MORAINE STRATIGRAPHY, WITH EXAMPLES FROM THE BASAL CAMBRIAN ("EOCAMBRIAN") AND ORDOVICIAN GLACIATIONS

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Abstract. Stratigraphical and lithological studies of both younger and older glaciations indicate that the vast majority of preserved glacial sediments have been ice-rafted into a marine environment. Both the original area of deposition and the possibilities of preservation will be in favour of a selective survival of such sediments. The"real"—ice-moved—tillites are rare and stratigraphically rather insignificant. The role of coastal ice as a transporting agent in non-glaciated (and glaciated) areas is stressed.

It is shown that the basal Cambrian glaciation has not produced a consistent geographical model, possibly due to considerable movements of continental plates. The Ordovician glaciation is in some respects easier to explain than the very complicated Pleistocene ones and appears to be of Antarctic type.

INTRODUCTION

Moraine stratigraphy has important advantages, as moraines (in the wide sense) are indicators of short-term events (geologically speaking), which can be traced over large areas. The moraines are in principle contemporaneous over the whole area covered with ice during the glacial period of the event and will in most cases yield excellent precision in relative dating.

The problems involved are first to identify the sediment as a till, then to place it in the stratigraphic sequence and time scale, and finally to utilize it to trace the extent of the glaciation and the movements of the ice.

The tills can often be identified with great certainty but, in other cases, there will be some doubt. The granulometry may be confused with slump and scree material, and the fabric with that of solifluction masses. These other rock types occur, however, as masses with a limited distribution, and can therefore often be distinguished from the more wide-spread tills (bottom moraines and glaci-marine tills). For a discussion of the criteria for identifying tills, see Harland, Herod and Krinsley (1966).

The precise dating of the tills may be difficult, as they normally do not contain indigenous fossils and as they are accompanied by either drastic changes in fauna and flora or by erosional disconformities or both. In the central part of the glaciated region, erosion is predominant and the situation with a bottom moraine resting on its ice-striated basement is seldom preserved in the geological record. One of the few instances seems to be the Bigganjarga tillite described by Reusch (1891) and Bjørlykke (1967). Normally the terrestrial glacial sediments are removed by erosion, which is increased by the isostatic upheaval of the land after the melting of the ice. Only in sheltered places and under very special circumstances are the terrestrial glacial sediments preserved, and the dating of these remains, which are normally bounded by marked erosional disconformities, is difficult.

In the ideal situation, with only one glacial period, it will be easy to correlate the glacial surfaces of erosion, even though the precision of dating will be low. In the marginal parts of the glaciated area, where erosion has been less, and in the surrounding area of glaci-marine sedimentation, the till can be much better dated, as the sequence will be more complete and it may be possible to reconstruct the climatic cycles with fairly high precision.

If there were several glacial periods in sequence, the problems of dating will increase, as there may be great difficulties in identifying the individual periods, since the later will tend to obliterate the traces of the earlier. Only in the case in which the first glaciation was also the strongest one and the succeeding ones were all weaker than the preceding one are there normally chances of making a complete record, and then only in the marginal areas.

The divergent directions of fabric and the differing contents of boulders have been used to discriminate between moraine horizons of different ages. The methods are simple, but the sources of error increase rapidly with the number of glacial episodes, and the geological and topographical complexity of the glacia-

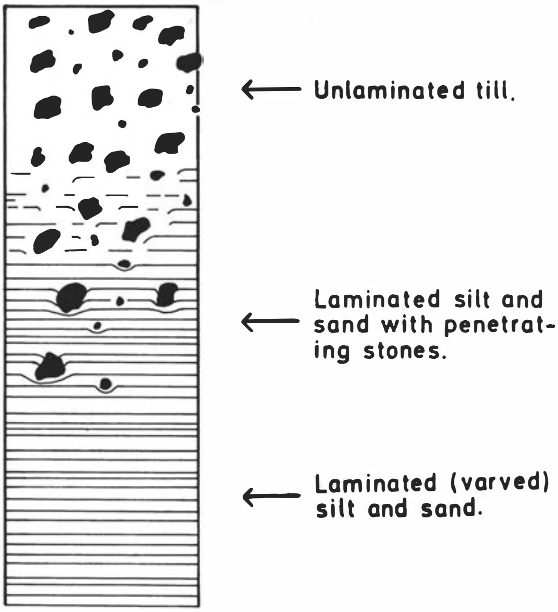

Fig. 1. Diagrammatic section showing gradational contact between varved silt and till, including ice-rafted stones penetrating the varves. This type of contact is taken to indicate that the upper, unlaminated till was also ice-rafted. The section was taken from Mols Hoved, W. of Aarhus, Denmark.

ted region. The Scandinavian Quaternary is therefore not immediately a promising area for such studies. The reason for the use of successive till fabrics is that the lower till was solid, forming part of the permafrost, when it was overridden by the next (presumably thin and cold) ice sheet. Such conditions have been observed on the Canadian Shield. If the tills were influenced by later ice movements when in a plastic condition, the original till fabric may easily have been distorted. Few, if any, experimental studies have been made on the secondary fabric produced in tills (including glacimarine, ice-rafted ones) by later ice movement. The consistent, normal, till fabric found even in bottom moraines transported for short distances indicates that even a slight amount of ice movement over a plastic older till (with or without till fabric) may produce a fabric related to the last ice movement.

The ice-rafted tills may also have an original fabric formed by the dropping of differently shaped stones through water. It can be expected that flat slabs will show a vertical *c*-axis, and that pear- or "pressing-iron"-shaped boulders with an eccentric centre of gravity may show a vertical *a*-axis. The latter will be particularly indicative, as this will be in the "forbidden" sector of the *a*-axis orientation of the normal till fabric. Because of the subjectivity involved in selecting the odd-shaped stones, it is difficult to make quantitative studies of this kind, but vertical *a*-axes of asymmetrical boulders have been observed by the author in a number of Danish Quaternary moraines, including the well-studied ones at Røjle Klint on Fyn. More studies are, however, necessary to identify these and other Quaternary tills as having been formed by ice-rafting.

Contacts

The contact between the till and its basement can be used to discriminate between bottom moraines and ice-rafted tills. Bottom moraines will normally have a markedly disconformable basal contact, either to a crystalline basement or to a previously frozen one. If the ice penetrated over soft, plastic sediments, the bottom moraine will normally be mixed with underlying sediments, and there will be marked deformations of the basement.

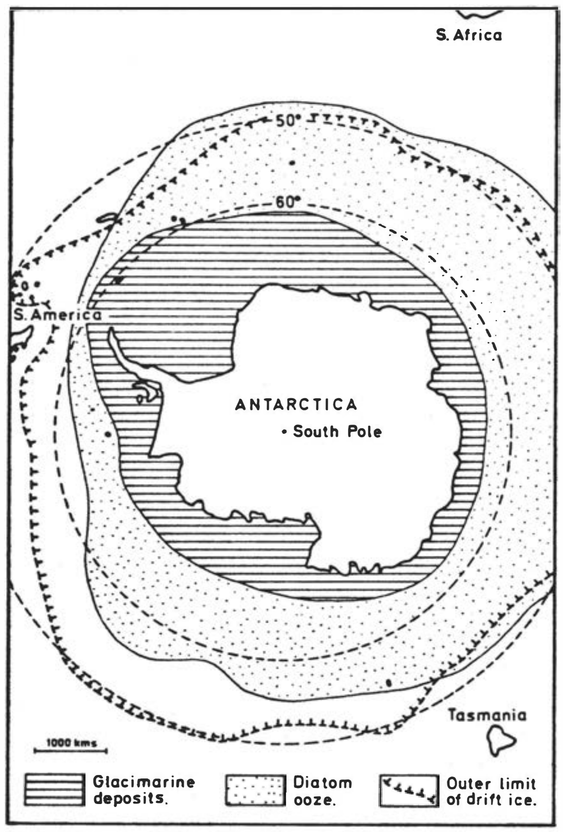

Fig. 2. Map showing distribution of drift ice and ice-rafted sediments around Antarctica. Note that the area of ice-rafted sediments is of about the same size as the continent, and the chances of preservation are, of course, much better in the marine environment. Modified from Hays (1967, text-fig. 2, p. 119).

Ice-rafted tills will be part of a normal sedimentary sequence and will therefore show a more or less gradual transition to the underlying rocks. An example of this is shown in Fig. 1. This section shows a gradual increase in coarse, ice-rafted material, first as a few, single stones penetrating the lamination of the silt-sand sediment and finally as a complete predominance of the ice-rafted material. The upper part of this sequence cannot be distinguished from an ordinary till by granulometry and general aspect. If the ice advanced over such sediments, they would probably be removed and not preserved or at least greatly deformed and overcompacted by ice load. The upper contact of tills is more susceptable to later erosion and modification, and therefore much more difficult to interpret than the lower one.

It is possible that a number of tills which have been described as bottom moraines—especially in the marginal part of a glaciated area—were really ice-rafted. Only a careful analysis of the contacts, boulder content, fabric and stratigraphic context can give a definitive answer. Pure probability will strongly favour the interpretation of these tills as ice-rafted, as the material deposited in marine sediments would have had much better chances of being preserved than that in the terrestrial ones and also covers equally large or larger areas. This is seen in Fig. 2, showing the sediment distribution around Antarctica, where the glacial marine sediments cover an area of the same order of size as the whole continent. In the Quaternary, ice-rafting (as indicated by H. Holtendahl, 1959) was widespread over large parts of the North Atlantic, probably covering an area considerably in excess of that actually glaciated.

Because of the increased rate of erosion due to the isostatic uplift of land after the glaciations, the terrestrial glacial sediments would have been especially subject to strong erosion, and most of them would eventuelly have been removed.

Material transport

Much of the material found in glacial sediments has been transported partly by the ice, by meltwater on, in and below the ice, and by floating ice. Studies of the distance of transportation in bottom moraines (cf. Lundqvist, 1935, Figs. 15—19) and the percentages of local material in proven bottom moraines indicate that large blocks and stones do not survive long-distance transport in the base of the ice. Blocks transported over long distances must therefore have been transported by other means. The most important are glacial melt-

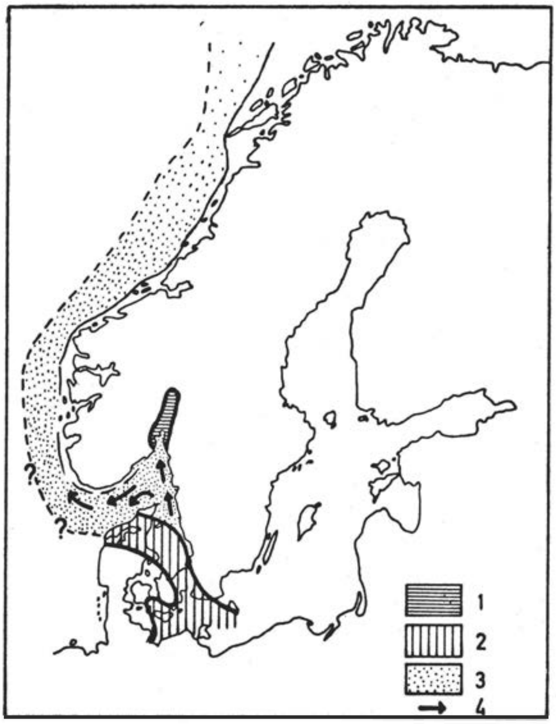

Fig. 3. Map showing distribution of flint and rhomb porphyry along the western coast of Norway. 1 = Oslo region (source area for the rhomb porphyry). 2 = Areas in Denmark and Sweden which were source areas for flint. 3 = Area with marked content of ice-rafted flint and rhomb porphyry on the shelf. 4 = Relevant currents and recent directions of drift-ice movements. Data partly from Holtedahl (1956).

water, boulders "riding" on and gradually sinking into the ice, and ice-rafting. It is difficult to evaluate the relative importance of these methods of transportation, as regards total sediment volume and the coarse fraction especially. Boulders transported from afar and found in bottom moraines may have been picked up a short distance away from ice-rafted material or meltwater deposits.

The potential distance of transportation is much greater with drifting ice than with glaciers, as is shown in Fig. 3, which illustrates the distribution of exotic stones of flint and rhomb porphyry on the Norwegian shelf. This transport certainly took place by drifting ice (cf. H. Holtedahl, 1955), and the amount of such material is surprisingly high (1—3 % of gravel), even very far from the source area. In this case, the transporting agent was probably floating coastal ice. Both the observations of the author (Spjeldnœs, 1964, pp. 40—41, Fig. 7) on the boulder content in the Oslo Fjord area and the mixture of flint (from Denmark and southern Sweden, which was deglaciated long before

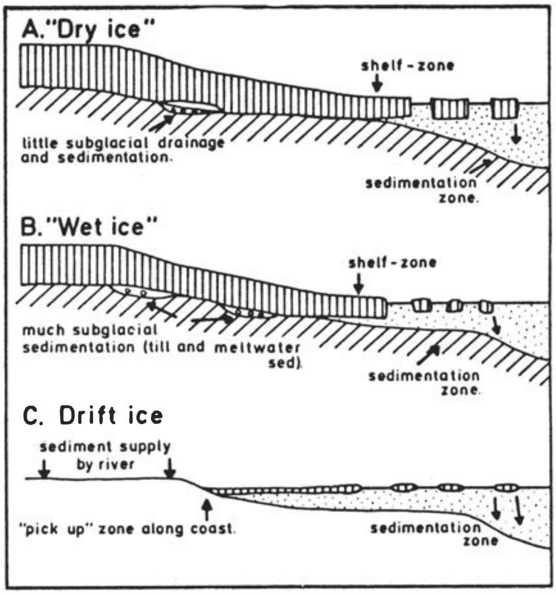

Fig. 4. Diagram showing sedimentation in different glacial regimes. The "dry ice" produces little subglacial sedimentation and also a small to moderate supply of ice-rafted material, resulting mostly in laminated tills (Antarctic conditions). The "wet ice" produces not only more subglacial sediments byt also such an influx of ice-rafted material in the sedimentation zone that lamination is oblitterated. The coastal ice may produce a highly varied and rich supply of ice-rafted material from non-glaciated areas. It is therefore not necessary to have a glaciation to get ice-rafted sediments. Cold conditions, with plenty of drift ice formed along the coasts, may be just as efficient for sediment transport as floating ice-bergs. A and B modified from Carey and Ahmad (1961).

the Oslo region) and rhomb porphyry indicate that drifting coastal ice may play an important role in material transport in cold regions, even outside the glaciated areas. This drift-ice transport was large enough to supply the Stone Age population in the Oslo Fjord region with flint from Denmark and southern Sweden.

No detailed studies have been made of the differences, if any, between the material picked up by the coastal ice, and that of ice-bergs calving from glaciers. It is also possible that much of the material transported by ice-bergs breaking off from glaciers was also picked up at the coast, if the glaciers formed a floating, or fixed ice shelf, such as the antarctic ice sheet (cf. Fig. 4).

In order to interpret the tills found both in recent/Quaternary and in older deposits, many more studies of their stratigraphy and transport mechanisms are needed. In this respect, the study of older glaciations may be helpful, because they are—at least in some respects—simpler and easier to interpret than the last one. The Scandinavian Quaternary glaciation is extremely complicated, partly because it affected an area which was of considerable geological complexity and was also topographically unstable, because of the one-sided upheaval during the Tertiary. The successive glaciations, of variable intensity, mixed and complicated the sediments of the preceding ones, leaving us with a picture which is rather difficult to interpret, both genetically and chronologically.

The Late Precambrian glaciation

The "Eocambrian" glaciation, discovered by Reusch (1891) and known from several parts of Scandinavia, Spitsbergen, Greenland, North America, Central Europe, North Africa, Asia and Australia, has been intensively studied. It is remarkable that the available data on distribution and transport direction do not give a coherent picture (Fig. 5). This may be due to later crustal deformations or to features peculiar to this glaciation. The palaeomagnetic evidence indicates that the glaciations reached very low latitudes. Even if the tillites are interpreted as having been formed by drifting ice, such a cooling of the earth is unacceptable in terms of current meteorological models.

Only in two cases is the till observed in the ideal situation, resting primarily on an ice-striated basement (Bigganjarga in northern Norway, and Eglab in the Sahara). Most of the preserved tillites are definitively glaci-marine, and are members of a normal stratigraphical sequence (cf. Bjørlykke, 1966).

In some cases, the tillites are resting on a basement with no indications of striations. Most of these tillites are probably also glaci-marine, but some of them may be bottom moraines or were deposited under a more or less floating coastal ice shelf.

The stratigraphy of the tillites often shows two tillite beds in the sequence, with variations of boulder content. This may be interpreted as a series in which the basal tillite was formed by ice-rafting from ice-bergs, with material indicative of the glaciated region, and the upper one was formed by droppings from coastal ice, with a quantitatively different boulder composition, due to the selection of boulders in the pic-up region (cf. Spjeldnœs, 1964, pp. 40—41, Fig. 7).

The alternative explanation that there were two ice movements, differing in time and direction, is less probable. In that case, there must have been two centres of glaciation, which operated with different strengths in the different parts of the glaciation. An example of this is the Canadian Shield in the Pleistocene. Widely diverging ice movements have been frequently observed but are normally due to local changes in direction. The migration of the ice divide in Scandinavia is an example of this, in which the ice movement was partly against the gradient of the underlying topography during most of the glaciation. In this case, the volume of sediments formed was rather small, and there are no records of sequences with two layers of moraine with different directions of movement (one from the initial phase and one in the opposite direction from the main phase).

During the final phase of the retreat of the ice, coincidences of the topography and thinning of the ice may produce widely diverging directions, but only locally (cf. Gjessing, 1953). A spectacular, and not yet adequately explained example of such a late, divergent direction is the final ice advance to the north through the Danish belts during the Würm glaciation. This particular ice advance was highly erosive and its tills are not likely to occur in normal sequence above the older ones, except in the distant marine tills, where the aberrant direction will be less apparent.

Both in boulder composition and general lithology (varved clays, general granulometry and boulder content), the Late Precambrian tillites resemble those of the Quaternary, and the geographical position and glaciological mechanisms may have been largely similar.

The Ordovician glaciation

The Late Precambrian glaciations were, probably like the Quaternary ones in Scandinavia, shield glaciations eccentric to the pole. In contrast, the Ordovician one was probably the advance of a polar ice-cap, where the conditions rather resembled those in the present Antarctica.

The presence of polar ice-caps in the Ordovician was indicated by Spjeldnæs (1961), and the glaciation was subsequently found and studied by French and Algerian geologists. The results have been excellently summarized by Beuf *et al.* (1971).

The glaciation occurred on a flat, peneplanized continent, covered with comparatively thin, older, Ordovician sandstones, indicating shallow, marine, stable conditions. Due to the lack of strong topography, the glacial features are unusually smooth and uniform. Erosional phenomena predominate, such as striated pavements, meltwater canyons and tunnel valleys, eroded by ice and later filled with glacigenous sediments. Sediments and especially tills are conspicous by their scarcity. The glacifluvial sediments consist mainly of reworked lower Ordovician sandstones and may be difficult to identify as glacial, unless the texture is typical.

Some of the rocks described as tillites by Beuf *et al.* (1971) are not normal tills. Even though their origin may be connected with the glaciation and they occur in connection with glacially eroded surfaces, they differ too greatly from tillites to be identified as such without reservations (cf. Beuf *et al.*, 1971, text-fig. 211, p. 268). The only unquestionable tillites occur in the "silt verte", which is especially common in the tunnel valleys. This rock differs also from the older Ordovician sandstones and from rocks resulting from their disintegration in its heavy mineral content. The tillites contain locally numerous exotic boulders, which can be seen to penetrate the lamination of the silt. The boulders are quite often (more often than the boulders seen in a normal Scandinavian moraine) striated by ice. Up to 50 % of the boulders may show distinct striation and, in addition, there are many boulders which are too weathered to show striation. The striation is both of the regular type, following the shape of the boulder, and of the striated-facette type. The latter type was formed when a

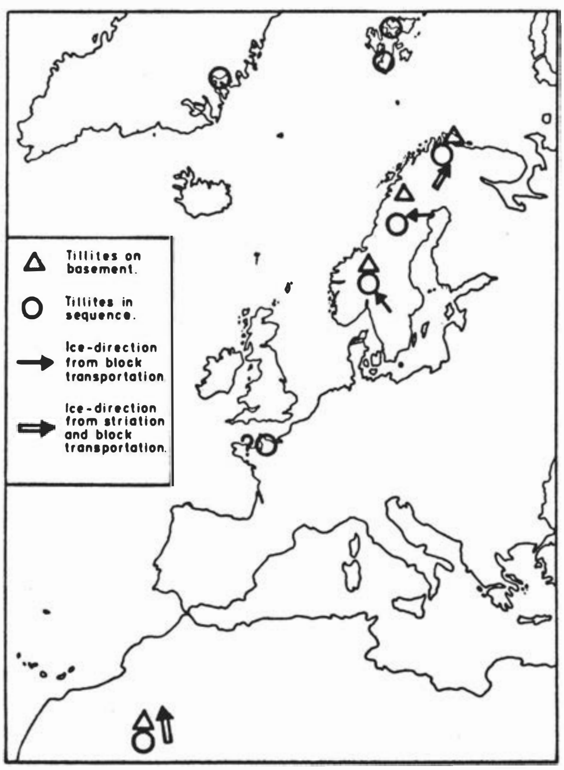

Fig. 5. Map showing distribution of Basal Cambrian ("Eocambrian") glaciations in the Arctic, Europe and North Africa.

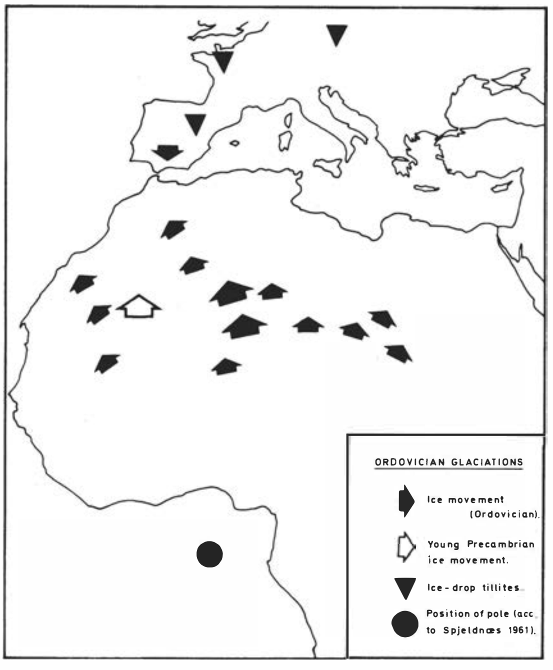

Fig. 6. Map showing directions of movements of ice, distribution of glacial sediments, and supposed pole position in the Ordovician of the northern hemisphere.

frozen till was overridden by a new ice advance and the tops were worn off the protruding boulders. Such "striated pavements" are well known from the Pleistocene glaciations and are a good indicator of multiple ice advances. In the central part of the Sahara, this is also indicated by several superimposed, striated surfaces. The facetted boulders in the ice-rafted tills in the "silt verte" are not orientated; the facettes are at random, indicating that the boulders were first incorporated in a till, which was subsequently eroded, facetted by a new ice advance and finally eroded again and then transported over considerable distances by floating ice. The sources of most of the boulders are unknown, and this also indicates a very long transport.

In some cases, a distinct lamination can be observed in the "silt verte", and the boulders have been observed to penetrate this lamination. Combined with the unusually wide distribution of the glacially striated surfaces and the fact that several of them may be found superimposed on one another, this may indicate that the ice was a dry one (cf. Fig. 4). It is not known if the glacial striation was formed in solid sandstone or in frozen sand. The sequence of striated surfaces in the same general lithology indicates frozen sand, but the often excellently preserved details of the striation indicate that they were formed in solid rock. Both in this respect and in a number of other structures of which there is no good explanation at present (the so-called "pingos" are among them), the Ordovician glaciation differs from the well-known Pleistocene ones. The reason may be that the Ordovician ice was a dry one, with conditions resembling those found in Antarctica. Since the subglacial conditions in Antarctica are almost unknown, it is impossible to use the present conditions there in a comparison with the features observed in the Sahara.

The position of the glaciated area in relation to the pole is also largely similar, as regards the Ordovician (cf. Fig. 6) and the present Antarctica, and different from the European and North American Pleistocene ice sheets.

The age of the Ordovician glaciation has been debated and is difficult to define. Spjeldnæs (1961) has demonstrated considerable fluctuations in the climate during the Ordovician and indicated several possibilities for the maximal cold period. The fossils found in the central part of the Sahara, below the glacial beds, are Llandvirn to Llandeilo, whereas they are directly overlain by basal Silurian beds. In the "silt verte", there are some fossilferous pebbles or concretions with fossils indicating the Middle Caradoc or younger. These fossils may, however, be derived and may be ice-rafted pebbles from older sediments. In Morocco, which had a more marginal position in relation to the centre of glaciation, the glacial beds are dated as upper Ashgill (*Hirnantia* fauna).

The problem is therefore whether there was only one major period in the upper Ashgill or whether there was a constant ice-cap over the Ordovician "Antarctic". This ice-cap may have expanded and receded, with a maximum expansion in the upper Ashgill just before the disappearence of the ice-cap in the lowest Silurian. More detailed stratigraphic studies, especially in the marginal area of the glaciation, are needed in order to solve this problem.

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