllites, gritty schists, and conglomeratic layers interstratified in them represent the bottom-beds of the Köli schists. By including a visit to the famous Tännfors, opportunities are given of seeing petrographical variations of the Köli schists in the interior of this area.

Enafors. This station is a well-situated starting-point for the study of the southern border of the Tännfors area. The unconformity of the Köli schists on the Åre schists, which form the great southern mountains (Snasahögen, Bunnerfjällen, etc.), can be best proved by following the river beds of Handölselfven, Bunnerån, and Westerån upwards. At Handöl the quarries in the magnesian-rocks deserve to be visited as well (cf p. 306). The Köli schists in this neighbourhood are generally more crystalline than in the eastern part of the area and

Fig. 7. *Landscape-forms of the Källi schists. NE. of Storlien [15].*

occur in a great number of varieties, as has already been described above (cf p. 305).

As for the Åre schists of the mountains south of Ånn it may be sufficient to say that they are of the same kind as the main mass of the schists of Åreskutan.

Storlien. This station, which lies close to the Norwegian frontier, is the best starting-point for excursions in the westernmost parts of the great overthrust. Only some kilometers further to the west, about half way between Storlien and the Norwegian station Meraker, the schists, which in the overthrust area generally have a gentle dip or lie with their structure-planes fairly horizontal, suddenly begin to dip almost vertically. This change takes place along a line which runs nearly parallel with the frontier for a length of more than 100 kilometers to the NNE. of the railway, and can be followed in the opposite direction more than 150 kilometers towards Tönset in Norway (cf. the map of TÖRNEBOHM [4]). East of this tectonic line the schists form a gentle anticlinal, which for a length of more than 200 kilometers coincides with the watershed between the Baltic and the Atlantic. The political frontier between Sweden and Norway also coincides, generally speaking, with this anticlinal. In the northern part, north of Storlien, a belt of Åre schists marks the axis of the anticlinal; in the southern part, south of Storlien, not only the Silurian Kōli schists, but also the underlying Åre schists have been removed by denudation; and thus the substratum of the Åre schists has been exposed. This substratum consists for the greater part of porphyries and granites, but in the northern end of this belt, in the neighbourhood of the mountain Glucken, quartzites, quartzitic schists, and phyllites also occur. These partly show a close resemblance to the Cambrian or Ordovician quartzites and phyllites, which at Mullfjället and some other localities further east come immediately over the porphyries. If this correlation is right, the eastern Silurian extends underneath the thrust-masses at

least as far to the west as the neighbourhood of Storlien, where it comes in sight, thanks to the removal of the superimposed thrust schists. On the other hand it has been shown that the western Silurian schists (the Köli group) extend as far to the east as the Ansätten mountain, north of Offerdal (p. 305). But the Köli schists of the Tännfors area and Ansätten are Ordovician or Cambrian, and the same is the case with the quartzites and phyllites now under consideration. Consequently — apart from other circumstances which point in the same direction — the minimum amount of the great thrust must be at least as great as the distance between Ansätten and the Norwegian frontier, or nearly 100 kilometers¹. Measured directly by the breadth of the great thrust-plate, from the above mentioned dip-line west of Storlien to the thrust front at the southern end of lake Storsjön, the minimum amount reaches 140 kilometers.

The anticlinal at Storlien shows a peculiar asymmetry, inasmuch as the western branch is formed by a higher member of the Köli schists than the eastern branch. In this respect it presents a noticeable analogy to the Dufed anticlinal. As in the latter, the Åre schists on the western side thin out and become overlapped by the bottom beds of the Köli schists; the lower Köli schists (the Tännfors schists) also thin out on the western side of the Storlien anticlinal and become overlapped by the upper Köli schists (the »Meraker group», TÖRNEB.²). The conspicuous mountain west of Storlien, Stenfjället, which forms the outcrop of the western branch of the anticlinal, is built up of these upper schists. At the foot of the eastern escarpment of this mountain, the greenish »Meraker schists»

¹ It may, however, be noted that the direction of the thrust movement is not Storlien—Ansätten, but that the Offerdal thrust mass, with its overlying schists of Ansätten, has moved in the direction NW.—SE., and that the amount of displacement really ought to be much greater than 100 kilometers.

² In this treatise I have not had any reason to divide up the metamorphic Silurian rocks of the highlands into their subdivisions, but have comprised them under the common term Köli schists. On the Swedish side of the frontier these schists are represented only by their lowest division, the Tännfors schists.

are strongly compressed and crushed close to the contact with the underlying (Silurian) quartzites. Therefore it is probable that a thrust has driven the schists over to the east and thereby covered the »Tännfors schists» and the Åre schists. In the continuation of the anticlinal to the north, the latter are to be seen again at the foot of the escarpment formed by the outcrop of the »Meraker schists» on the western side of the anticlinal.

The anticlinal ridges at Storlien and Dufed, which, with their exposed belts of porphyries and granites, form conspicuous topographic features, have been interpreted by TÖRNEBOHM as pre-Silurian mountain ridges that have been overridden by the post-Silurian thrust movements. On this view, the plates of porphyry which, as already described, occur at the bottom of the eastern overthrust areas, must have been seized by the thrust-masses in their passage over these ridges. Also the thinning out, on the western side, of the formations which lie opposite to the direction of the movement must have been caused by the rolling out of the rocks on the slopes most exposed to the tectonic forces. To me, however, it seems more probable, that the anticlinals were formed in post-Silurian time, and this opinion is founded essentially on the mode of development of the adjacent Silurian, which bears no evidence of having been deposited at the foot of any considerable mountain slopes. On the other hand, it also seems probable that, as TÖRNEBOHM thinks, the anticlinals already existed at the time of the overthrusts and that they influenced the thrust movements. If this is true, they may represent a beginning of the post-Silurian movements, or at any rate an earlier stage than the thrusts.

The number and extent of the excursions from Storlien will depend upon the weather and the time at the visitors' disposal. At all events it is well worth making a tour (in some few hours) from Storlien to the west to see the railway cuttings which pass exactly through the anticlinal. The moun-

tains Stenfjället in the west and Storli fjället in the east show the outcrops of the two branches of the anticlinal very distinctly, and in the railway between Storlien and the Norwegian frontier the basement beds of the Kùli schists and the underlying Seve schists are exposed. Going further west, to the waterfall Brudslöjan, or to the SW., in the direction of the mountain Glucken, one meets with the compressed porphyries, granites, and quartzites which occur underneath the Seve schists. The exposure of the former rocks south of the railway (while they are covered by the Seve and Kùli schists north of the railway) is due to a gentle northward dip of the anticlinal axis. The occurrence of compressed granites and quartzites here, in the bottom of the great overthrust, has been interpreted by TÖRNEBOHM as analogous to the occurrences, above referred to, of porphyries in the bottom of the thrust-masses in other localities. Consequently, according to this author, the great thrust-plane does not lie between the Seve schists and the compressed granites and quartzites of Brudslöjan, but may come between these rocks and the quartzites and pre-Silurian igneous rocks which occur farther to the south in the axis of the anticlinal and have been overridden by the great thrust.

Close to the station Storlien, and along the tourist path north of the station, can be seen some types of the western mica-schists of the Tännfors area, by which the contrast between these and the eastern schists of the same area (Dufed) is well illustrated.

For the interesting glacial deposits and river-beds at Storlien, the excursionist may consult another paper by the author [16]. It lies beyond the plan of this present paper to demonstrate the geology west of the frontier, but the geologist will be well-advised to make at least a railway tour from Storlien to Meraker. From the train itself he can see how the dip of the schists a little west of the frontier changes to steep angles. Instead of the gently inclined or horizontal

structure-planes of the thrust areas, the dip now becomes nearly vertical. From this excursion the geologist ought to understand the reasons why the root of the great Jämtland thrust (which he has already followed from Offerdal to Storlien) may be looked for first in this belt, west of the frontier. It may, however, be suggested that the strong folding of the Norwegian part of the highland range may be younger than the great thrust, and that the root therefore may really be situated yet still further to the west. Such a hypothesis seems to be indicated by the tectonics further to the north, north of the lake Torrön (cf. the map of TÖRNEBOHM [4]). But as this tract lies outside the route of the excursions and besides is comparatively less known geologically, this is not the proper occasion on which to discuss the problem.

Concluding remarks.

As the purpose of this paper and of the excursions here recommended is to make those geologists who are interested familiar with some of the fundamental facts on which the thrust theory is based, I have laid particular stress on the demonstration of such localities as can give information about the great main thrust and its extent. As for the minor thrusts occurring in the great thrust-masses, they are not yet sufficiently recognized and mapped to give a basis for theoretical comments on the mechanics of the thrust geology. Therefore I have only touched upon this subject by the way. A difference between the tectonics of the thrust-masses of Åreskutan, on the one side, and of Offerdal or Hålland on the other, may, however, be noted. In Åreskutan only one great thrust-level, at the base of the mountain, can be proved, and no signs of differential movements in the overlying schists are to be seen. In Hålland on the contrary, and still more evidently in Offerdal, two or three different thrust-planes occur. Thus in Offerdal one great thrust lies in the mylonite

belt below the conglomerate, and another thrust separates the conglomerate from the overlying Almåsa flagstones (Plate 7). It may be suggested that the behaviour of the Offerdal conglomerate to the thrusts depends upon the relatively great resistance of the rock to the tectonic forces, and is similar to that of the overthrust porphyries, which the rock further resembles in its situation with respect to the great thrust-planes. Where the overthrust masses were more homogeneous, as for example the Åre schists, which were already crystalline before the thrust-movements, they have been driven forwards as a whole, but when different rocks or heterogeneous rock-complexes were affected, secondary or subordinate thrusts have been developed between them.

For estimating the original thickness of the great thrust-mass no data are available. The thickness of the still remaining schists of Åreskutan, Snasahögarna, Anjeskutan, and other of the high mountains can be estimated at 1500 meters at least, but how much has been removed by denudation cannot be computed. At all events, the original thickness was very insignificant in comparison with the extent of the mass. The ratio, estimated on the still existing maximum thickness, is only 1 : 80 or 1 : 90.

The geologist who sees the overthrusts of Jämtland for the first time, probably feels doubtful as to the truth of the interpretation to which TÖRNEBOHM and the other Swedish geologists have been compelled *par la force des choses*. When a combination of all the facts from Offerdal, Undersåker, Kall, Åreskutan, Dufed, Storlien, and other localities visited in the various excursions, leads to the comprehension of the fact that no root for the thrust masses can be concealed anywhere on the Swedish side of the frontier, even then it will be difficult to accept the theory. It is not easy to imagine how a rock-plate of several hundred kilometers in length and with a thickness at the utmost of some few thousand meters has been driven as a unit no less than 140 kilometers over

younger rocks. Even supposing that the movement took place in the underlying rocks, and that the thrust-plate remained in its place in relation to the earth's crust, the tectonic displacements involved do not seem much more credible. Against the doubters I may, however, cite the concluding words of TÖRNEBOHM in his monograph on the overthrusts: »Wenn die Natur uns zeigt, dass so grosse Überschiebungen wirklich vorkommen, so sind sie auch möglich, mögen sie uns immerhin noch so unerklärlich erscheinen». This sentence was written in 1896. Since that time overthrusts have been proved to play a far greater part in the tectonics of the earth's crust than was then imagined, and the Scandinavian thrusts, although still unsurpassed, have found rivals of nearly equal dimensions in the Alps and other mountain ranges.

A rejection of the thrust theory of TÖRNEBOHM would force one to accept another theory which is much more unlikely, namely the older hypothesis of TÖRNEBOHM [18], involving a recapitulation of the Silurian system and the Silurian fauna after an intervening geological period during which the Seve group was not only formed, but also metamorphosed and to a great extent removed by denudation. The western Silurian (the Kõli schists) would, on this hypothesis, represent a much later geological time than the eastern Silurian, although their faunas contain the same species of Graptolites, Corals, Brachiopods, etc. This is, on a much greater scale, the theory of colonies once brought forward by BARRANDE for the Silurian of Bohemia.

The absurdity of this idea really speaks in favour of the thrust theory, the only interpretation by which we can avoid a hypothesis so improbable, and so opposed to all palæontological experience.

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Description of Plate 7.

- Fig. 1.* Östberget. Length of the section 7 kilom.; *p*, porphyry, strongly crushed; *s*, Silurian shales and *Orthoceras* limestone.
- Fig. 2.* Offerdal, Berge. Length of the section 400 m.; *l'*, *Brachiopod* shale; *Kv*, *Phacops* quartzite; *K*, *Pentamerus* limestone; *l''*, upper *Graptolite* shales.
- Fig. 3.* Offerdal, Ede. Detail from fig. 7, showing the relation of the *Phacops*quartzite (*kv*) to the underlying *Brachiopod* shale (*l*) and to the overlying *Pentamerus* limestone (*K*).
- Fig. 4.* Offerdal, Hällänge. Length of the section 1 kilom.; *t'*, thrust plane; other signs the same as in fig. 2.
- Fig. 5.* Offerdal, Kläppeberget. Length of the section 700 m.; *Kv*, *Phacops* quartzite; *K*, *Pentamerus* limestone; *Mkv* and *MI*, quartzite and slaty mylonite rocks; *Kgl*, conglomerate, belonging to the great overthrust mass.
- Fig. 6.* Offerdal. Length of the section 14 kilom.; *T*, *T'* and *t*, thrust-planes; *p*, porphyry; *qv*, Cambrian quartzite?; *Sh*, Silurian shales (chiefly *Brachiopod*- and upper *Graptolite*-shales); *l'*, *l''* and *l'''* represent the *Phacops* quartzite and the *Pentamerus*-limestone, exhibited in the fig. 2, 3, 4, and 7; *Cgl*, conglomerate (cf. fig. 5); *Sps*, sparagmite schists, mica-schists, flagstones. The quartzite and the limestone have been marked only where exposed. Really they are much more continuous.
- Fig. 7.* Offerdal, Ede. Length of the section 1 kilom.; *t'*, thrust-plane; other signs the same as in fig. 2.
- Fig. 8.* Alsen, Røde-berget. Length of the section about 2 kilom.; *S*, Silurian shales; *Mkv* and *Msl*, mylonitic quartzites and slates of the great thrust-horizon.
- Fig. 9.* Åre, Ullån. Length of the section about 5 kilom.; detail from fig. 11. *a*, porphyry; *b*, Cambrian quartzite; *c*, Silurian phyllites; *d*, *Phacops* quartzite; *e*, *Pentamerus* limestone; *f*, Silurian phyllites and phyllitic mylonites; *g*, mylonised

schists; *h*, Åre schists (mica-schists, amphibolites, gneiss); *T*, the great thrust-plane.

Fig. 10. Dufed, Forsaberget. Length of the section about 8 kilom.; *T*, the great thrust-plane; *t*, minor thrust; *a*, porphyry; *b*, Silurian; *c*, schists, partly mylonised; *d*, Åre schists (amphibolites, gneisses); *e*, Kõli schists (western metamorphic Silurian). The section is seen from the North (Åre valley).

Fig. 11. General section in the direction of the thrust-movement (NW—SE) showing the main features of the thrust-architecture. Length of the section 150 kilometers. *T—T*, the great Jämtland thrust; *t*, the Hofverberg thrust; *t'*, minor thrusts. *gr* and *p*, fundamental rocks (granites and porphyries); *kr*, Cambrian and Ordovician quartzites; *s*, Silurian shales; *sk*, *Pentamerus*-limestone and *Phacops*-quartzites; *pkr*, overthrust porphyries and Silurian quartzites; *sps*, sparagmitic schists and mica-schists of the great overthrust mass; *ås*, Åre schists (amphibolites, gneisses etc.); *k's*, Kõli schists (metamorphic western Silurian) of the lower divisions; *k''s*, Kõli schists of the upper divisions (containing Silurian graptolites).

Note. The height-figures of the sections mark the height above the sea in meters.

Geological map of the overthrust region of Jämtland.

Cederquists Graf. A.-B. Stöhl.
View from Nordfingrâ. The mountains in the foreground consist of gabbro and Labradorite. The table-mountain in the

Map showing the igneous rocks of Nordingrå (After Hj.Lundbohm)