# Ordovician reefs and climate: a review

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Ordovician reefs have a relatively restricted distribution within carbonate depositional belts of the world. Most may be inferred to have formed in warm waters of the tropical-subtropical belts, like the associated bahamitic sediments. Early Ordovician reefs have a restricted distribution and mainly comprise undifferentiated algal- or sponge-dominated mounds of small size. The largest have a rigid organic framework in their upper parts and are true patch reefs. Middle Ordovician reefs have a much broader geographical distribution, a wider range of morphological differentiation (on-shelf patch reefs, shelf-edge reef complexes and on-shelf and down-slope carbonate mud mounds), and some attain barrier-reef dimensions. A much greater variety of frame-building organisms are represented including stromatoporoids, corals and bryozoans. Late Ordovician reefs are similarly widely distributed but not as large. They include restricted marine algaldominated "pinnacle" reefs associated with evaporites, normal marine stromatoporoid-coral patch reefs and carbonate mud mounds. Of the two phases of warming suggested by reef occurrences in Baltoscandia, the first in the late Caradoc probably results from a short-lived maximum expansion of the tropical-subtropical belts with accompanying reduction in the latitudinal temperature gradient. The second in the late Ashgill coincides with the period of major glaciation. An associated increased latitudinal gradient is suggested by representatives of the cool (possible deeper) Hirnantia fauna occurring in relatively close proximity to reefs both in North Europe and North America. Reefs continued to grow at the height of the glaciation but apparently in much narrower tropicalsubtropical belts.

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A wide variety of reef and reef-like structures have been reported from Ordovician carbonate successions of North America, Europe, Asia and Australia (Fig. 1). Best documented are those in North America and Baltoscandia. The range of morphologies includes carbonate mud mounds, patch reefs and reef complexes. These structures are mainly of small size and usually lack the sort of clear-cut differentiation into fore-reef, reef-core and back-reef facies seen in some Middle Palaeozoic, and most modern, reefs. However, the Ordovician reefs still show a remarkable degree of variation in form and organic composition.

A most dramatic evolutionary development of the reef ecosystem occurred during the Ordovician, with successional changes from algalsponge dominated assemblages in the Early Ordovician to bryozoan dominated and stromatoporoid-coral dominated associations in the Middle Ordovician. Both these latter associations apparently co-existed for a time but then the stromatoporoid-coral assemblages seem to have taken over as the main frame-builders in the late Middle and Late Ordovician (Newell, 1971; Heckel, 1974; Copper, 1974).

Secondly, in the organically more complex patch reefs (or bioherms), Walker & Alberstadt (1975) have demonstrated the presence of vertical ecological changes from stabilization to colonization, then to diversification and finally to domination stages as the structure grew upward into the surf zone. James (1979) argues that carbonate mounds in the sense that they only exhibit stabilization and colonization stages may be viewed as "half-reefs", and presumably they did not grow into the zone of turbulence. He classified the reefs of the Early Ordovician as entirely carbonate mud mounds, while those of the Middle-Late Ordovician included

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Fig. 1. Map showing worldwide distribution of Ordovician reefs. Note also probable position of Ordovician south pole in Africa and equator (E-E) for North America.

both mud mounds and patch reefs.

The term "reef" is here used in a broad sense to include all sorts of carbonate buildups with topographic relief, irrespective of their internal composition. This includes various types of carbonate mounds, ranging from the "halfreefs" of James (1979) to the stromatactisbearing mounds of Jaanusson (1979a; 1982). Some lack a preserved "rigid organic framework" perhaps because they were formed by non-calcareous mud-trapping organisms such as some algae and sea grass, or their small areas of framework were destroyed by physical or biological processes prior to burial (Longman 1981). Others, like the stromatactis-bearing mounds, appear to lack any trace of organic control, and may have been formed by a process of early lithification converting loose sediments into hard rigid structures as in modern lithoherms (Neuman et al. 1977). But since only a few stromatactis-bearing Ordovician occurrences of this latter type, for example in the probable late Arenig of Nevada (Ross et al. 1975; 1982) and in the late Caradoc Kullsberg and Ashgill Boda mounds of Sweden (Jaanusson 1979 a; 1982), have so far been differentiated from carbonate mounds of more strictly organic origin, and they usually occur at times and in regions where organically constructed buildups are also well developed, there seems little justification for excluding them from this survey of Ordovician reefs.

For convenience I have used a tripartite division of the Ordovician including Tremadoc and Arenig in the early Ordovician, Llanvirn, Llandeilo and Caradoc (to the top of *Dicranograptus clingani* Zone) as Middle Ordovician, and the topmost Caradoc and the Ashgill as Late Ordovician.

#### Early Ordovician reefs

The world-wide distribution is confined to the North America and to Siberia (Figs. 1-2). In the western United States reefs are recorded as having formed in shallow, normal marine waters of gently shelving platforms to the north and south of the Transcontinental Arch (Ross 1976; 1977). To the north, the oldest in the House Limestone of western Utah (Rigby 1966) are of Tremadoc age. They are predominantly algal with sponges only a minor consistent. Others from Arenig horizons (Fillmore and Wahwah Formations) have sponges and the receptaculitid Calathium as dominant consistuents (Rigby 1966; 1971; Church 1974). There are also large stromatactis-bearing carbonate mud mounds of probable late Arenig age in Nevada (Ross 1972; Ross *et al.* 1975; 1982). The largest, though up to 76 m high and about 300 m across, have no organic frame.

South of the Transcontinental Arch, Toomey & Ham (1967), Toomey (1970) and Toomey & Nitecki (1979) have described late Canadian (early-mid Arenig) mounds in the McKelligton Canyon Formation of Western Texas and the Kindblade Formation of southern Oklahoma. They are typically small domical structures, but much larger mounds also occur, up to 20 m high and 87 m across. The largest has stabilization and colonization stages with cystoids, sponges (Archaeoscyphia), Calathium, brachiopods and trilobites; a diversification stage including digitate stromatolites, Girvanella, Nuia, Archaeoscyphia, Calathium, cystoids, the problematical stromatoporoid-like *Pulchrilamina* and various shelly fossils; and a domination stage with frame-building *Pulchrilamina*. Despite the predominant lime mud content (60-75% by volume) these larger mounds are strictly patch reefs since their upper parts include a rigid organic framework of *Pulchrilamina* allowing them to grow up into the surf zone.

Early Ordovician algal-sponge buildups have also been recorded from western Canada (Rigby 1965) and Newfoundland (Stevens & James 1976), and algal buildups from the Moiero River section, Siberian Platform (Miagkova *et al.* 1977). The Newfoundland structures have been documented recently by Pratt & James (1982) as algal (thrombolite)-dominated buildups, with associated corals (*Lichenaria*) in the earliest Ordovician (Tremadoc), and rare sponges and *Pul*-



Fig. 2 – Diagrammatic representation showing regional and tectono-environmental distribution of main types of reefs through Ordovician time. Note that the numbers in brackets refer to the maximum heights of reefs in metres. Also note different representation of Early Ordovician Texan and Oklahoman sponge reefs which have stromatoporoid-like upper parts, and Late Ordovician algal pinnacle reefs from Melville Peninsula which exhibit abundant corals in upper parts. In Newfoundland earliest corals (Lichenaria) appear in algal mounds (A), and earliest stromatoporoid-like organisms (Pulchrilamina) in sponge-algal mounds (B).

chrilamina in the succeeding Arenig, occurrences (Fig. 2).

# Middle Ordovician reefs

These have a much wider distribution in North America, Baltoscandia, Siberia, Kazakhstan and New South Wales. They also exhibit morphological differentiation into a number of types (on-shelf and down-slope carbonate mud mounds, on-shelf patch reefs and shelf-edge reef complexes).

The record in the pre-Chazyan (early Llanvirn) is limited to occurrences of small, 3 m high algal-sponge patch reefs in the Table Point Formation of western Newfoundland (Klappa *et al.* 1980, Klappa & James 1980).

In the Chazyan (late Llanvirn-Llandeilo), however, there was a dramatic appearance of more complex reef communities (Pitcher 1964; 1971; Newell 1971; Copper 1974; Heckel 1974). For the first time in the geological record a number of different groups of massive skeletal organisms began to contribute significantly as frame builders and binders in the growth of reefs. In the lower part of the Chazy Group (Day Point Formation) of New York and Vermont, the reefs are relatively small, apparently lacking any vertical zonation and dominated by bryozoans. Kapp (1975) has argued that these reefs formed in slightly deeper water (at wave base or below) than those of the succeeding Crown Point Formation. The Crown Point reefs are much larger, and some exhibit vertical growth stages – stabilization at the base with pelmatozoan debris, colonization by stromatoporoids and bryozoans, diversification by various groups including corals, stromatoporoids, bryozoans, algae and sponges, and domination at the top by frame-building stromatoporoids (Alberstadt et al. 1974). The reefs contain a lime mud matrix (up to 60% by volume) and those dominantly composed of stromatoporoids grew up into shallow waters above wave base. Bryozoan mounds have also been recorded from the Chazy Group of Quebec (Hofmann 1963; Kobluk 1981).

While the Chazy Group reefs are taken to represent on-shelf accumulations, the much larger, and slightly younger (latest Llandeilo – eraly Caradoc) Holston mass of east Tennessee (southern Appalachians) is regarded by Walker

& Ferrigno (1973) as having formed in a shelfedge location. It is composed of interconnected reef core and flank deposits, and in being up to 100 m high and at least 40 km long assumes barrier-reef proportions. The reef tract is overwhelmingly dominated by bryozoans, with up to 19 different, predominantly encrusting types in the core, and mainly ramose types in the flanks. The absence of algae has suggested to Walker (1977) that it formed at moderate depth, and recently this has been confirmed Ruppel & Walker 1982; Stock & Benson 1982). Thus a deeper water origin may help to explain the absence of stromatoporoids and account for the difficulties of Alberstadt et al. (1974) in defining the vertical growth stages of the Holston mass.

To the north, in Virginia, there are even larger carbonate masses (Read 1982), up to 250 m high and 60 km in length. Apparently they formed during a period of continuing rise in sea level (or subsidence). The main types of accumulation include shelf edge (shallow ramp) and down-slope buildups, both with associated core and flank deposits. Usually the core of the shelf-edge buildups exhibit more encrusting bryozoans, algae and sponges. The core of the down-slope buildups has more ramose bryozoans. Algae are present in the down-slope mounds suggesting that they grew up into the photic zone, although they are surrounded by deeper-water deposits. Stromatactis is common especially in the down-slope buildups.

Other small patch reefs are recorded from the Blackriveran (early Caradoc) Lourdes Limestone of western Newfoundland (Fåhraeus 1973; Bergström *et al.* 1974; Copeland & Bolton 1977; James 1979). The reefs are dominantly built by the coral *Labyrinthites*. In the Rocklandian (middle Caradoc) Carters Limestone stromatoporoid-coral patch reefs were developed in shallow on-shelf sites of the Central Basin, Tennessee (Walker & Alberstadt 1975). The reefs are most similar to Chazy reefs in having frame-building stromatoporoids and corals and exhibiting a fourfold vertical growth succession.

In Baltoscandia, Middle Ordovician reefs have been recorded from Norway, Sweden and Estonia. Harland (1981) has described relatively small on-shelf coral-stromatoporoid patch reefs and a larger shelf-edge reef complex in late

Caradoc successions of the Oslo region. The shelf-edge reef complex is a composite of a number of separate reefs, the largest being 15 m high and 50 m wide. This larger reef mass exhibits a crude lateral zonation with massive, close-packed domical stromatoporoids and talus on the "offshore" side more loosely packed laminar to domical stromatoporoids in the middle, and more diverse assemblages of corals, algae and ramose bryozoans on the "in-shore" side. Mounds with an organic fame also occur in the Vasalemma Limestone (Oandu stage) of north-west Estonia (Röömusoks 1980; Jaanusson 1979 a). Both Norwegian and Estonian buildups have associated bahamitic sediments (Jaanusson 1973).

More-or-less contemporaneous stromatactisbearing carbonate mud mounds occur in the Kullsberg Limestone of Sweden (Thorslund & Jaanusson 1960; Jaanusson 1982). Reef cores are 40-50 m high and 300-350 m wide, and the shelly faunas and algae occur in nests or lens-shaped pockets. The mounds which lack an organic frame seem to have formed in on-shelf sites.

Nestor (1977) and Miagkova *et al.* (1977) noted occurrence of a small reef with stromatoporoids and algae in the Krivoluk Stage (earlymiddle Caradoc) of the Moiero River, Siberian Platform. Also much more extensive developments of reefs occur in the middle-late Caradoc of northern Kazakhstan (Vinogradov 1968; Nikitin 1973).

Australian occurrences are restricted to the small coral-stromatoporoid patch reefs of the Fossil Hill Limestone, central New South Wales (Webby & Packham 1982). The reefs, of probable early Caradoc age, are dominantly composed of the coral *Tetradium*.

### Late Ordovician reefs

North American successions of Edenian and Maysvillian (latest Caradoc – early Ashgill) age seem to be devoid of reefal structures. Carbonates (Red River Formation and equivalents) are well developed in the western Midcontinent but no reefs have been reported.

In the succeeding Richmondian (middle Ashgill), however, there is a remarkable development of pinnacle reefs on the Melville Peninsula of Arctic Canada. Each reef rises up

to 30 m above the surrounding interreefal deposits and is 0.8 km or more in diameter. Reef cores are described by B. V. Sanford (1977) as primarily composed of an "algal and stromatolitic limestone framework". The reefs are believed to have been linked by an open seaway to the north-east, explaining the presence of corals and other organisms. But to the south, on the margins of the Hudson Bay Basin, only reefs formed in more restricted conditions (B. V. Sanford 1977). Evaporites formed in the centre of the Hudson Bay Basin. Late Ordovician "algal buildups" shown by Ross (1976) at the margins of the Williston Basin in Montana and North Dakota are similarly flanked by basin-centre evaporites.

On Anticosti Island coral-stromatoporoid dominated patch reefs occur in late Richmondian-Gamachian horizons of the Vaureal and Ellis Bay Formations (Petryk, 1981 a). The Vaureal buildups in the upper part of Member 4 are not well documented. In the succeeding Ellis Bay Formation however one isolated reef occurs in Member 4 (Copeland & Bolton 1975; Bolton 1981), and a more significant development is recorded in what was originally the basal part of Bolton's (1972) Member 6, now Petryk's (1981 a) Member 7. The reefs of Member 7 are up to 8 m high and 100 m across and contain a variety of frame-builders and encrusters but especially corals and stromatoporoids (Copeland & Bolton 1975; Bolton 1981).

Reef development also occurred in the latest Ordovician of northern Europe. Small patch reefs dominated by corals and stromatoporoids occur in the 5b-limestones of the Oslo region (Hanken & Owen 1982), and in the Porkuni stage of Estonia (Jaanusson 1979 a). The sediments associated with these "organic reefs" are of bahamitic type (Jaanusson 1972). In the Swedish Boda Limestone there are much larger stromatactis-bearing carbonate mud mounds, 100-140 m high and up to 1 km across (Jaanusson 1982). They appear to lack any sort of organic frame. Similar reef-like bodies of limestone are represented in the Keisley Limestone of northern England (Ingham & Wright 1972), in the Chair of Kildare Limestone of Ireland (Wright 1968), the Pirgu stage of Estonia (Männil 1966) and the 5a-limestones of Norway (Brenchley & Newall 1980). Elongate, mound-like, massive limestone bodies

with a fauna of bryozoans and pelmatozoans have also been reported by Hafenrichter (1980) from the early-middle Ashgill of Spain, but may represent erosional remnants of more continuously bedded sequences rather than true reefs.

In the Asian part of the Soviet Union, Late Ordovician "reef massifs" have been recorded from the Kolyma River, and small single reefs, from various localities in northern Kazakhstan and the Siberian Platform (Vinogradov, 1968).

## Climatic significance

Spjeldnæs (1961) first recognized the marked temperature fluctuations of the Ordovician Period, and predicted polar ice caps prior to Late Ordovician glacial deposits being found in the Sahara (Beuf et al. 1971). He recognized major phases of cooling, the first in the early Llanvirn and the second in the early Ashgill (Fig. 3A). The polar ice cap in North Africa is now thought by Spjeldnæs (1981) to have existed continuously from Arenig to latest Ordovician time, expanding greatly in one or more episodes, even into low latitudes, at the end of the Ordovician. The effect of its continued existence was to markedly increase the climatic zonation (i.e., latitudinal temperature gradient) so that Ordovician climate (with the possible exception of the Tremadoc which was climatically similar to the Late Cambrian) was more like that of the present than that of the Cambrian or Silurian. With such a marked latitudinal gradient, the extremes of climate, i.e. at the pole and the equator, could be easily and reliably identified. Accordingly, the "bioherm/ bahamite, warm water facies" could be regarded as a good starting point for regional analysis of the equatorial zone (Spjeldnæs 1976). However identification is not so easy because of the relatively limited number of preserved Ordovician reefs, and their tendency to exhibit a very wide range of morphological and evolutionary diversification, of apparently differing climatic significance.

Secondly there are no direct means of establishing the geographic limits of Ordovician reef growth, other than by comparing the distribution with palaeomagnetically-determined latitudes. The likely limits of coral-stromatoporoid reef growth relative to the pole within a

single lithospheric plate can be obtained in (Middle Palaeozoic) successions. vounger Middle Devonian reefs in north-west Africa (Dumestre & Illing 1967) are about 55° of latitude away from the position of the south pole, as determined palaeomagnetically and by the distribution of elements of the "cool water" Malvinokaffric Province (Oliver 1976; Heckel & Witzke 1979; Boucot & Gray 1979) in southern Africa. This suggests that these particular reefs flourished about 35° south of the equator. In their reconstructions of the Devonian world Heckel & Witzke (1976) have shown the reef and stromatoporoid distribution restricted to the warm climatic belt between 35° N and 40° S.

Of the various types of buildups stromatoporoid-coral reefs of the Middle-Late Ordovician may similarly have been useful indicators of deposition in warm climatic tropical-subtropical belts, especially where they are associated with bahamitic sediments. Counterparts in the Early Ordovician may have been the sponge-dominated reefs. Algal buildups seem also to suggest warm conditions of low latitudes particularly where associated with evaporites. Middle-Late Ordovician bryozoan reefal complexes appear to have had a wider climate range. The Holston and Day Point reefs of the Appalachians apparently grew in relatively deeper waters (Kapp 1975; Walker 1977; Ruppel & Walker 1982; Stock & Benson 1982), but in similar low latitudes to the stromatoporoid-coral buildups. In contrast the Spanish bryozoan mounds may have formed in higher latitudes but do not seem to be true reefs. There is the record of a near-polar bryozoandominated biostrome in the late Caradoc of the Anti-Atlas mountains in Morocco (Destombes 1971).

The climatic significance of on-shelf and down-slope carbonate and mounds is less certain. Apparently, the late Caradoc Kullsberg mounds of Sweden are not associated with "warm water" bahamitic sediments (Jaanusson 1973), and the late Ashgill mound complex in Ireland has intercalated mudstones towards its top containing the "cool water" *Hirnantia* fauna (Wright 1968). The carbonate mounds may have had a slightly wider latitudinal spread than the stromatoporoid (or stromatoporoid-like) dominated buildups, but they mainly occur at times and in regions where such reefs are also well developed (Fig. 2).

Apart from the buildups in Newfoundland (Pratt & James 1982) and Utah (Rigby 1966) there is very little evidence of reef development in the Tremadoc, even though algae, sponges and earliest corals (*Lichenaria*) were available to contribute to buildups. Possibly this reflects a period of relatively less favourable (possibly cooler) climatic conditions in the equatorial zone. However by Arenig times conditions in the equatorial zone had become far more favourable to reef growth with the rise of frame-builders like *Pulchrilamina* and the development of ecologically zoned patch reefs of comparatively large size. This would seem to be consistent with the suggestion by Spjeldnæs (1961) of a temperature rise through the Arenig (Fig. 3A).

The only reefs recorded during a period of



Fig. 3. Diagram showing Ordovician climatic curves for world (A) and North Europe (B) after Spjeldnæs (1961; 1978), the temporal distribution of reefs in North America (circles) and North Europe (crosses), inferred latitudinal positions of North American and North European plates with movement of North European plate into low latitudes (see Fig. 4), and the superimposed warming and cooling event, based in part on the occurrences of reefs. Circled numbers depict periods in the Ordovician when the following events occurred: 1-2, advent of main frame-bulding assemblages (1, bryozoans; 2, stromatoporoids and corals); 3, warming and reduced climatic zonation; and 4, intense polar glaciation and increased climatic zonation.

major early Llanvirn regression and cooling (Spjeldnæs 1961; see Fig. 3) are the small patch reefs in Newfoundland. These occurrences all seem to have formed in a position near the palaeomagnetically inferred equator (Ross 1976).

Significantly, the complex Middle Ordovician reef communities of bryozoans, corals and stromatoporoids made their appearances in the warming phase immediately following the major early Llanvirn cooling event (Spjeldnæs 1961). From this time onwards a wide variety of frame-building organisms particularly stromatoporoids and corals were available to contribute to the growth of reefs.

Some of the palaeomagnetically-based Ordworld map reconstructions show ovician northern Europe (including Baltoscandia) in low latitudes (Smith et al. 1973; Zonenshayn & Gorodnitzkiy 1977; Morel & Irving 1978; Kanasewich et al. 1978), while others place it in the middle-high latitudes (Noltimier & Bergström 1976; Bergström 1977; Ziegler et al. 1977; 1979; Scotese et al. 1979). The development of Baltoscandian late Caradoc reefs, with the accompanying bahamitic sedimentation and temporary invasion of new faunal elements in the Oslo region and Estonia is explained by Jaanusson (1973; 1979b) as due to a short-lived marked increase in temperature. If the North European plate had occupied a middle-high latitude position in the Middle Ordovician (see Llandeilo-earliest Caradoc reconstructions of Ziegler et al. 1977; 1979; and Scotese et al. 1979) then an abnormally high rise in temperature and concomittant expansion of the tropical-subtropical belts would have been required. The more likely alternative would involve the North European plate having already moved from high to middle-low latitudes by late Caradoc times (Figs. 3-4). This move also coincided with the narrowing of the Iapetus Ocean (Spjeldnæs 1978; Webby 1980). Northward movement of the North European plate towards the equator may be assumed to have been at a relatively uniform rate, with the temperate to warm (subtropical-tropical) to temperate climatic changes indicated by Jaanusson (1973) for the middle Caradoc-middle Ashgill interval superimposed on it (Fig. 3). The warming event, if it took place while the North European plate was still in middle-low lati-



Fig. 4. Map reconstruction showing inferred northward drift of North European plate and closing of the Iapetus Ocean during Ordovician time.

tudes, records a period of maximum expansion of the tropical-subtropical belts, and reduced climatic zonation (Fig. 3).

The lack of reefs in contemporaneous North American successions is less easily explained, though it may be in part due to glacioeustatic rise in sea level which accompanied the warming. Certainly there was a period of widespread flooding and deposition of graptolitic shales in the eastern Midcontinent (J. T. Sanford 1978; Copper 1978).

By middle-late Ashgill time the North European plate have moved into low latitudes, and reef growth was again flourishing but this time while there was an increasingly intense continental glaciation developing in North Africa (Beuf et al. 1971; Spjeldnæs 1981). There was also contemporaneous reef formation in North America including major algal buildups on the flanks of evaporite basins in the continental interior. This seems to have been a period of heightened climatic zonation for while "warmwater" bahamitic sediments were associated with the Oslo and Estonian coral-stromatoporoid patch reefs and the large Swedish Boda carbonate mounds, these latter were forming contemporaneously with a slightly deeper water facies containing the "cool" Hirnantia fauna

(Sheehan 1979). The *Hirnantia* fauna is seemingly even more closely associated with the carbonate mounds in Ireland and northern England (Wright 1968; Ingham & Wright 1972).

Brenchley & Newall (1980) have argued that at the end of the Ordovician a dramatic lowering of sea level occurred and this seems to be related to the major expansion of the polar ice caps. They have interpreted both the Stage 5b patch reefs of the Oslo region and the Boda mounds as developing a karst topography after becoming emergent during the major regressional phase. There was substantial erosion of previously deposited facies in the Oslo region (Størmer 1967; Brenchley & Newall 1980).

No such erosional break is reported from the latest Ordovician-earliest Silurian succession on Anticosti Island. Petryk (1981 b) has interpreted glacioeustatic changes of sea level as responsible for the regressional/transgressional cycles of deposition in the upper Vaureal and Ellis Bay Formations, with the reefal horizons being inferred to have formed in the shallower, regressive phases. The extensive development of reefs in the Member 7 bioherms of the Ellis Bay Formation formed during the last and perhaps the most significant regressional phase marking the end of the Ordovician Period. The regressional phase and period of formation of the Member 7 reefs probably coincides with the maximum of glaciation and expansion of polar ice caps. By analogy with glacial phases of the Ouaternary where there is evidence of "intensified oceanic circulation during times of expanded continental ice sheets", there may have been a higher carbonate productivity in the oceans of the equatorial zone (Bloom 1974). Although there may have been increased climatic zonation with a narrowing in width of the tropical-subtropical belts during the later Ordovician glacial phases, it is unlikely that there would have been any significant reduction in the degree to which reef growth flourished in well circulated shallow seas of the near equatorial zone. This narrowing of tropical-subtropical belts is supported by palaeomagnetic evidence of Anticosti Island lying within 20° of the late Ordovician equator (Petryk 1981 b), and the presence of a possible cool-water Hirnantia fauna in beds 6 m below the regressive deposits of Member 7 (Cocks & Copper 1981).

It may be concluded that during the Ordovi-

cian Period the tropical and subtropical belts alternately expanded and contracted (Newell 1971) with the world-wide oscillations of climate, as first recognized by Spjeldnæs (1961). At times of reduced climatic zonations, as for instance in the late Caradoc warming, reef building appears to have been flourishing in middle-low latitudes, possibly to at least 40° from the equator. In contrast at times of increased climatic zonation, as for example during the period of most intense glaciation at the end of the Ordovician, reef formation seems to have been limited to within a relatively few degrees, perhaps to within 20° of the equator.

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