The marine transgression in the Middle Carboniferous of Brøggerhalvøya (Svalbard)

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The change from continental to marine conditions in the Middle Carboniferous on Brøggerhalvøya started at the end of the Bashkirian with short-term transgressive events at the top of the Brøggertinden Formation. Local basin subsidence was responsible for the pulsatory nature of the transgression. The establishment of a shallow marine carbonate-dominated environment is represented by the Moscovian Scheteligfjellet Member which overlies the post-Caledonian red beds of the Brøggertinden Formation. The Scheteligfjellet Member is the lowermost member of the Nordenskiöldbreen Formation and shows distinct lateral facies variations. Three facies associations can be distinguished: lagoonal facies, shoal facies and open marine facies. The succeeding two members were deposited in subtidal areas of the carbonate platform. A basin subsidence event at the Carboniferous/Permian boundary was responsible for a short shift into deeper depositional environments during a time of worldwide regression. After this a continuous regression led to supratidal conditions at the top of the Nordenskiöldbreen Formation.

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Metamorphic rocks (Hecla Hoek), which were folded during the Caledonian orogenesis, are unconformably overlaid by Upper Palaeozoic rocks on the Brøggerhalvøya peninsula, situated in the NW of Svalbard (Fig. 1). These post-Caledonian sediments consist of a terrigenous redbed succession overlaid by shallow marine platform carbonates. The carbonates, which mark the establishment of marine environment in the Upper Palaeozoic of Svalbard, will be described and interpreted in terms of their microfacies.

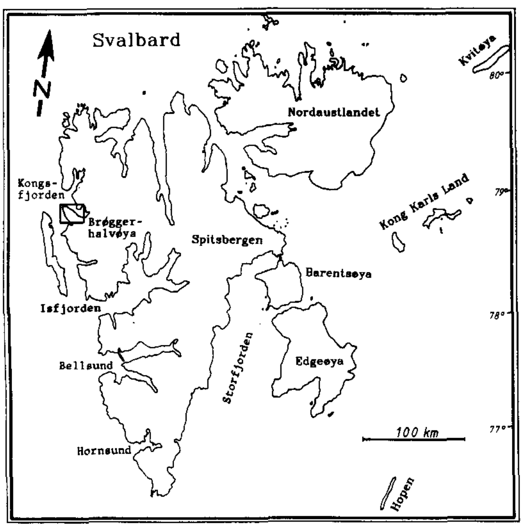

Fig. 1. Location of Brøggerhalvøya on Svalbard.

Stratigraphical setting

The Upper Palaeozoic sediments on Brøggerhalvøya were first described by Holtedahl (1911, 1913) and in more detail by Orvin (1934). For the investigations presented in this paper the revision of the stratigraphical scheme by Cutbill & Challinor (1965) is used (Fig. 2).

The base of the Upper Palaeozoic succession on Brøggerhalvøya is mainly represented by the Middle Carboniferous Brøggertinden Formation which rests unconformably on Hecla Hoek rocks.

The presence of the Lower Carboniferous Orustdalen Formation on the SW coast of Brøggerhalvøya led Barbaroux (1966, fig. 4) to the incorrect assumption that the Orustdalen Formation is present throughout the entire peninsula.

The terrigenous red beds of the Brøggertinden Formation, deposited in a local half-graben (Ludwig 1989), are overlaid by the Nordenskiöldbreen Formation which is of Moscovian to Sakmarian age and therefore spans the Carboniferous/Permian boundary (Cutbill & Challinor 1965).

The Nordenskiöldbreen Formation on Brøggerhalvøya is about 370 m in thickness and is divided into three members: Scheteligfjellet

	Stage	Group	Formation	Member
Upper Permian	Kungur	Tempelfjorden Group	Kapp Starostin Formation	
Lower Permian	Artinsk	Gipsdalen Group	Gipshuken Formation	
	Sakmara		Nordenskiøld-breen Formation	Tyrrellfjellet Member
	Assel			
Upper Carboniferous	Ural			Mørebreen Member
Middle Carboniferous	Moscov			Scheteligfjellet Member
	Bashkir		Brøggertinden Formation	
Lower Carboniferous		Billefjorden Group	Orustdalen Formation	HECLA HOEK
Lower Palaeozoic & Upper Proterozoic				

Fig. 2. Stratigraphical scheme for the Permo-Carboniferous succession on Brøggerhalvøya. Modified after Cutbill & Challinor (1965).

Member, Mørebreen Member, and Tyrrellfjellet Member (Cutbill & Challinor 1965; Challinor 1967). The type localities of the two lower members are situated on Brøggerhalvøya. The Scheteligfjellet Member and the underlying Brøggertinden Formation together represent the Middle Carboniferous of Brøggerhalvøya.

This investigation concentrates on the Scheteligfjellet Member and the establishment of marine environment on Brøggerhalvøya.

The Scheteligfjellet Member

Lithology

The Scheteligfjellet Member is a fossiliferous limestone succession with locally intercalated siliciclastics and dolomites.

Based on fossils Moscovian age was first proposed for the Scheteligfjellet Member by Holtedahl (1911, 1913). Challinor (1967) mapped Brøggerhalvøya using the stratigraphical scheme of Cutbill & Challinor (1965) and described the Scheteligfjellet Member, but he did not define its exact boundaries.

For lithological and palaeoenvironmental reasons the base of a blue-grey limestone containing abundant *Multithecopora* sp. probably *Multithecopora syrinx* (Etheridge 1900; Oekentorp, pers. comm.) is defined as the boundary between the Brøggertinden Formation and the Scheteligfjellet Member in this investigation. This syringoporid coral (Oekentorp & Kaever 1970), which occurs *in situ*, presumably was the fossil identified by Holtedahl (1911) as *Syringopora parallela* Fischer. This limestone forms an easily perceptible marker horizon on Brøggerhalvøya, and after the recommendations of the Norwegian Committee on Stratigraphy (Nystuen 1989), it is suggested as being an informal unit.

The upper boundary of the Scheteligfjellet Member corresponds to the top of the uppermost siliciclastic bed. Where these beds are missing, the Scheteligfjellet Member consists solely of fossiliferous limestone, and the transition to the overlying Mørebreen Member is gradual. In this case the base of the Mørebreen Member is only indicated by the appearance of dolomites. Though this might be a postdepositional characteristic, it is useful for mapping purposes. The thickness of Scheteligfjellet Member was estimated at 150 m by Challinor (1967) and 160 m by Barbaroux (1967). This investigation shows lateral thickness variations from a little over 10 m to 100 m.

Petrography and microfacies

The Scheteligfjellet Member displays significant facies variations between the different outcrops on Brøggerhalvøya. The successions can be grouped into three facies associations: L, S, and O (Fig. 3). Their original relative position was changed by Tertiary thrust tectonics (Ludwig 1988).

Facies association L. – This facies overlies a typical succession of the uppermost Brøggertinden Formation, which is characterized by alternating beds of bluegrey limestone, black calcrete – both of intertidal origin (Ludwig 1989) – and coarse alluvial fan conglomerates.

The Multithecopora Limestone forms the base of facies association L. This massive limestone is characterized by layers with abundant *Multithecopora* sp. (Fig. 4) and some single chalcedony nodules with concentric structure and diameters of from 10 to 30 cm. Thin layers of red jasper (4 to 10 cm thick) with irregular lower and upper boundary surfaces occur between the individual limestone banks. The Multithecopora Limestone shows the following microfacies: A

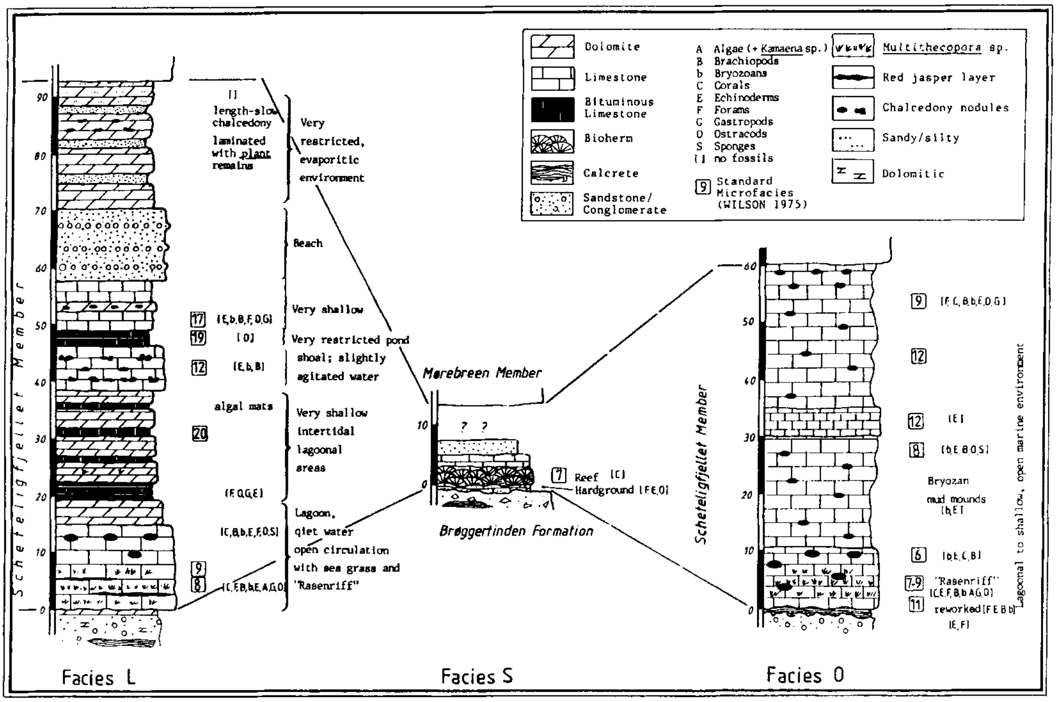

Fig. 3. The three facies association of the Scheteligfjellet Member exemplified by three profiles of the Brøggerhalvøya.

crumbly micritic matrix containing echinoderms, brachiopods, bryozoans and corals (*Multithecopora* sp. and probably *Caninia* sp.) as coarse sand-sized bioclasts (Fig. 5). The smaller-sized bioclasts are forams, pellets and *Kamaena* sp. (Buggisch, pers. comm.) (Fig. 6). Some whole ostracod shells also occur.

The brachiopods are dominated by productids which are mostly preserved as whole shells (Fig. 7) which have been altered to red jasper. In addition the athyridine brachiopod *Composita* sp. occurs (Fig. 8).

Most of the delicately branching multithecopores are altered to red jasper and are restricted to several intercalated thin horizons in the basal part of the Multithecopora Limestone. Small sparitic particles with a lanceolate shape occur dispersed around their stems. These are probably calcitic elements into which the outer shells of the multithecopores disintegrated.

The multithecopores covered wide areas and built up colonies. They are associated with solitary corals. No real bioherms are found, but small patch reefs, up to 20 cm in height, appear in thin horizons between the *Multithecopora*-bearing layers.

In this facies association the Multithecopora Limestone is succeeded by thin dolomites and bituminous limestones, partly by a sparitic limestone with fragments of echinoderms, bryozoans and brachiopods that are well-rounded and sorted. The overlying laminated dark limestone contains a poor fauna dominated by ostracods. Irregular laminae reflect the probable development of algal mats. The dark limestone is overlaid by a massive arkosic litharenite showing thin layers with well-rounded sediment-pebbles. It is succeeded by bituminous dolomitic mudstones with wavy lamination and with intercalated red and green fine-grained sandstones (lithic arkose). Silt-sized, angular quartz grains partly occur as thin layers in the laminated mudstone. Besides scattered carbonaceous plant remnants, ostracods and gastropods are the only fossils that are found (Fig. 9). Irregular white nodules of length-slow chalcedony are abundant.

Feldspars, though lacking in the underlying red beds of the Brøggertinden Formation, make up a relatively high portion of the sandstones in the Scheteligfjellet Member, and they show authigenic overgrowth. Facies association L shows varying lithologies and its thickness varies from

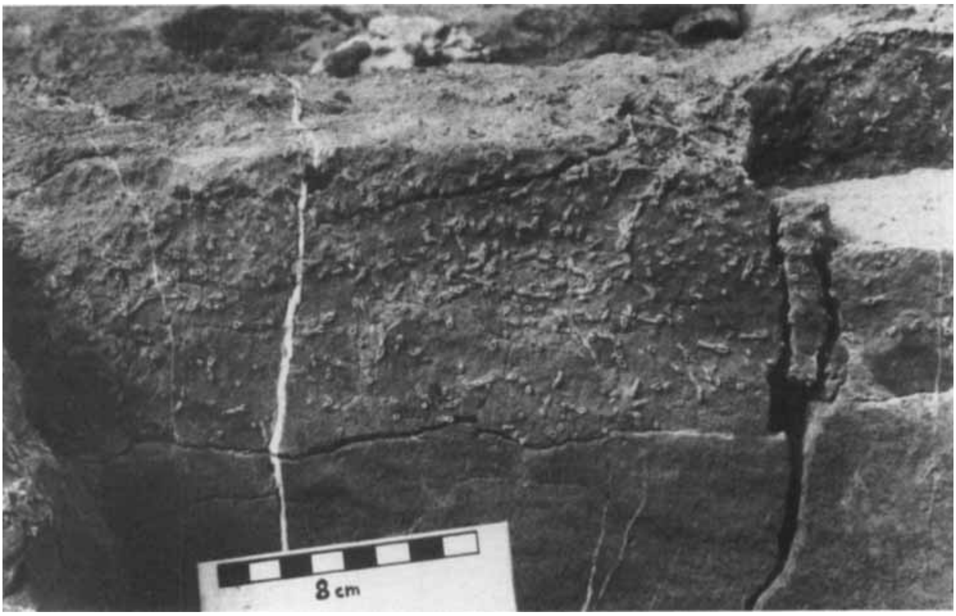

Fig. 4. Beds with *Multithecopora* sp. in the lower part of the basal limestone (Multithecopora Limestone) of the Scheteligfjellet Member.

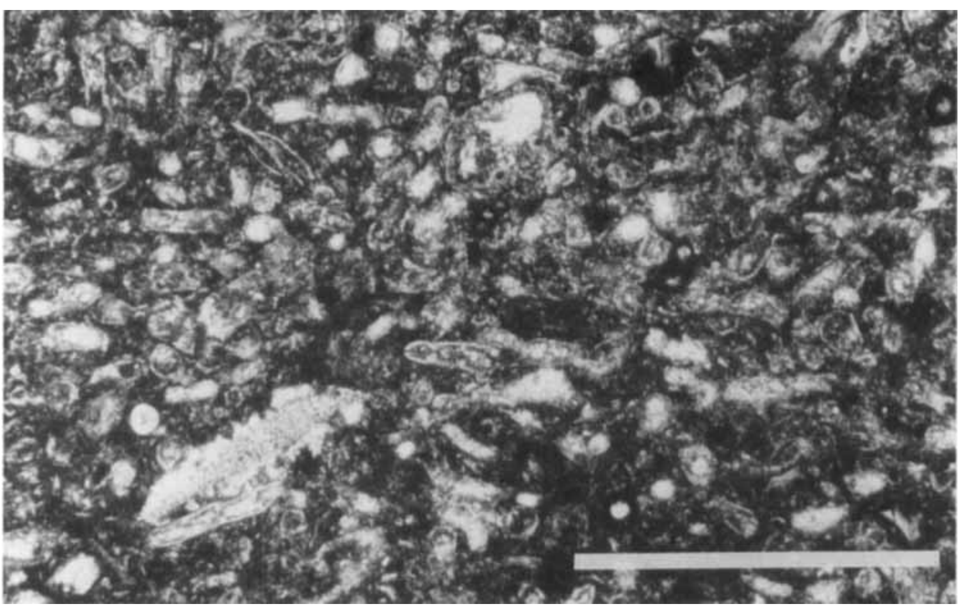

Fig. 5. Cross-section of *Multithecopora* sp. A central cavity filled with internal sediment or micrite is surrounded by a shell that began to alter into red jasper outwards. Scale: 1 mm.

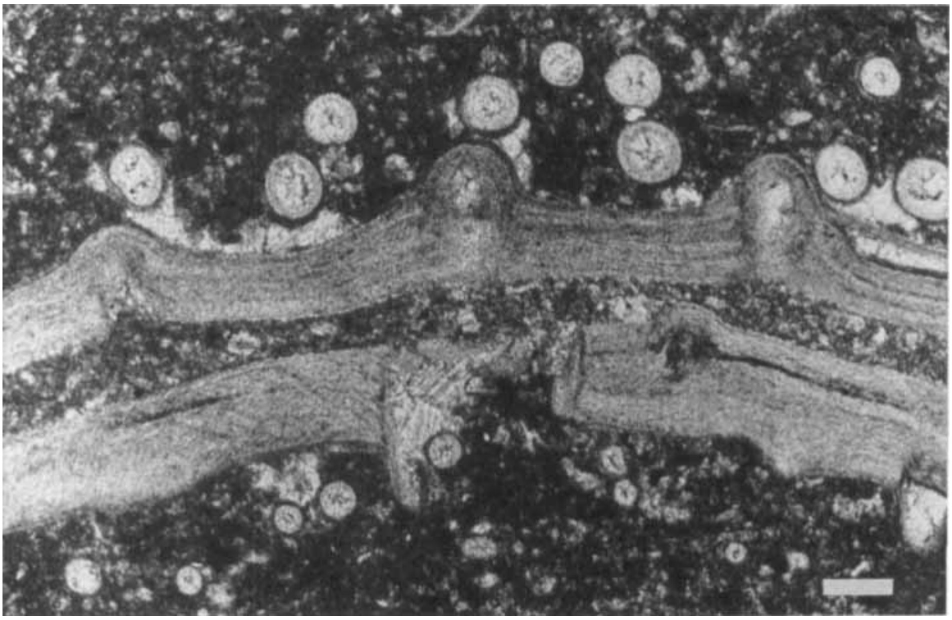

Fig. 6. Kamaena sp. (Buggisch pers. comm.) which is very abundant in the Scheteligfjellet Member limestone. Scale: 1 mm.

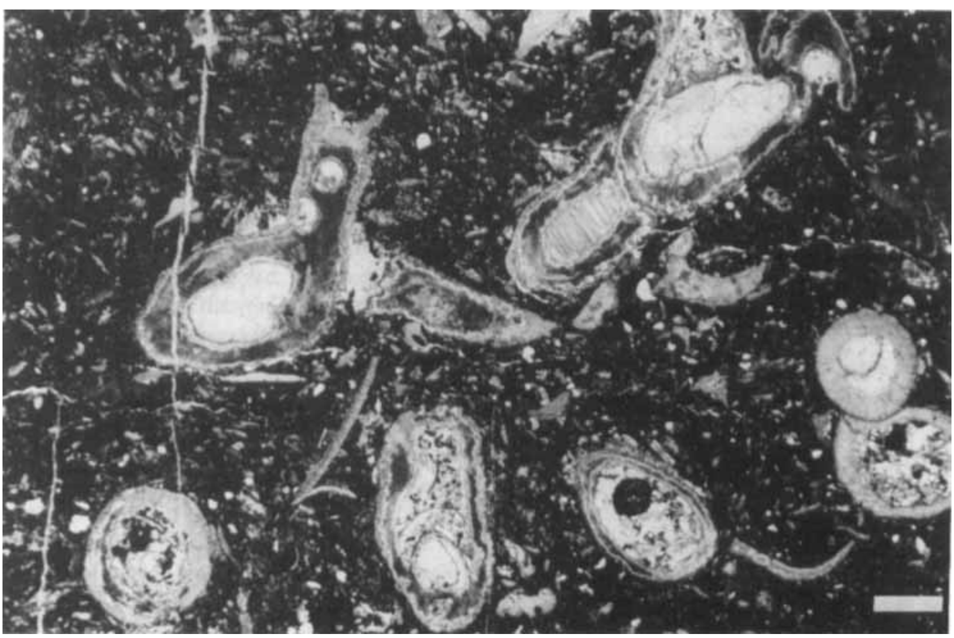

Fig. 7. Basal limestone of the Scheteligfjellet Member (Multithecopora Limestone); middle part of a productid brachiopod. Normal foliated structure of the shell and the cross sections of the spines are typical. Scale: 1 mm.

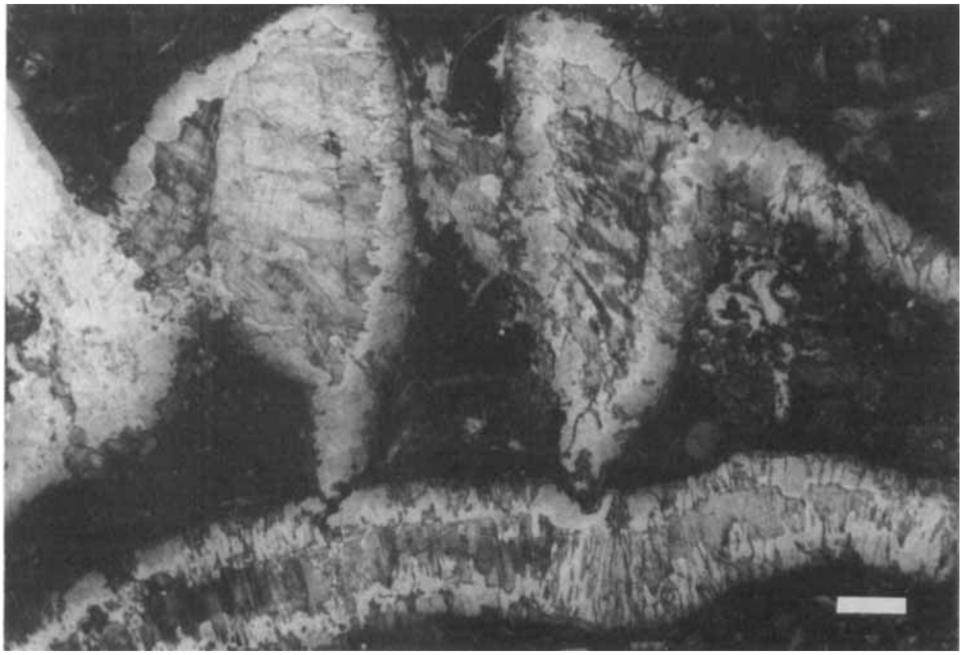

Fig. 8. Cross-section of *Composita* sp. in the basal limestone of the Scheteligfjellet Member (Multithecopora Limestone). The prismatic structure of the shell differs from the normal brachiopod structure. Scale: 1 mm.

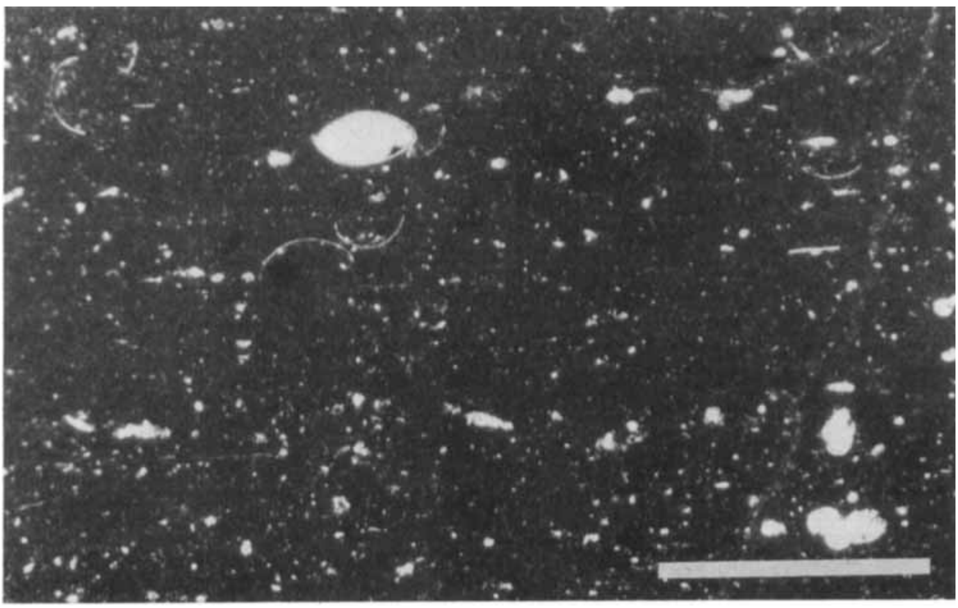

Fig. 9. Upper layers of the Scheteligfjellet Member, facies association L. Dark limestone with ostracods and some gastropods deposited in restricted areas. Scale: 1 mm.

30 m to 100 m. It is exposed in the mountainous center of Brøggerhalvøya (Brøggerfjellet, Zeppelinfjellet and Traudalen (Ludwig 1989)).

Facies association S. – Facies association S is characterized by a 2 m thick boundstone representing the Multithecopora Limestone (Fig. 3). This build-up was established on a hardground and consists mainly of *Chaetetes radians* Fischer and *Campophyllum kiaeri* Holtedahl (Holtedahl 1913). *Multithecopora* sp. is rare. The overlying fossiliferous limestones are several metres thick and of shallow marine origin. They are in turn overlaid by red and green fine-grained sandstones (arkosic litharenites) and locally also by thin conglomeratic layers. Though not fully exposed, it appears that facies association S is only a little more than 10 m thick. It is only found on the SW coast of the Brøggerhalvøya at Kjærstranda, where it was described by Barbaroux (1967). It overlies a condensed section of the Brøggertinden Formation, represented by a debris flow breccia of shallow marine origin with calcrete lenses (Ludwig 1989).

Facies association O. – Facies association O rests directly on a supratidal calcrete horizon (Fig. 3) that forms the top of the Brøggertinden Formation (Ludwig 1990). The basal layer is a reworked marine horizon with small intraclasts mainly derived from the calcrete limestone. This horizon grades upwards into the Multithecopora Limestone which shows similarities to the development in facies association L. A bryozoan-echinoderm-packstone is deposited on top of the limestone. This in turn is followed by micritic limestones with bryozoans, productids, and ostracods as whole shells together with fragments of echinoderms. These packstones, rudstones, and floatstones are overlaid by different wackestones with abundant chalcedony nodules (up to 40 cm in diameter) of concentric structure.

This facies association is differentiated because of its lack of siliciclastic and dolomitic interbeds. It is found along the north-west coast of Brøggerhalvøya.

Facies interpretation

During the Middle Carboniferous, Brøggerhalvøya was situated at about 30° North and the climate was semi-arid (Steel & Worsley 1984).

The microfacies and faunal content of the Multithecopora Limestone corresponds to SMF-type 8 and 9 of Wilson (1975) (Fig. 3). The multithecopores appear to build up extensive biostromes (German term 'Rasenriffe') in a shallow bay or lagoon with sea grass around and with open circulation seawards but only little water agitation (Facies Belt 7, Wilson 1975). Such an environment can explain the often parallel bend of all individual tubes of a *Multithecopora* colony. Coral tubes in similar environments today grow upwards even if the colony turns over in the soft substrate (Kühlmann 1984). The quartz grains in the Multithecopora Limestone as well as the associated sandstones display considerable terrigenous influx from nearby land areas. The delicately branching growth of the multithecopores prevented them from being buried by sediment. Associated with the multithecopores, spherically shaped coral colonies which colonized sandstone clasts occur. Such corals can be rolled over by the slightly agitated water of shallow lagoons, so that each individual receives light and nutrients from time to time (Kühlmann 1984). This steady movement protects the corals from sediment cover.

Algal laminites, dismicrites, and limestones with well-rounded bioclasts from open marine fauna as well as feldspar-rich sandstones with layers of well-rounded pebbles (facies association L) were probably deposited in shoal or beach environments (Facies Belt 6 or 8 of Wilson (1975)). Their occurrence indicates that after deposition of the Multithecopora Limestone, lagoonal areas became shallower and were sporadically and locally cut off from open circulation.

A similar environment today seems to be Florida Bay, a shoaling bay protected from the open sea by a rim of coral islands (Enos & Perkins 1979). Sediments consist of lime mud with molluscs, forams and ostracods (Ginsburg 1956). Many small mud-mounds, fixed by algae and partly showing algal laminates, are surrounded by delicately branching corals and red algae (Bosence et al. 1985).

A comparable shoaling of the bay in the Scheteligfjellet Member was caused by rapid carbonate deposition so that basin subsidence could not keep pace. The Scheteligfjellet Member therefore forms a fining-upward sequence. Dark limestones with algal mats and laminated dolomitic mudstones succeed the beach deposits. Nodules of length-slow chalcedony suggest an evaporitic origin (Folk & Pittman 1971), an interpretation supported by the feldspar overgrowth in the intercalated sandstones (Kastner & Siever 1979). These uppermost beds of facies association L were deposited in higher intertidal to supratical regimes (Facies Belt 8 of Wilson (1975)), suggested by James (1984) to represent the uppermost part of a shallowing-upward sequence. Above the shoal deposits ostracods represent the dominating fauna; below, forams are more abundant. Thornton et al. (1980) conclude from an investigation of a recent lagoon in Tunisia that ostracods dominate over forams in restricted marine areas, while the opposite is the case in open marine environments. The carbonates in the lower part of the Scheteligfjellet Member represent open marine, well-aerated lagoons in the process of a slow shoaling. The carbonates in the upper part of facies association L display a temporary cut-off of the lagoons from the open sea as a result of this shoaling.

Since the Multithecopora Limestone can be found in all the profiles, its depositional environment must have been an extensive shallow bay. The water depth of such an environment was probably not more than 10 m (Flügel 1978). In facies association L the irregular laterally thinning layers of red jasper are possibly of pedogenic origin (silcrete) and therefore may be attributed to a periodical emergence of the limestone. The underlying red sandstones, as well as dust from nearby land areas, could have supplied the silica and iron-oxides. Periodic changes of the environmental conditions in the Multithecopora Limestone are also indicated by the confinement of the multithecopores to several thin horizons.

In conclusion, the microfacies of the Scheteligfjellet Member suggests stillwater conditions, the depositional environment being a shallow bay with lagoons along the coast protected by shoals or barriers from the open sea (Facies Belt 7 of Wilson (1975)). The bay was characterized by sea grass and a faunal association of forams, bryozoans, algae, brachiopods, and species of corals which were protected from being buried by sediment because of their shape and which were also able to adapt to sudden changes of temperature and salinity.

Due to the high rate of sediment accumulation that exceeded the rate of basin subsidence, the lagoonal areas progressively shoaled and developed into restricted and finally evaporitic supratidal areas (Facies Belt 8 of Wilson (1975)). This was possible mainly because extensive coastal regions were so shallow that insignificant sea level fluctuations or basin infilling could cause considerable facies changes in the coastal area. This is exemplified by a typical tidal flat profile in the center of Brøggerhalvøya (Traudalen) assigned to facies association L, where vertical and lateral facies changes occur within decimetres.

Facies association L represents a lagoonal facies which developed from normal marine open lagoons to restricted tidal flat areas with evaporitic conditions.

On barriers or shoals that protected the lagoons from the open sea, a low sediment supply allowed a hardground to develop on which a coral build-up could grow (SMF-type 7 of Wilson 1975)). Hence facies association S represents a shoal facies that is reduced in thickness compared to facies association L. Upward-shallowing is indicated by siliciclastic sedimentation above the reef.

In facies association O, open marine platform conditions prevail above the Multithecopora Limestone. The echinoderm-bryozoan-packstones with brachiopods are typical for a flank facies of mud-mounds (Wilson 1975). The lime mud was fixed by bryozoans and subsequently colonized by crinoids and productids. The depositional area was situated outside the lagoons beyond the coral shoals in the open bay. In facies association O deposition took place in subtidal areas after deposition of the Multithecopora Limestone.

Sea-level fluctuations and tectonics

The distinct environmental change in the Middle Carboniferous of Brøggerhalvøya – terrigenous to marine sedimentation – reflects sea-level rise. This rise was not confined to Svalbard but was responsible for similar sedimentation patterns in the whole American-European arctic province. In the Sverdrup Basin, Beauchamp et al. (1989) recorded a marine succession over red beds which they explained by a substantial transgression with a culmination in middle Moscovian times. Stemmerik & Worsley (1989) found as characteristic for the Middle Carboniferous of the European arctic a sea-level rise due to second order sea-level fluctuations that resulted in extensive shallow-shelf and lagoonal sedimentation by mid-Moscovian time.

According to Crowell (1978), the large-scale transgression in the Carboniferous of NW Europe

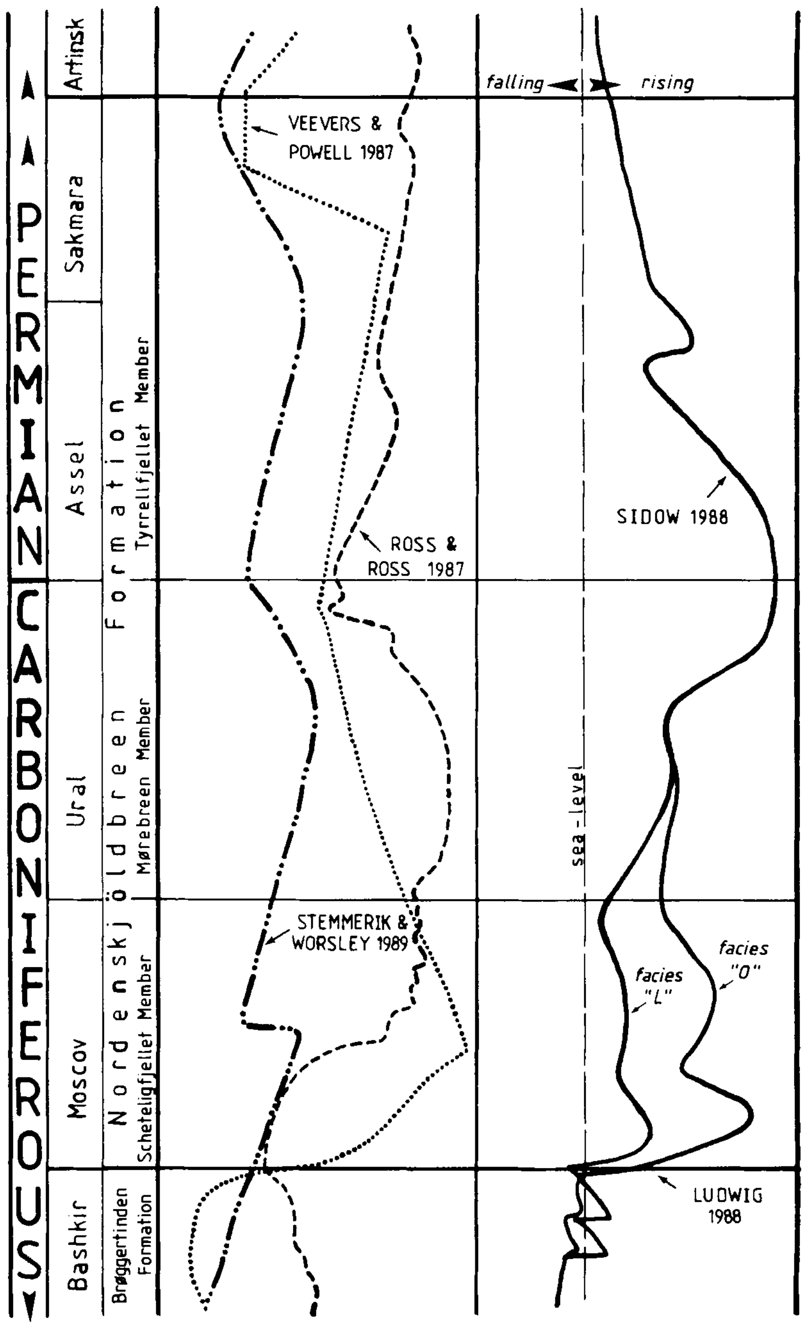

Fig. 10. Sea-level curve of the Nordenskiöldbreen Formation on Brøggerhalvøya compared with a global sea-level curve (Ross & Ross 1987), a sea-level curve of the Russian platform (Veevers & Powell 1987), and a sea-level curve of Svalbard and Greenland (Stemmerik & Worsley 1989).

(Ramsbotton 1979) was triggered by the melting of the continental ice cap in an interim period. In contrast, Gjelberg & Steel (1981) explain the transgressional stage in the Middle Carboniferous by an uplift of the Hercynian Europe that contemporaneously forced the NW Barents Shelf to subside.

The sea-level curve of the Nordenskiöldbreen Formation on Brøggerhalvøya is compared with the following local and regional sea-level curves in Fig. 10:

1. Third-order curve, global (Ross & Ross 1987)
2. Third-order curve, Russian platform (Veevers & Powell 1987)
3. Second-order curve, Svalbard and Greenland (Stemmerik & Worsley 1989)

These three curves have several similar trends:

—a beginning sea-level rise in early Moscovian,
—highstand in the middle Moscovian,
—lowstand around the Permo-Carboniferous boundary,
—sea-level rise starting in the earliest Permian,
—sea-level fall in the late Sakmarian.

A significant difference of the Nordenskiöldbreen Formation on Brøggerhalvøya to the compared sea-level curves is the sea-level highstand at the top of the Mørebreen Member. Veevers & Powell (1987) found a major regression during the Stephanian which they relate to the highest amount of ice volume of the Gondwana glaciation during that time. The contradicting sea-level highstand at the end of the Stephanian (Uralian) on Brøggerhalvøya is obviously due to renewed basin subsidence. Local movements at that time (upper Mørebreen Member) are suggested by a syndiagenetic breccia described by Sidow (1988). In contrast Worsley & Aga (1986) mention discontinuity surfaces and intraformational carbonates caused by minor uplift around the Carboniferous/Permian transition elsewhere on Svalbard.

The sea-level curves do, however, show some similarities, as the curve of the Nordenskiöldbreen Formation on Brøggerhalvøya also displays a regression in the Sakmarian and the beginning of a transgression in the early Moscovian. More precisely this transgression started already in the late Bashkirian and had a distinct cyclical or pulsatory pattern. The two cycles at the top of the Brøggertinden Formation display short-term transgressions due to basin subsidence followed by renewed coarse terrestrial sedimentation (Ludwig 1989). The intercalated pedogenic horizons of intertidal origin (Ludwig 1990) suggests a high amplitude of relative sea-level oscillations. According to Read et al. (1986) a sea-level fall faster than the subsidence of tidal flats causes unconformities and a thick vadose profile.

The relatively rapid environmental shifts, especially in facies association O, from a tidal flat characterized by non-deposition at the top of the Brøggertinden Formation to intertidal carbonates at the base of the Scheteligfjellet Member perhaps do not implicitly reflect the real transgressional (tectonically controlled) patterns. A time lag can exist after a transgression until carbonate production reaches its full potential (Read et al. 1986).

The marine environment finally was established with the beginning of the Moscovian. High sediment accumulation rates in the shallow water regimes led to autocyclical upward-shallowing of the Scheteligfjellet Member (Fig. 10) still slightly influenced by tectonical subsidence.

Local tectonic movements in the Middle Carboniferous of Svalbard are not restricted to Brøggerhalvøya. Gjelberg & Steel (1983) recorded a similar development with a continental to marine transition on Bjørnøya. Superimposed on this long-term transition they found several submergence-emergence events which they interpreted as basin floor sinking. In the south of Svalbard Birkenmajer (1984a) described mid-Carboniferous Red Beds (Hyrnefjellet Formation) with an age corresponding to that of the upper Brøggertinden Formation and the Scheteligfjellet Member. In his opinion the basin for the sediment accumulation was formed by mid-Carboniferous tectonics (Adriabukta phase). The overlying Upper Carboniferous to Lower Permian sediments (Treskelodden Formation) have a cyclical character which Birkenmajer (1984b) explains with glacial-eustatic sea-level fluctuations. Nevertheless a fan-delta sequence in the southwest of Svalbard deposited in Late Carboniferous to Early Permian times reflects sporadic fault movements also after the Middle Carboniferous (Kleinspehn et al. 1984). Microtectonic analysis by Lepvrier et al. (1989) suggest several faulting episodes in the Middle and Upper Carboniferous of Bjørnøya and indicate strike-slip motions also on the northwest of Svalbard.

Intense faulting was emphasized already for the Late Devonian (Svalbardian deformations), characterized by oblique-slip movements (Harland et al. 1979; Steel & Worsley 1984). Obviously local faulting episodes, creating and controlling sedimentary basins on Svalbard, also occurred in the Early Carboniferous (Fairchild 1982), continued through to the Middle Carboniferous (Ludwig 1989; Worsley & Aga 1986), and locally were also active in the Late Carboniferous (Kleinspehn et al. 1984).

Steel & Worsley (1984) suggested oblique-slip dominated movements for the Middle Carboniferous of Svalbard and underlined the considerable record of tectonic movements, strike-slip to dip-slip, for the entire Carboniferous. Together with sea-level fluctuations and sedimentational controls these movements induced and regulated the shift from terrigenous to marine environments in the Middle Carboniferous of Brøggerhalvøya.

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