ORDOVICIAN CLIMATIC ZONES

By

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Abstract: It is suggested that the Ordovician faunal provinces largely represent climatic zones, and the biological and lithological argument for and against this hypotesis are discussed. The pattern of climatic zones obtained indicate that 1) that Eur-Africa and the Americas have drifted 30—40° apart in an E-W direction since the Ordovician, but the evidence for this is not conclusive. 2) that one of the poles was in or just W. of Central Africa. Both of these features are supported by paleomagnetic studies. It is suggested that polar ice-caps existed during the Ordovician, and that the close correlation of the climatic changes, with faunal migrations and transgressions-regression might be used for long distance correlations. The correlation between climatic changes and orogenies could be observed, but it is not very good, and there is no good correlation between climatic changes and volcanic activity in the Ordovician.

Introduction.

Not much has been done in the study of the climate of the Ordovician, even though a large number of details and isolated observations have been published. Due to this, and the difficulties in interpretation of the observations, most general papers on paleoclimatology have treated the Ordovician rather briefly, and generally (i.e. SCHWARTZBACH 1950) suggested that a warm and uniform climate prevailed during that period.

The present study started with the authors work on the Ordovician faunas of Europe and North Africa, the details of which might be published as a separate paper. The references to the vast litterature on the stratigraphy, lithology and regional distribution of the Ordovician is therefore ommitted here. The same is the case with the references to the litterature on the Ordovician orogenies and volcanic activity.

The results given in this paper have been presented at some occasions earlier (cf. SPJELDNÆS 1958), and the author is indebted to a number of scientists for valuable critizism, and advice. Among them, I would like to mention professor K. C. Caster, Cincinnati, Dr. P. C. Cloud jr. and. Dr. A. R. Palmer of the U.S. Geological Survey, and professor O. Holtedahl, Oslo. I am especially indebted to professor W. C. Sweet, Ohio State University, who has not only discussed the problems, but also read the manuscript critically.

I wish also to express my thanks to Mrs. K. Gran and Miss I. Lowzow who have made the maps and diagrams.

Faunal Provinces.

Not knowing the exact ecology of the Ordovician animals, it is very difficult to limit faunal provinces which will equal the recent zoogeographical ones. The faunas will of course vary widely with depth and oxygen content of the water, and the present study is therefore restricted to the non-euxinic, fairly shallow water shell deposits. Fortunately these deposists were widespread in the Ordovician, probably more so than in any other period. The faunal elements considered are chiefly the benthonic and semibenthonic. Planc-thonic forms, mainly graptolites, are not considered here. The primary factor regulating the distribution of the faunal provinces is regarded to be the water temperature.

As mentioned below, the borders of the faunal provinces change with time, and like the recent faunal provinces or zones, they are believed to be controlled by the climate. The changes in their distribution is regarded to be due to climatic changes.

The lithology of the sediments in which the faunas are found, reflects the ecology of the area, and also, to a certain degree, the temperature of the water. The characteristic lithologic features of each faunal province that are supposed to be of some climatological importance, are therefore mentioned in the description of the faunal provinces.

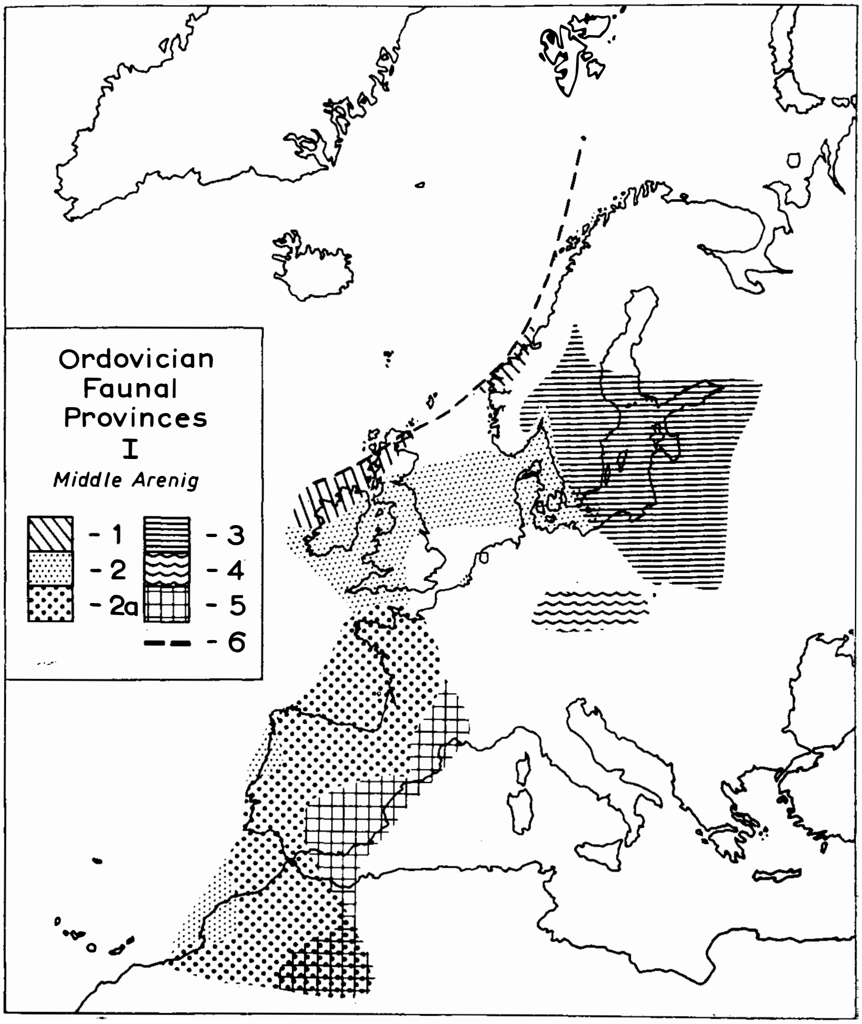


Fig. 1. Ordovician Faunal Provinces in Europe in the middle Arenig. 1 = Faunas of Scoto-Appalachian type, 2 = graptolite shale facies (both in Anglo-Scandic and Mediterranean province), 3 = Shallow water limestone facies of the Scando-Baltic (Orthoceros-limestone facies 2a = Armorican Quartzite, 4 = Bohemian facies, 5 = Trilobite facies, mudrock in Mediterranean province. 6 = S-E-ern limit of American-Arctic province.

The American-Arctic Province.

This province is, in its typical development, found in the N-W part of Europe: in Scotland (Durness), Norway (Smøla), Bear Island and W Spitsbergen. It has its main distribution in Greenland, Arctic and Central Canada, and in the U.S.A.

In the Lower Ordovician (Canadian) the American-Arctic province included large parts of North America, but in the Middle Ordovician it was resticted to a belt extending from Greenland through Arctic Canada, the Rocky Mountains region, to New Mexico and western Texas.

The fauna is thick-shelled, and is dominated by mollusks, especially gastropods and cephalopods. Sponges and corals are also common, end reefs are found from the base of the Middle Ordovician. The rocks in which the fossils are found are mainly massive limestones and dolomites. The sandstones and shales found are generally of the orthoquartzite suite, in this case probably indicating an origin by rapid and complete weathering in a warm climate.

The typical fauna of this province is the upper Middle Ordovician Red River fauna, especially rich in cephalopods, which according to FLOWER (1957) indicate warm water.

In Europe this faunal province is mainly represented in the Lower Ordovician. Only in Durness and Bear Island have Middle Ordovician beds been positively identified. The Bear Island beds were correlated with the Black River by HOLTEDAHL (1919), on the base of the cephalopods. The best preserved forms, *Gonioceras* sp. and *Actinoceras ursium* FOERSTE (1921), indicate that this is correct. *Gonioceras* ranges through the whole Middle Ordovician, and *Actinoceras ursium* belongs to the group of *A. centrale*, which according to FLOWER (1957, pp. 33—34), ranges from the Lowville through the Rockland in North America, probably being a good indicator of Wilderness (=Black River) age.

The area in which the beds of this faunal province were deposited was a stable shelf. This fauna is generally not found in areas with contemporaneous folding and volcanism, and the «geosynclines» were generally shallow depressions, in which no orogenic movement took place, at least not until long after the Ordovician. One of the few exceptions is the Smøla locality, where beds are found in an area of Ordovician orogeny and volcanism. It has to be mentioned that the Lower Ordovician (Canadian) part of the sequence in Europe (Durness, Smøla, Bear Island and Spitzbergen) might belong to either this province, or to the Scoto-Appalaccic. The development of the upper part of the Lower Ordovician is fairly similar lithologically in these two provinces, and the faunas found in Europe are small and not conclusive. The Smøla fauna might also be Middle Ordovician, not Lower.

The shelf deposits of this province are limited by graptolite shale and siliceous rocks in the western part of North America (Vinini Formation). In the south-east (Oklahoma) the same conditions are found. In the typical area the shelf deposits are rather incomplete The Lower Ordovician is represented by dolomitic rocks (Manitou a.o. form.) which are followed by high Middle Ordovician sandstones (Harding, Eureka a.o.). The youngest member of the Ordovician is the generally coarse-grained dolomitic rocks with the typical Red River Fauna. (Fremont, Bighorn, Hanson Creek a.o.). Along the edges of the geosynclines the sequence is more complete. The low Middle Ordovician Whiterock stage is found in Nevada, Western Utah and Oklahoma. ("Upper Pogonip", Joins and Oil Creek Formations).

The Whiterock Stage is known from Greenland and possibly Durness (POULSEN 1951). In continental Europe, it is found in the Hølonda Limestone Trondheim Area, Norway, where *Goniotelus*, *Anomalorthis* and *Syndielasma* are characteristic representatives. At Chabarova, Northern Russia, material collected by NANSEN has yielded an Appalachian fauna including *Isoteloides* and a genus resembling *Paraplethopeltis*.

The rocks in which this fauna is found are generally highly calcareous, but also contain amounts of shale, and the fauna is generally rather thin-shelled, in spite of some few corals, sponges and thick-shelled forms present. The forms mentioned above are typical, others are described by ROSS (1951) and HINTZE (1952).

It is possible that the higher Middle Ordovician in the Central Basin of Tennesse, in Kentucy, the Cinncinnati region and the Upper Mississippi Valley belong to this faunal province. It might also be a transition between this and the following province.

The Table Head beds in New Foundland and the Tourmakeady beds in Western Eire might also belong to the same faunal province, but they were deposited under different conditions, as geosynclinal sediments. In Eire they are also interbedded with volcanic rocks. They are, therefore, not considered further here.

The Appalachian and Anglo-Scandic Provinces.

These two provinces, which are intimately related formed a broad belt trending from Alabama along the eastern part of North America, and continuing along the North-Western part of Europe, through Great Britain, Eire, southern Scandinavia and Esthonia. The provinces crossed the Caledonian system of geosynclines at a low angle. This produced a very complicated picture of the distribution of the faunas, partly because there were active geosynclines (subsiding areas), orogenic movements, volcanism and other features that led to rapid changes in environment, both horizontally and vertically (in time). Furthermore later orogenic events partly destroyed the beds and fossils through metamorphism, and partly displaced them geographically through folding and thrust-faulting.

The Appalchian province is found in Eastern N. America and the Girvan District of Scotland, including parts of Ireland. The Anglo-Scandic anclude parts of Eire and Wales, England, the Oslo Region in Norway, and the Baltic Region. In addition it may also be found in Belgium, and perhaps in the Carnic Alps. Both these provinces contains a complete range of sediments from euxinic graptolite shales with exclusively planctonic faunas, thick geosynclinal sediments, coarsegrained littoral or even terrestrial sediments to shallow-water limestones indicating oxygen-rich conditions with a rich benthonic fauna.

The faunas found in the different environment in these provinces are, of course, widely different, and this has led to great difficulties in correlation of the beds. A typical example of this is found in the Chasmops Series (Middle and Upper Middle Ordovician) of the Oslo Region (Størmer 1953). Along the western and northern margin of the Region, there are beds which indicate deposition in very shallow water (calcarenites, constant silt content in terrigenous material, rich algal flora). The fauna is very similar to that in Esthonia, which is found in beds deposited on a stable shelf, under the same conditions. Nearer the central part of the region (Ringerike, parts of Hadeland), there are beds which were also deposited in ventilated but slightly deeper water, (absence of calcareous algae, few calcarenites, little silt, mainly clay and marl sediments). The fauna is remarkably similar to that found in beds of same age in Shropshire, where at least some of the beds were deposited under the same condition as the Norwegian beds mentioned.

In the central part of the Oslo Region, the beds were deposited under partly euxinic conditions, with occasional ventilation, and the fauna is highly variable, both horizontally and vertically because of this. The rocks are mainly dark gray to black shales with some marly limestones. Bedded calcarenites and calcareous algae are unknown. Similar faunas are found in beds probably deposited under the same condition in North Wales.

It is generally easier to correlate the types of faunas mentioned from the Oslo Region with the resembling distant ones than to correlate the faunas within the Region (cf. SPJELDNÆS 1957, pp. 196—199).

This indicates that all these faunas, in spite of their differences, belong to one faunal province, because in the whole area a similar environment would have produced a similar fauna. In each shallow clear-water environment, the baltic fauna would have appeared, in an environronment with changing oxygen content, the North Wales fauna would have appeared. This also indicates that the factor governing the distribution of the faunal provinces was temperature (=climate).

Because of the complexity of the faunal provinces mentioned here, it is very difficult to define them. There is also a gradual transition between them, and a certain amount of interfingering. In the Oslo Region the number of Appalachian forms is higher in the north than in the south (in the same environment). There is more similarity between the fauna of the Oslo Region and the Girvan district than between the Girvan faunas and those in England. In the Appalachian region, there are certain formations which have a much more «Baltic» fauna than these above and below (Boutetort Lst., Oranda and, especially, Pratts Ferry), indicating that they are "fingers" with Anglo-Scandic faunas.

Generally the Anglo-Scandic elements in North America, and the Appalachian ones in Europe (except Scotland and Ireland) are a small fraction of the species present. An exception from this rule is the fauna described by COOPER & KINDLE (1936) from Percé, Canada, which is dominantly Anglo-Scandic.

The resemblance is generally at the generic level. The percentage of common genera and species might be used to evaluate the relative positions of the continents in the Ordovician (see below).

It is difficult to define characteristic genera and species for the two provinces, for the genera that are common anough to define the faunas are generally restricted to one of the several environments, or they are found in both provinces, but often with a different vertical distribution. The genus *Christiania*, f.i. is known from the basal Middle Ordovician in Esthonia, the Leningrad District, and the Oslo Region, continues intermittently through the whole Ordovician in the latter area, is restricted to the Porterfield Stage in the Appalachians, Girvan and Central Eire, and is found in the Ashgillian in England, Wales and Belgium. Similar patterns of distribution are found in other genera also. A number of genera are restricted to one province, but they are generally not common and widespread. One of the few sets of genera that seem to be characteristic includes *Calliops*, which is the dominating phacopid trilobite in the Scoto-Appalachian province and *Chasmops*, which is the common one in the Anglo-Scandic province.

Further studies of the faunas in the two provinces will certainly lead to a higher number of common and characteristic genera or even species.

The Southern and Eastern limits of the Anglo-Scandic province are not well defined, it is found in the Caradocian of Belgium, and some of the faunal elements, otherwise unknown in the Mediterranean province, are found in the Carnic Alps (*Christiania* and *Sowerbyella*). The faunas typical of this province are also found in Kazakstan (RUKAVIŠNIKOVA 1956 a.o.) and possibly in Himalaya and in Western S. America.

The papers by TRUMPY (1943), and especially by HARRINGTON (in JENKS 1956) and HARRINGTON & LEANZA (1957) show that the Lower Ordovician of South America is strikingly similar to that of Northern Europe (Scandinavia and Great Britain). The Middle Ordovician is less well developed, and it is generally found as graptolite shales. There is, however, a slight indication in the development of facies (cf. HARRINGTON in JENKS 1956) that the western parts of the region belong to the Anglo-Scandic faunal province, and some of the eastern ones to the Mediterranean one, with *Synhomalonotus*.[1])

[1]) After this was printed, the author became aware that WHITTARD (Mem. Paleontogr. Soc. *139*, 1960) had established *Neseuretus* to be the senior synonym of *Synhomalonotus*.

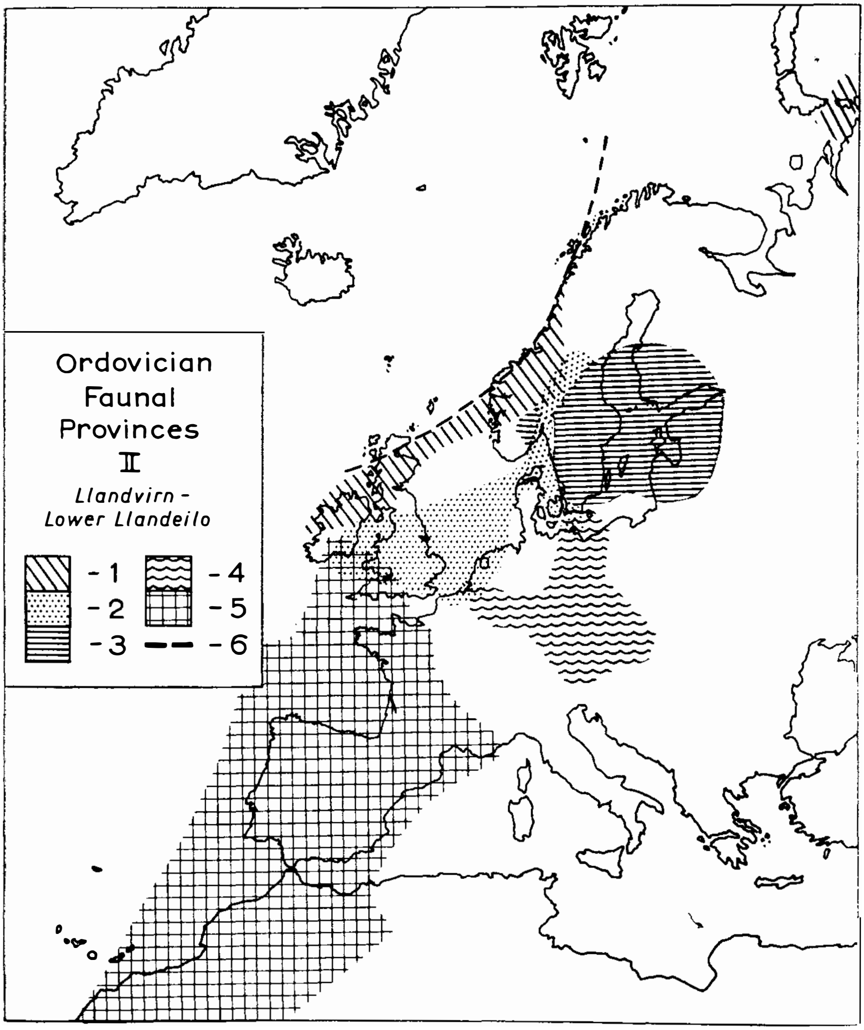


Fig. 2. Ordovician Faunal Provinces in Europe in Llandvirn-Lower Llandeilo. 1 = Faunas of Scoto-Appalachian type, 2—3 = Faunas of Anglo-Scandic type, 2 = mainly graptolite shales and geosynclinal sediments, 3 = shallow-water limestones of Baltic type. 4 = Bohemian faunas, almost undistinguisable from 5. 5 = *Synhomalonotus tristani* province (extends also eastwards to Syria, and westwards to Florida and Alabama, possibly also to Argentina). 6 = approximate limit of American-Arctic province.

Mediterranean province. This province is much more uniform in its faunas than the other ones, and is found in an area reaching from Syria (SUDBURY 1957) in the east to Florida and southern Alabama on the west, and from Belgium, Czechoslovakia and parts of southern Wales on the north, to the Sahara or NW Argentina on the south.

It is typically developed in Bohemia, Normandy, Brittany and Portugal. The "type-fossil" for the province is *Synhomalonotus tristani*. The fauna is composed largely of trilobites, lamellibranchs, and, locally, graptolites. Brachiopods and ostracodes are minor constituents, and cephalopods, bryozoans and corals are very rare. At one horizon, however, in the upper Middle Ordovician, a fauna similar to that in the Anglo-Scandic province invaded the area covered by this province. This fauna contains abundant brachiopods, bryozoans and cystids, some trilobites and a few rugose corals. This is the only limestone horizon in the Mediterranean province.

Except for this bed, all the rocks in this region are dark coloured sandstones, siltstones and shales. In spite of their appearance, the rocks are not generally graywackes; most of them belong to the ortoquartzite suite.

The characteristic phacopid trilobite genus of this province is *Dalmanita*, other genera are *Colpocoryphe*, *Calymenella* and especially *Synhomalonotus*. In the Middle Ordovician, the distribution of the fauna is very uniform, but in the Lower Ordovician it is possible to discriminate environmental (facial) subprovinces. In the western part of Brittany and Portugal, and possibly Western Morocco the Upper Arenig is developed as graptolite shales and siltstones. Then follows a belt of the Armorican Quartzite, a thick light-coloured sandstone, ranging from orthoquartzite to subgraywacke, in some cases with slumping structures. It is found mainly in a N-S belt from Normandy to Morocco. On the eastern side of this belt, the Tremadoc, which like the lower Arenig seems to be missing on the western side, is developed with the *Euloma-Niobe*-fauna (cf. BRØGGER 1896), which is found not only in most parts of Europe, including the Ural Mountains, but also in South America (cf. HARRINGTON & LEANZA 1957). The Arenig is developed in some few regions only(Montaigne Noire and Southern Morocco) as mudstones and sandstones with a trilobite fauna dominated by asaphids.

In the lowest part of the Middle Ordovician, the faunas of this province extended into Belgium, most of Germany, and possibly into Cornwall, and South Wales. In the latter district a mixed fauna is found, this is also the case in S. Eire (Tramore and Raheen Beds). In Bornholm and Scania, some elements of this fauna are also found, especially in the Upper Ordovician.

One of the most interesting occurences of this faunal province is in the subsurface of Florida and southern Alabama. (WHITTINGTON 1953, APPLIN 1951 and BRIDGE & BERDAN 1950). Here, the Ordovician sequence begins with a thick sandstone series (the Armorican Quartzite), which rests upon rhyolite lavas and tuffs, probably corresponding to the Cambrian or Infracambrian volcanics of Brittany. Above the sandstone, there is a series of dark mudstones, which resemble the *Synhomalonotus tristani* beds of Brittany and Normandy lithologically. The trilobite described from these beds by WHITTINGTON (1953) *Colpocoryphe exul*, is a typical Mediterranean one. The graptolites found in the lowest beds of the mudstone series, in the transition to the sandstone, are similar to those found at La Pile-en-Erbray, S. of Rennes in Brittany. One species is common, the age is probably the same, and even the lithology is remarkably similar (cf. PHILLIPOT 1950).

A remarkable fact is that this sequence is not metamorphic, and not folded in spite of its occurring in the continuation of the central part of the Appalachian geosyncline.

Evidence for the Climate in the Ordovician.

The evidence bearing on the climate of the Ordovician is partly of biological, and partly os physico-chemical nature. Since this study is necessarily restricted to marine environments, the problem is to determine the temperature of formation of the shallow-water, shelf deposits.

An absolute determination of the temperature with oxygen isotopes is out of question because all fossils of Ordovician age seem to be too recrystallized to give reliable results.

The known temperature range of living species can be used to determine the climate of fossil deposits in which they are found, but the method is limited to young beds, where living species are still found, and can, therefore, not be used directly in Ordovician beds. It is not possible to use the temperature range of genera and higher taxonomic units, because these are generally too wide, and will give highly inaccurate results. (Might have changed habiat with time!)

There are, however, some generalized rules that might assist in evaluating paleo-temperatures. Large, thick calcareous shells are generally found in warm water. This does not mean that large, thick shells do not occur in cold water; on the contrary, many large, thick-shelled lamellibranchs are found in the arctic fauna. The warm water forms generally, however, have more excess calcification and are, as a rule, more spinose and highly ornamented. This might be connected with the higher solubility of calcium carbonate in cold water, which will benefit forms with the smallest possible surface of the shells. Several cold water shells also have a strongly developed periostracum or live buried in clay, thus preventing corrosion by the sea water.

The quantitative distribution of certain species is also difficult to use when their temperature range is not known. Changes in salinity, clearness of the water and supply of food and oxygen might lead to changes which resemble those of a temperature change. The presence of dwarfed faunas will in most cases indicate lower oxygen content and not lower temperature, whereas a reduction in the number of species and specimens in a fauna is more likely to be the result of changes in salinity or food supply than in temperature. Even if temperature changes might be involved in these ecological variations, they are not reflected directly in the observed facts, and it is very difficult to interpret the role of temperature changes in such cases.

It is still more difficult to determine the temperature of euxinic deposits. They form closed systems with fairly constant temperature, independant of the surroundings, and the fauna consists either of highly specialized forms, or of drifted in planctonic forms. Such environments (the graptolite shales) are therefore not considered here, they might occur in all climatic zones, and are found in the present oceans from the tropics to the arctic.

Within the same species it seem to be a rule that the individuals living in warm water are larger, and have thicker shells than those living in cold water. This is of course valid only if not animals lived in environments of the same type, with equal salinity, oxygen content

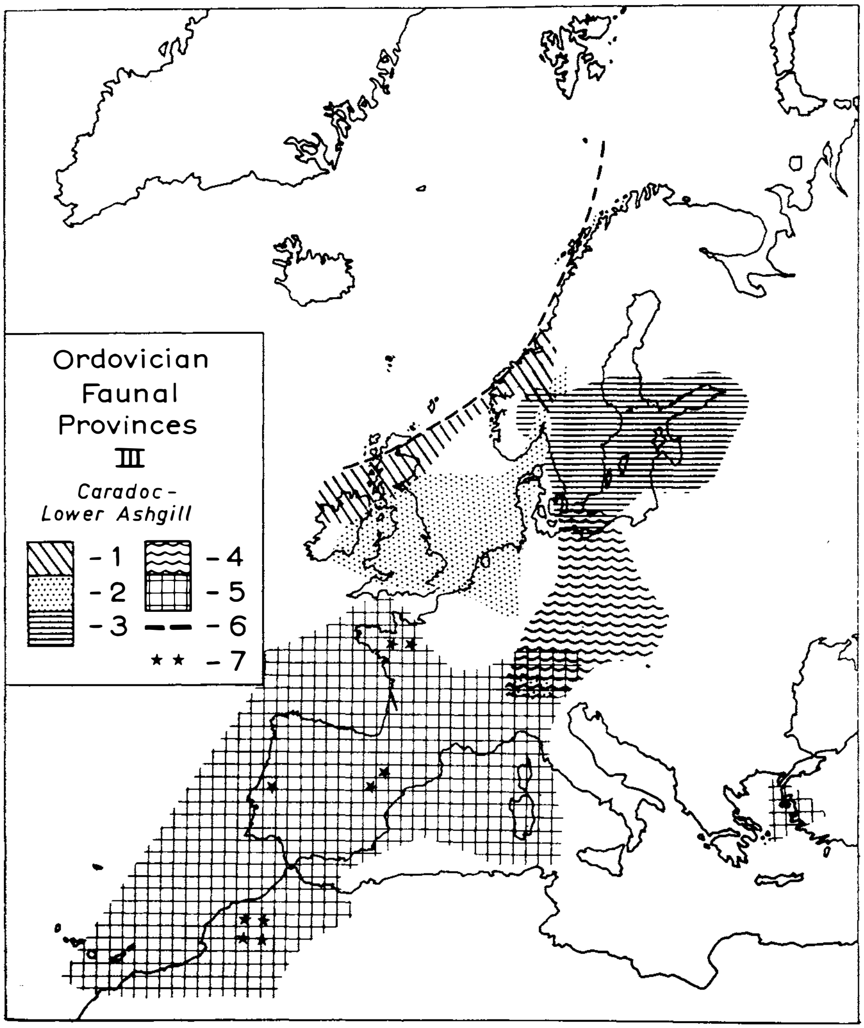


Fig. 3. Ordovician Faunal Provinces in Europe in Upper Caradoc-Lower Ashgill. 1 = Faunas of Scoto-Appalachian type, 2 = Faunas of Anglo-Scandic type (mainly geosynclinal facies), 3 = Baltic type faunas in the Anglo-Scandic province. 4 = Faunas of Bohemian type. 5 = Cystid-Limestone type faunas in the Mediterranean province. 6 = Approximate limit of American-Arctic faunas. (elements of this province are found also in the Anglo-Scandic province in this period) 7 = Occurence of the *Kloucekia*-fauna above, or replacing the Cystid-limestone fauna.

etc. This rule has been used by FLOWER (1946) to suggest that the Red River faunas lived in warmer water than the Cinncinnatian ones. The rule applies, however, only to forms with continuous growth. Forms with growth-stages, moulting, such as most arthopods, are generally smaller in warm water because of the higher rate of growth. This is especially well known from living ostracodes and copepods, and might well have been valid for the trilobites also.

Coral and algal reefs are supposed to be indicators of warm waters and there can be not doubt that the great majority of them were built in warm waters; but exceptions are found, as indicated by TEICHERT (1958). The cold-water coral reefs differ, however, in several respects from the warm-water ones. The sediments concentrated in the "frame-work" of the cold-water reefs are mainly clay and unabraded shells, whereas calcilutite and calcarenite dominate in the warm-water ones, with very little clay. This is because the cold-water reefs are necessarily also deep-water reefs, where the currents do some sorting, but not much abrasion. Because of the depth, the reefs of this type are continuously buried by terrigenous material, whereas the warm-water reefs, being found in shallow water, are seldom reached by the deposition of terrigenous material, and the "framework" sediments are often higly abraded by wave action.

Calcareous algal masses are less distinctly divided into cold and warm water types than the coral reefs, and they are found also at fairly shallow depth in cold water. It is therefore, more difficult to evaluate the temperature of deposition of algal mass deposits, even if the same criteria as for the coral reefs (fragmentation etc.) can be used in some cases, and that the cold water algal masses are more apt to be dissolved, and therefore not preserved. Because of the stronger sunlight, and therefore deeper penetration of light, and the generally clearer water in the lower latitudes, the lime-secreting algae are also more common and more diversified in warm-water.

The annual rate of growth of certain animals, especially corals has also been used to evaluate the relative temperature. (MA 1937, 1956). This method is certainly very valuable, but in order to get reliable results, it is necressary to have a great, and exactly determined material (both stratigraphically and zoologically) in order to eliminate local, ecological variations. This has not yet been done systematically.

The evidence provided by the lithology of the beds will give a more direct temperature than the faunistic evidence, because it might be supposed that the same physico-chemical rules governed the formation of the sediments both in the Ordovician and the present oceans. If, therefore, the process of formation of a type of sediment depends upon temperature, the ancient ones must have been formed at the same temperature as recent ones.

The formation of sediments is, however, governed by other features than temperature, and a purely lithological temperature determination will in most cases be rather uncertain. Generally only a maximum or minimum temperature can be found.

The presence or absence and type of calcium carbonate deposits is probably the best available temperature indicator obtainable for the lithology of the rocks (cf. WISEMAN 1959).

It is well known that calcium carbonate is much more soluble in cold than in warm water, and therefore deposition is not likely to occur in cold water. This does not mean that limestones cannot be formed in cold water, but they will be much less common there than in warm water. In cold water, the calcium carbonate is formed purely biochemically, as shells of organisms. The limestones will consist of coquinas and coarse-grained calcarenites or calcirudites. They are often cemented by clay, but might also have calcite cement, because the pore-water in these sediments easily will have a much higer carbonate content than the sea-water, and therefore permit chemical deposition of calcite. Because the smaller carbonate grains have a proportionally larger surface than the larger ones, they will be dissolved more rapidly, and are seldom found in pure carbonate rocks from cold water deposits. Most fine-grained calcareous rocks have a high clay content, because the clay will prevent the solution of the carbonate, by restricting circulation between the pore-water in the sediments and the sea-water. Corrosion surfaces (diastems) are also more common in cold than in warm waters, but they indicate primarily a drop in temperature, not necessarily to very low ones. They might also be due to invasion of masses of water undersaturated with calcium carbonate, but not much colder than under the previous conditions.

Accretionary calcarenites of the bahamite type definitely indicate warm weater, for they are the result of chemical deposition and contemporaneous abrasion. The fine calcilutites of the drewite type are also indicative of warm water. As mentioned above, calcareous mud deposited in cold water is generally mixed with considerable quantities of clay.

The discrimination of cold and warm water deposits with the criteria mentioned here, is rather difficult, because the thick sediments formed in areas with an ample supply of terrigenous material, will look "colder" than the contemporaneous sediments deposited in areas with the same temperature, but with less deposition of terrigenous material. If it is supposed that the rate of calcium carbonate deposition is constant, the resulting sediments will be much less calcareous in the areas with much terrigenous material, and more mixed with clay than the more purely calcareous deposits in the area without.

This is specially important when comparing subsiding basins (geosynclines) with stable shelf areas. Generally a large amount of observations is needed to get an opinion as a whether the changes are the results of changes in temperature, or if they are due to differences in the supply of terrigenous material In a larger area, this is simpler, just because it is then possible to trace changes parallel to the basin, and compare them with the total thickness of the beds.

The type of clay mineral found in sediments might also give clues to determination of temperature, since different clay minerals are formed by weathering under different climatic conditions. Recently, a number of authors have studied this problem but not general agreement as which clay minerals are indicative of which environment has been reached, except that previously known, that kaolinite and bauxite indicate a warm humid climate, and that cold climates generally are indicated by illite, clorite and muscovite. It seems however, that some clay minerals are changed into others when redeposited in marine environments, and this process is not yet completely investigated. The clay minerals are also primarily formed by terrestrial weathering, and their composition is therefore indicative of the land climate of the erosion area, which is not necessary significant of the temperature of the sea in which the clay minerals were deposited.

Several cases are known in which the temperature of the sea water is much higher or lower than would be expected from the climate of the adjoining land. In most cases this is due to oceanic currents and the topography of the land-masses.

The more intense and rapid weathering in warm water will also affect the feldspar content of sandy or silty sediments. Because the decomposition of the feldspars is mainly a chemical process, they will endure longer transport and more abrasion in cold than in warm water. As far as the author knows no detailed studies of the rate of deposition of the feldspars due to temperature and way of transport has been made, but it seems possible that sorted sandstones and siltstones with a notable amount of clastic feldspars are formed in cold water. The absence of feldspars in unsorted sediments, especially graywackes, is not absolutely conclusive evidence of warm water because the source material might have been poor in feldspars.

It is supposed that graywackes deposited in cold water will show a higher feldspar content than ones deposited in warm water if the source area and the distance and time of transportation is the same. In order to use this feature as a temperature criterion, it is, therefore, necessary to have rather complete data on the geological history and stratigraphy of the region studied.

As mentioned above, sediments in the graywacke facies look "colder" than those in the orthoquartzite facies. Generally it is difficult to discriminate between cold and warm water sediments in the graywacke facies, exept for variations in the feldspar content. Interfingering of calcareous sediments, might in some cases given a clue to the determination of temperature.

In the orthoquartzite facies the cold water rocks will have a superficial resemblance to the graywackes, but a closer examination reveals that the sand- and siltstones are cemented with quartz, and not with clay. The thickness of the beds will in many cases be greater in cold than in warm water, because the chemical weathering and higher solubility of weathering product in warm water will contribute to transport of material in solution, in contrast to the almost purely mechanichal weathering in a cold climate.

It might be concluded that it is not *generally* possible to determine the temperature of formation of a certain sediment from its lithology, but it can be done in a number of special cases. The same conclusion has been arrived at with the biological evidence. If the special cases are numerous enough, it might still be possible to get a fairly reliable basis for the determination of the paleoclimate. In most cases it will not be possible to tell the temperature in a single sample of a single section, a large number of observations, combined with a thorough knowledge of the geological history of the area is necessary.

The best results might be expected where it is possible to use a combinations of lithological and biological evidence, reconstructing types of environment, the temperature of which can be estimated within narrow limits, because they are known also from recent oceans.

Two examples can be mentioned: The presence of rapidly lime-secreting organisms, such as calcareous algae of the family Dasycladaceae in mud-rocks with little or no carbonate in the matrix are indicative of cold water (the algae are used as en example here, instead of the more commonly occuring lamellibranchs, because some of the latter will be burrowing forms).

In warm water the algae-bearing sediments are in most cases highly calcareous, due either to chemical precipitation, or to fragmentation of biologically precipitated carbonate. Only in cold water there will be both an ample supply of dissolved carbonates, which can be utilized by the plants and still no chemical precipitation, and no deposition of clastic carbonate material. In the few and special cases in warm water where the supply of clay is large enough to suppress the carbonate precipitation completely (in deltas of large rivers) there will generally be features indicating the special conditions, such as impoverished or specialized faunas due to low or variable salinity and possibly deposition of silica and iron, which are less soluble in salt than in fresh water.

The other example is the pure, almost unfossiliferous calcilutites ("dove limestones", "birdseye limestones") in which the fauna is restricted mainly to smooth ostracodes and gastropods. They are in most cases interbedded with thin layers of very fossiliferous calcarenites. This type of environment correspond perfectly to the calcareous muds known from shallow water shelf and lagoons in warm water, i.a. from island in the Pacific, and especially from the Bahamas. This environment is characterized by chemical deposition of the calcerous mud (drewite), and by its very poor fauna, due to lack of nutrients. The calcarenitic beds are due to occasional periods with currents, resulting in erosion of the drewite, and supporting a rich bottom life. A typical feature of these calcarenite beds is that the lower surface is a sharp, erosional contact, and the upper one is gradational into the calcilutite.

"Calcilutites" from somewhat colder water, are seldom purely lutitic, they are mixed with calcarenites, often in small lenses and nests, which might have a considerable vertical extent. If they are deposited in colder water, they often have a considerable content of clastic clay.

The Position of the Poles during the Ordovician.

The limitation of the climatic zones (=faunal provinces) is not always quite clear, and might be subject to discussion, but the trend in their arrangement, from warm to cold is obvious. In Europe this is from N and NW to S, and in N. America it is from NW and W to E and S. This clearly indicates that the location of the poles and the equator was quite different in the Ordovician from their position at present. The fact that the so called "Arctic" Ordovician faunas were warm water ones has been pointed out by a large number of authors, the first was possibly HOLTEDAHL (1920), and strong faunal evidence has been given i.a. by FLOWER (1957 a.o.). The logical interpretation of this is that the equator passed over the present arctic, and the poles must therefore have shifted almost 90°.

The question of the stability of the poles, and of their movement has been thoroughly discussed, as though no general agreement has been reached. Some other evidence for shift of the poles is obtained from study of the Cretaceous climatic zones, which seem also to have been inclined obliquely to the present ones, and in the same direction as the Ordovician ones.

Salt deposits are generally supposed to form in the trade wind belts (15—25° N or S), at least on the northern hemisphere (LOTZE 1938 pp. 154—159, textfig. 78). The distribution of the salt deposits in the Mesozoic and Paleozoic seems to indicate a shift of the poles similar to that suggested here, even if the amount of movement is supposed to be less than 90° (LOTZE l.c.).

Some data regarding polar shifting come from paleomagnetic studies (cf. RUNCORN 1959).

Paleomagnetic research is in a very rapid development, and the constant reevaluation of important principles makes the uncritical use of all published data somewhat dangerous. There is, however a general agreement on the point that it is possible to determine the

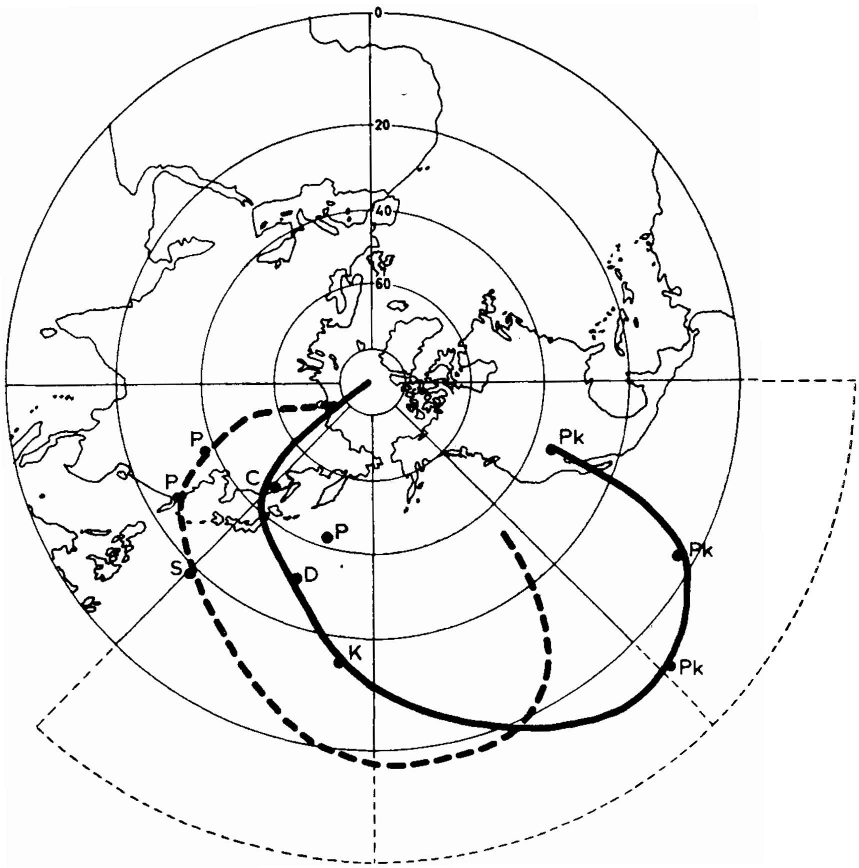


Fig. 4. The position of the magnetic north pole according to paleomagnetic data. Unbroken line indicate the path of the magnetic north pole based on observations in Europe, the broken line the path for North America. P = Permian, C = Carboniferous, D = Devonian, S = Silurian, K = Cambrian, Pk = Precambrian. Simplified from Runcorn 1959.

position of the magnetic poles of an earlier period in geologic history by studying the remnant magnetism of rocks from that period. It is also generally accepted that the poles have moved during geologic history, and most published data seem to indicate that the general movement of the magnetic north pole can be traced back, accross the Arctic Ocean, and southward to Korea or North China, where possibly it was located in the Permian and upper Carboniferous (RUNCORN 1959, cf. textfig. 4).

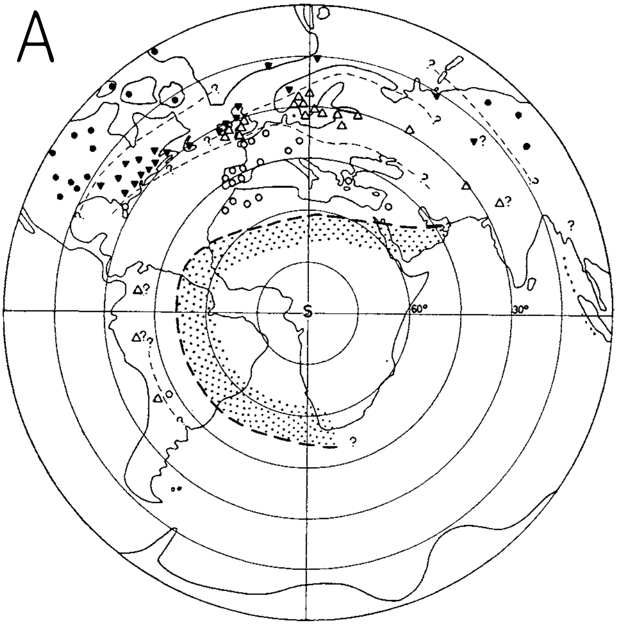
The data for older periods are very scanty, and not consistent in details. It seems however to be a trend in the same direction as in the later periods. An extrapolation would give the magnetic north pole not far from equator, possibly somewhat to the north of it, and at about 165° E. This estimate correlates well with the few, and admittedly inexact data for the Lower Paleozoic. The figures mentioned here are highly inaccurate, but it seems probable that the Ordovician magnetic north pole was from 0 to 25° N. of the present equator, and at between 150° E and 180° W.

The paleomagnetic determination of the magnetic poles is not a determination of the axis of rotation of the earth. At present the magnetic north pole is ab. 15° from the geographic pole, and there is no reason to believe that this distance was smaller in the Ordovician. It is, probable, however that the geographical pole in the Ordovician was also near equator, somewhere in the central Pacific.

The antipode of this pole would have been somewhere in, or W. of Africa, which corresponds surprisingly well with the picture obtained from the distribution of climatic zones, with warm water in the N. and NW. in Europe, being gradually colder towards S., and similar conditions in N. America. It might therefore be concluded that the paleomagnetic evidence does at least not contradict the arrangement of climatic zones suggested here.

The question of whether the movements of the poles indicate a movement of the whole mass of the earth, or whether such movement means that only the continents have moved in relation to the axis of rotation, is a problem which is outside the scope of this paper.

Continental drift also has to be mentioned in connection with the arrangement of the climatic zones. The climatic zones in Europe and North America do not fit well together with the present position of the continents, and a much better agreement is obtained if they are moved closer together. In the maps (textfigs. 5A—B) the two continental blocks on both sides of the Atlantic are moved about 40° closer, and this gives the best possible arrangment with the data available. This must not be regarded as any proof of continental drift, it is purely an empirical geometrical adjustment. There are too many variables in the reconstructions behind these maps to regard them as conclusive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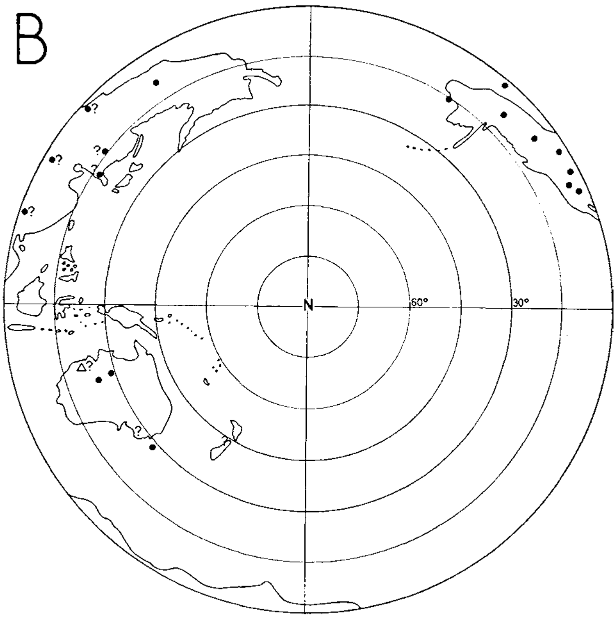
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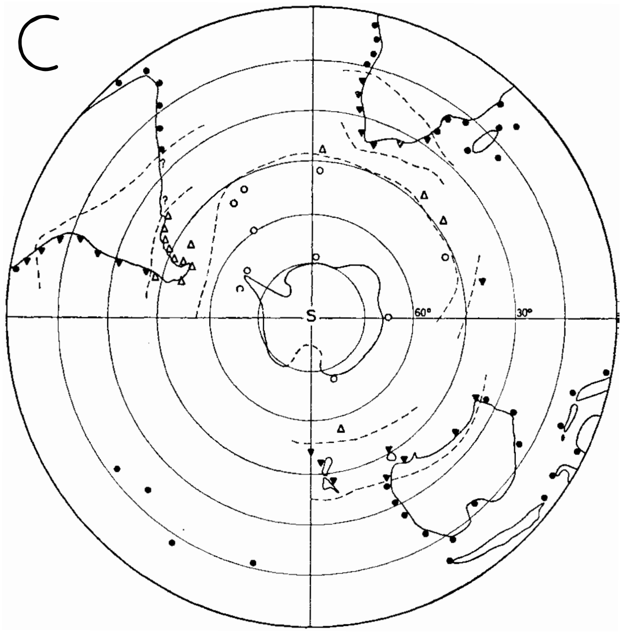

Fig. 5. A-B: Reconstruction of the climatic zones and geography of the Ordovician (Mainly Middle Ordovician) based on the distribution of the faunal provinces. C. The recent faunal provinces on the southern hemisphere, introduced for comparison. (Mainly after EKMAN 1953).
Filled circles = Tropical faunas, Filled triangles = Warm temperate faunas, Open triangles = Cold temperate faunas, Open circles = Antarctic and Arctic faunas.

evidence for any theory, exept that of climatic zoning. The pole might have been farther to the west, and the climatic zones are not strictly parallel to the latitudes, oceanic currents aie responsible for considerable discrepancies (cf. textfig. 5 C). Such discrepancies were certainly present in the Ordovician also. If all these sources of error are biased in the same directiou, the resulting inaccuracy might reach the same order of size as the supposed continental drift. The amount of continental drift, if present at all, can therefore not be determined from the data available.

It has also been suggested that India and Australia have drifted apart from Africa, but no evidence is found for that in the study of the climatic zoning. The Ordovician in India is along the edge of the old continental block, in the Himalaya and Burma, and it is not well enough known to give much information on the climate. However, it possibly belongs to neither the very cold nor the very warm areas.

Australia might have drifted from a position symmetrically on the other side of the Ordovician equator, that is about 60° nearer Africa, but no direct evidence is found for this drifting either.

It might be concluded that the arrangement of the climatic zones in the Ordovician gives no direct evidence for or against continental drift. It is possible that a more detailed study of the distribution of the faunal zones might give some evidence, especially the striking lithological resemblance between the rocks in Brittany-Normandy and in the subsurface of Florida and Alabama. Many studies have to be made, however, before any conclusions can be reached. The only positive thing that can be said about continental drift based on the evidence present in this paper is, that if continental drift has occurred since the Ordovician, it must have been in the direction generally supposed, away from Africa, and generally in an E-W direction. Considerable movements of the continents in other directions would not fit with the picture of the climatic zoning obtained here.

The number of common species and genera in the Ordovician on both sides of the Atlantic might give some evidence on the possible amount of continental drifting. In the recent Atlantic a sharp zoogeographical boundary is found at Cape Cod, at the NE-ern coast of U.S.A. North of this point, the arctic fauna is found with a higher percentage of genera and species which are also known on the other side of the Atlantic. South of Cape Cod there are comparatively few common genera and species in the boreal fauna. This is probably due to the short or almost nonexistant distance between the shelfs in the Arctic Basin and its surroundings, and the long distance between the shelfs across the Atlantic at the latitude of Cape Cod. Even if the situation is complicated by the system of oceanic currents, it might be interesting to compare the percentages. According to EKMAN (1953 p. 140) the percentage of common species in two animal groups (fishes and ascidians) are 50% and 88% N. of Cape Cod, and 8% and 9% S. of it. When these figures are compared with the number of common genera and species between the Appalacians and Scotland and Scandinavia in the Ordovician, it is evident that the figures at least in the best known groups of benthonic animals (trilobites and brachiopods) are much nearer to those of the arctic than to the boreal faunas. This seems to indicate that the distance between the continental shelves of Europe and North America was considerably smaller in the Ordovician than it is now. It must be mentioned, however, that it might not be justified to compare the precentages between the recent and fossil genera and species, because they are probably not biologically equivalent. Further, and more detailed studies along these lines might give more exact data to evaluate the presence and amount of continental drift.

An interesting feature seen from the maps (textfig. 5A—C), is that the Ordovician climatic zones do not seem too much distrupted by later orogenies. In Europe, the climatic zones are cut at low angle by three mountainchains, the Caledonian, the Hercynian, and the Alpine, and the total compression seems to be smaller than the displacements which can be ascribed to oceanic currents.

The figure given for the shortening of the upper crust by the formation of mountain chains are highly variable. The highest for the Alpine folding are several thousand kilometres. Judging from the position of the Ordovician climatic zones, these figures must be vastly exaggerated. The right figure is probably a few hundreds of kilometeres.

Variation in Climate during the Ordovician.

The climate was probably not stable through the whole Ordovician, climatic changes were numerous and important. In fact, the exact limitation of the climatic zones is made difficult by their change with time.

If the temperature increases, the warm water faunas will migrate towards the poles, and a parallel migration will be found in the intermediate faunas. When the climate becomes colder, the reverse migrations will take place, the cold, and intermediate faunas will migrate towards equator, (cf. textfig. 6).

Judging from the migrations of the N. European marine lamellibranch fauna in post-glacial times, the movements of the faunas are wide, and take place very fast, geologically speaking. The *Tapes*-fauna, indicating the post-glacial climatic optimum in Scandinavia, migrated more than 1000 km towards the north pole, and back in less than 3000 years. It is suggested that most observed faunal migrations in the Ordovician are due to such climatic changes.

Since these changes are contemporaneous over at least one hemisphere, they are of high potential value for long distance correlations. At present, it is difficult to identify the specific climatic changes in all areas, due to lack of detailed studies.

The sharp climatic zoning found both in the Ordovician and at present, is possibly due to the presence of polar ice-caps. That has been indicated i.a. by EWING & DONN (1956, 1958). If no polar ice-caps were present, the oceanic current system would have been considerably different, large part of the oceans might have been stagnant, and the earth as a whole would have a much more uniform climate, with no sharp zoning. Such periods are possibly the Devonian (including parts of the Silurian), the Jurassic, and the Cretaceous. These are all periods with a rather warm, and uniform climate.

The periods with sharp climatic zoning coincides generally with the periods of glaciation, such as the Eocambrian, the Permo-Carboniferous and the Pleistocene-Recent. These periods of glaciation are also accompanied by maximal orogenic activity, in the two last cases mentioned by the Hercynic and Alpine orogenic system. The Caledonian orogenic system which had its most active phases in the Ordovician is exceptional, in being not accompanied by a regional glaciation. This might partly be due to the long duration of that orogenic system, from the base of the Ordovician to the Middle or Upper Devonian. The Ordovician climate was probably just as cold as in the other periods, in which glaciations are found, but the meteorological conditions were probably different, and high mountains near the ocean coasts, necessary for the accumulation of a continental ice-

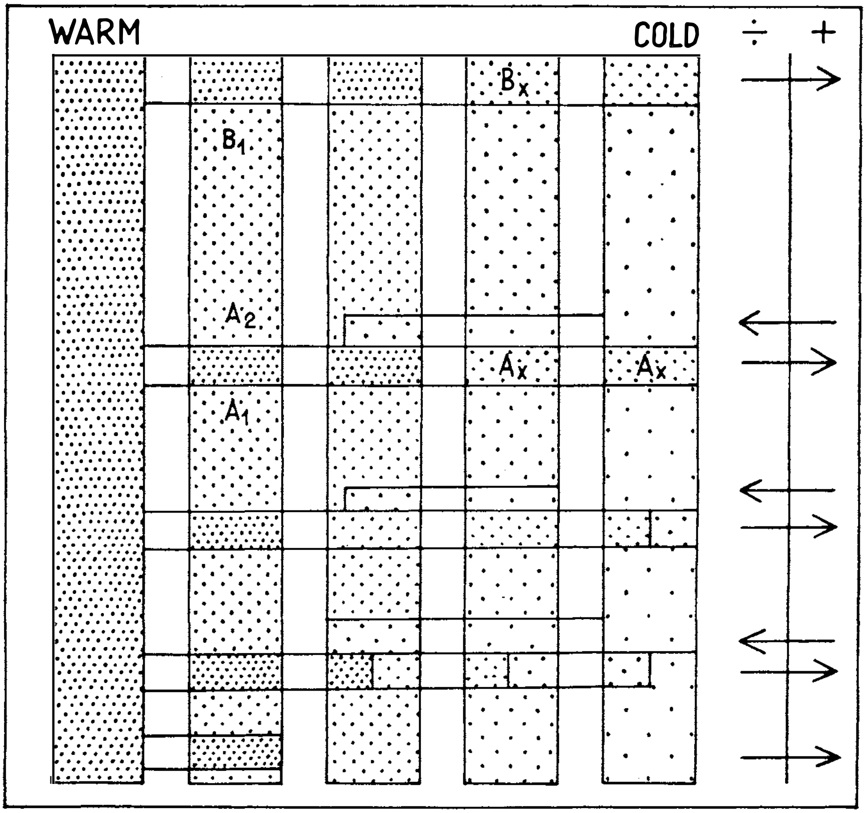

Fig. 6. Diagram showing the faunal sequence in a number of hypotetical sections due to faunal migrations induced by climatic changes. Denser punctation indicate warmer faunas. The migration of warm faunas into "cold" areas and vice versa due to change in climate is illustrated. Faunas like Ax are not strictly contemporaneous with the highly similar A^1 or A^2, they should be correlated with the "warm" fauna between the two latter. In this way the climatic changes might be used for long distance correlations.

cover, were probably not present. This will explain both the absence of a glaciation in connection with the Caledonian foldings, and the presence of sharp climatic zoning in the Ordovician.

The presence of polar ice-caps has a great stratigraphic importance. The climatic changes will increase and decrease the volume of water bound in the ice-caps, and that would lead to transgressions in warm periods, when the ice-caps are reduced, and to regressions in cold periods, when more water is bound in the ice-caps. This climatic dependence of the transgressions and the regressions is especially well illustrated by the changes in sea level known in connection with the last glaciation. There are certainly other causes for changes in sea level, but with the widespread occurence of shallow continental shelves known from the Ordovician, the climatically induced ones must have been very important.

As a conclusion, the author will attempt to give a brief outline of the climatic development during the Ordovician (diagramatic in textfig. 7).

The climatic conditions in the lower and middle Lower Ordovician are not well known, but seem to be warm to intermediate. The upper part of the Lower Ordovician was very warm, the "warm-water" faunas had a wide distribution (Canadian in N. America, *Orthoceras* Limestone in N. Europe). The beds are also transgressive in several areas, such as S. Norway, Portugal and N. Africa.

The lower part of the Middle Ordovician is marked by cold water, a very abrupt change from the preceding stage. In Europe the beds are regressive only locally, but in N. America, the largest Ordovician regressions is found at this time, and the beds, (Whiterock Stage) which are found only along the margins of the continental mass, in Newfoundland, Oklahoma and parts of Utah and Nevada, indicate somewhat colder conditions than in the beds below.

In the Llandeilo, and the Caradoc, the temperature seem to have increased slowly and regularly, except for some fluctuations about the time of the *Climacograptus peltifer*-zone (a slight maximum, and later a slight minimum). An important temperature maximum is found in the upper part of the Middle Ordovician, in the zone of *Dicranograptus clingani*. The beds are locally transgressive, especially in S. Europe and in N. Europe there are a number of limestones with an american fauna (mainly Appalachian, but also some "Arctic" faunas). The Vasalemma in Esthonia, Kullsberg in Sweden, Encrinite, Mjøsa and Kalstad in Norway, Craighead in Scotland, Keisly in England are the typical representatives. In S. Europe there was an invasion of the fauna which previously lived in N. Europe, dominated by bryozoans, cystids and brachiopods. At this level the only limestone horizon occur in this otherwise purely cold-water province.

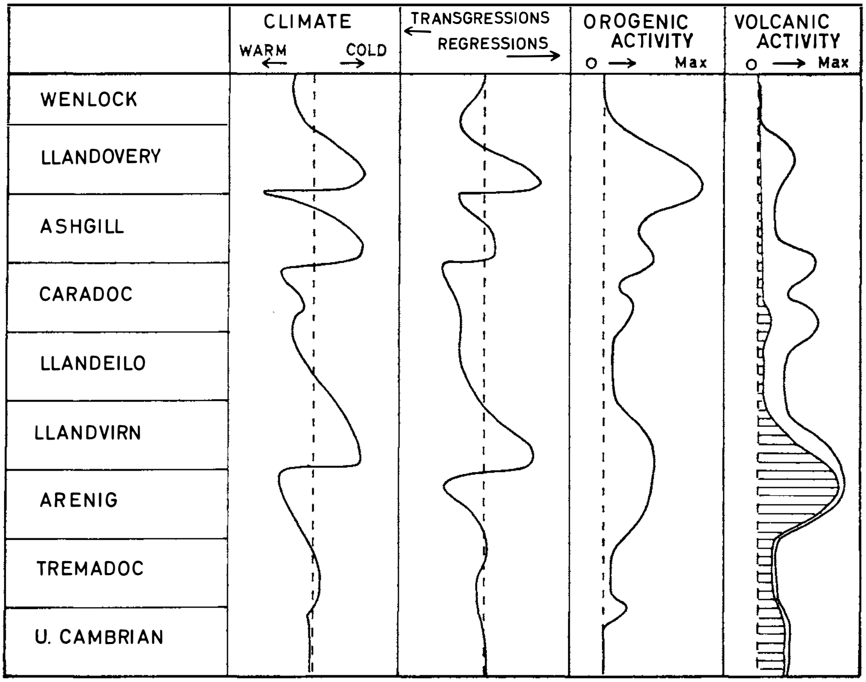

Fig. 7. Diagram illustrating the correlations between climate, transgressions and regressions, orogenic activity and volcanic activity in the Ordovician and parts of the Cambrian and Silurian.
The data for climate, transgression and regressions from the whole world, those for orogenic activity and volcanic activity are mainly from Europe.The shaded part of the column for volcanic activity indicate approximately the fraction of basaltic volcanic activity. The strength of the orogenic activity is indicated by the degree and distribution of metamorphism, and the distribution of distinct angular disconformities. The strength of the volcanic activity is taken as the approximate volume of extruded lavas and tuffs.

The maximum is abruptly followed by a minimum in the zone of *Pleurograptus linaris*. Return of "colder" faunas, and widespread regressions, especially in Europe, and in Eastern and Western N. America marks this stage.

During the Ashgillian, the temperature seems to have risen gradually, until it reached a new maximum in the uppermost Ordovician. In N. Europe this stage is defined by limestones with coral-reefs, and faunal elements from the "Arctic" (= Red River) province, especially among the cephalopods. The Porkuni of Esthonia, the Boda and Slätdal of Sweden, the 5b ot Norway are typical examples. In North America the climatic changes are less sharp than in Europe, but it is possible that the recurrent faunas represent climatic changes, so that the comparatively cold Maysvillian represent the temperature minimum in the low Upper Ordovician, and the warmer Eden and Richmond represent the maxima. This has already been suggested by ULRICH (1910), who refered to these faunas as "austral" and "boreal". (cf. SWEET, TURCO, WARNER & WILKIE 1959).

The maximum in the uppermost Ordovician is followed by a sharp minimum with widespread regressions in the basal Silurian. Then came a gradual increase through the Middle and Upper Llandovery, accompanied by a great, worldwide transgression.

A distinct, but crude correlation is also found between the orogenic periods, periods of volcanism and the climatic changes. The first major orogenic period in the Ordovician ranges through Arenig and Llandvirn, and is accompanied by strong basaltic volcanism in the Arenig, and more local, mainly andestitic volcanism in the Llandvirn. This corresponds well with the climatic changes at the Arenig-Llandvirn border. A slight disturbance is found in the lower Caradoc, accompanied by considerable andesitic volcanism. The next major orogenic maximum is found in the Upper Caradoc and lower Ashgill. (Ekne phase of VOGT (1945), probably the same as the Sardic and Pallaresic ones, and movements in eastern N. America). This orogenic maximum is accompanied by considerable, mainly rhyolitic volcanism, and correspond to the climatic change between the *Dicranograptus clingani* and *Pleurograptus linearis* zones. The border between the Ordovician and the Silurian is marked by an orogenic maximum, ranging from the Middle Ashgill to the Upper Llandovery. It corresponds to the climatic change on the Ordovician-Silurian boundary.

The following empirical conclusions might be drawn from the data presented above:

1) The increase in temperature seems to be a slow process, whereas the decreases are much more rapid.

2) A definite correlation is found between the major transgression and regressions, and the climatic changes. The regressions seem to

follow immediately after the decrease in temperature, but the transgressions come sometime in the long interval of temperature increase.

3) A distinct correlation is found between the orogenic maxima and the temperature changes. The maximal temperature is generally reached after the orogenic period had started, and the orogeny continues after the temperature change. The climatic changes are therefore supposed to be better time-indicators than the orogenies.

4) The correlation between the volcanic activity and the climatic changes is very crude, and possibly a secondary feature, due to the correlation of volcanism with the orogenies. There is no quantitative correlation between the volcanic activity and the climatic changes, and the maximum of volcanism during an orogenic maximum might come before, after, or be contemporaneous with the climatic change.

As mentioned above, these conclusions are purely empirical, and can at present only be used for the Ordovician, because they are based on a small number (3—4) of correlated cycles.

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