Stratigraphic framework of Upper Carboniferous (Moscovian–Kasimovian) strata in Bünsow Land, central Spitsbergen: palaeogeographic implications

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Recent field studies and new fossil dating of the Upper Carboniferous strata of central Spitsbergen have led to a reappraisal of the traditional lithostratigraphic framework, and two new stratigraphical units (the Black Crag and Pyefjellet Beds) are defined in the lower part of the Cadellfjellet Member (Wordiekammen Formation). The Black Crag Beds, previously used in an informal sense, are here formally defined as a series of limestones characterized by the presence of 5 units (2–30 m thick) of massive sparsely to non-fossiliferous carbonate mudstone (micrite). The Black Crag Beds, of early to late Kasimovian age, can be traced throughout Bünsow Land and form the base of the Cadellfjellet Member in western areas, where they directly overlie evaporites and dolomites assigned to the Minkinfjellet Formation. However, in central and eastern Bünsow Land the Black Crag Beds are separated from strata typical of the Minkinfjellet Formation by a series of fossiliferous limestones whose constituent facies show a cyclic distribution. Each cycle is capped by an exposure surface. These limestones, of late Moscovian to early Kasimovian age, are here termed the Pyefjellet Beds and form the base of the Cadellfjellet Member (Wordiekammen Formation) in central and eastern Bünsow Land. The stacked limestone cycles of the Pyefjellet Beds are considered to constitute a distinct Late Carboniferous (late Moscovian–early Kasimovian) carbonate platform, the Ny Friesland Platform, which developed within the Billefjorden Trough on the hanging-wall dip-slope of the Ny-Friesland Block. The Ny Friesland Platform marked the eastern margin of a contemporaneous low-relief topographic basin (the Campbellryggen Basin) which lay between the platform and the footwall of the Nordfjorden Block. The margin of the Ny Friesland Platform is marked by an abrupt westward thinning of the limestone cycles that constitute the Pyefjellet Beds and a concomitant interfingering with evaporites and dolomites of the uppermost Minkinfjellet Formation. The evaporites and dolomites are considered to represent the off-platform 'basin-fill' of the Campbellryggen Basin and were deposited predominantly during sea-level lows when the Ny Friesland Platform was exposed. Consequently, the exposure surfaces bounding the marine limestone cycles in the Pyefjellet Beds are considered to be time equivalent to the evaporites and dolostones deposited in the basin. Relative sea-level highs resulted in the deposition of the Pyefjellet Beds. Aggradation and progradation of the Ny Friesland Platform was therefore a highstand phenomenon. The vertical transition from the Pyefjellet to Black Crag Beds probably reflects a large-scale change in circulation patterns across the central Spitsbergen carbonate platform. Indeed, the rocks within the Cadellfjellet Member are considered to represent a single late Moscovian to mid-Gzelian regressive sequence. Regressive sequences of similar magnitude, and spanning the same time interval, have also been documented in Arctic Canada and Greenland, and are apparently the result of a regional fall in relative sea level which affected the northern margin of Pangaea.

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Introduction

Situated ca. 25° to 30° north of the equator (Drewry et al. 1974; Steel & Worsley 1984; Scotese & McKerrow 1990) Spitsbergen was an area of extensive carbonate and evaporite deposition during Late Carboniferous time. The sedimentary successions deposited across central Spitsbergen normally show a cyclic distribution of facies. Deposition appears to have been partly controlled by active faulting, which was initiated in Early to Late Carboniferous (Serpukhovian–Bashkirian) time (Johannessen & Steel 1992), and partly by relative changes in sea-level. Indeed, cyclic Upper Carboniferous sequences are a world-wide phenomenon and are generally believed to be related to global eustatic sea-level changes (Ross & Ross 1985) caused by changes in ice volume associated with the southern Gondwanaland glaciation (Veevers & Powell 1987).

The Upper Carboniferous and Lower Permian strata of central Spitsbergen have been the focus of numerous studies (McWhae 1953; Gee et al. 1953; Forbes et al. 1958; Cutbill & Challinor 1965; Winsnes 1966; Lønøy 1981, 1995; Sundsbø 1982; Skaug et al. 1982; Dons 1983; Steel & Worsley 1984; Dallmann 1993; Johansen 1994). However, recent field studies (1992–96) in conjunction with more precise biostratigraphic control (Nilsson 1988, 1993), have resulted in a reappraisal of some of the Upper Carboniferous successions in central Spitsbergen. This paper aims to reassess the traditional stratigraphical framework for the Upper Carboniferous strata in central Bünsow Land. It revises some of the stratigraphic units (the Black Crag and Gerritbreen Beds) and defines a new unit (the Pyefjellet Beds) which is assigned to the Cadellfjellet Member of the Wordiekammen Formation (formerly the Nordenskiöldbreen

Formation,[1] see Table 1). The Pyefjellet Beds consist primarily of bedded limestones whose constituent facies are arranged in a cyclic manner. Moreover, the cyclic limestones which define the Pyefjellet Beds can be mapped across central and eastern Bünsow Land and are considered to represent a distinct Late Carboniferous (late Moscovian–Kasimovian) carbonate platform (the Ny Friesland Platform) that developed on the eastern margin of the Billefjorden Trough. A contemporaneous topographic low (the Campbellryggen Basin) lay between the western margin of the Ny Friesland Platform and the Billefjorden Fault Zone. Consequently, a series of revised Late Carboniferous palaeogeographical reconstructions are presented for central Spitsbergen.

Geological setting

Extension in Early to Late Carboniferous (Serpukhovian–Bashkirian) time created a series of NNW–SSE trending rift basins in Spitsbergen which possessed half graben (tilt-block) geometries (Johannessen & Steel 1992). In east–central Spitsbergen two major fault blocks are recognized, the Nordfjorden and Ny Friesland Blocks (Cutbill & Challinor 1965; Harland et al. 1974; Fig. 1). Rotation of these blocks during extension created two asymmetrical depositional centres; the St. Jonsfjorden Basin and the Billefjorden Trough separated by the footwall high of the Nordfjorden Block (Figs. 1, 2). Active rifting is generally considered to have ceased by late Moscovian time when regional subsidence and accompanying sea-level rise resulted in the deposition of transgressive sequences throughout the Barents Sea region (Steel & Worsley 1984; Nøttvedt et al. 1993). This period of relative sea-level rise can be correlated with similar Moscovian transgressive events in Greenland (Stemmerik 1993) and Arctic Canada (Beauchamp et al. 1989a, b).

In central Spitsbergen a thick and well-documented succession of syn-rift clastic and evaporite sediments was deposited in the Billefjorden Trough (Johannessen & Steel 1992). The transition to post-rift sedimentation is generally considered to have occurred during the Moscovian with the deposition of the Minkinfjellet Formation (formerly the Minkinfjellet Member of the Nordenskiöldbreen Formation, see Table 1; Johannessen & Steel 1992; Lønøy 1995). However, several aspects of the Upper Carboniferous sedimentary fill of central Spitsbergen are indicative of continued, albeit subdued, subsidence along the major fault systems. These features will be fully discussed below but include (i) pronounced thickness and facies variations across the Billefjorden Fault Zone; (ii) the development of localized unconformities on the footwall of the Nordfjorden Block; and (iii) rare horizons of event beds.

[1] The Late Palaeozoic stratigraphy of Svalbard is presently being revised by the Norwegian Stratigraphic Committee for Svalbard. Here the newly proposed (albeit presently unpublished) stratigraphic framework has been adopted and is presented in Table 1 with the permission of the authors.

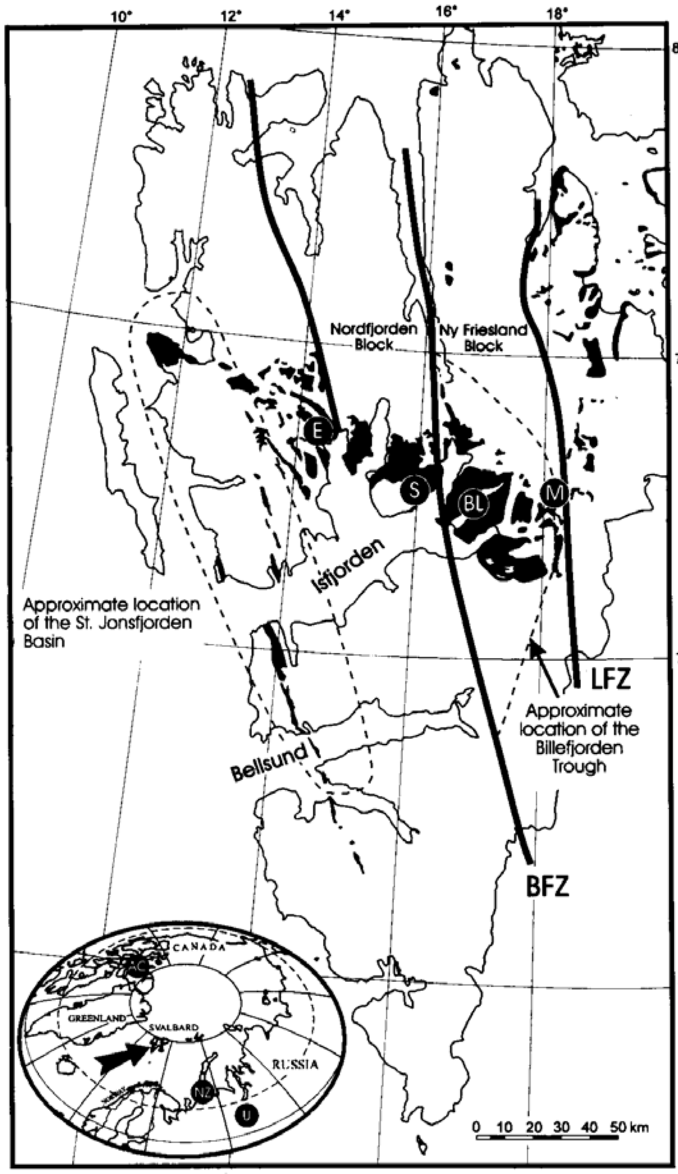


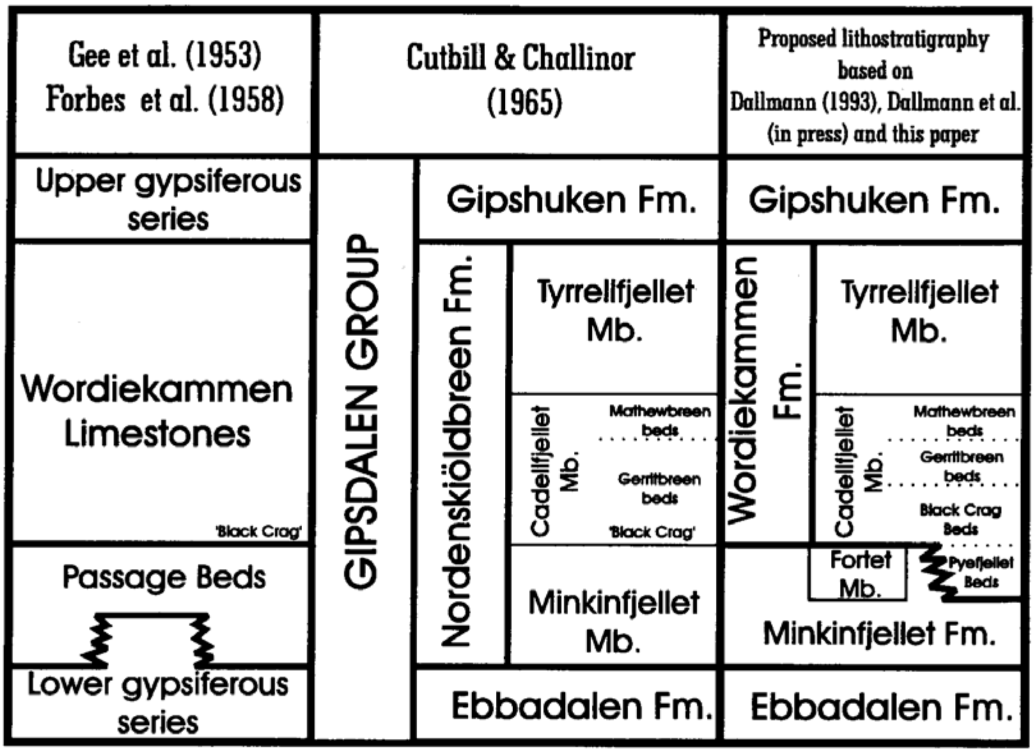
Fig. 1. Locality map illustrating the principal areas investigated, outcrop of Carboniferous and Permian strata and the main structural and palaeogeographical elements in central Spitsbergen during Late Carboniferous time. E – Ekmanfjorden; S – Skansen; BL – Bünsow Land; M – Malte Brunfjellet; BFZ – Billefjorden Fault Zone; LFZ Lomfjorden Fault Zone; Inset map; AC – Arctic Canada; NZ – Novaya Zemlya; U – Urals.

Lithostratigraphy

Gee et al. (1953) erected an Upper Palaeozoic lithostratigraphy for central Spitsbergen (Table 1) which was subsequently modified and formalized by Cutbill & Challinor (1965). Cutbill & Challinor divided Carboniferous and early Permian rocks into two groups; pre- and syn-rift clastic sequences of Early Carboniferous age were assigned to the Billefjorden Group while late syn-rift and post-rift carbonate and evaporite sequences were placed in the Gipsdalen Group (Table 1; Figs. 2, 3).

Confusion exists over the present subdivision of the middle part of the Gipsdalen Group. Cutbill & Challinor (1965) originally divided the group into three formations, a lower clastic and evaporitic Ebbadalen Formation, a middle carbonate-dominated Nordenskiöldbreen Forma-

Table 1. History of lithostratigraphic nomenclature for the late Carboniferous and early Permian strata of Bünsow Land, central Spitsbergen. The lithostratigraphy adopted here follows the recently proposed stratigraphy of Dallmann (1993) and Dallmann et al. (in press).



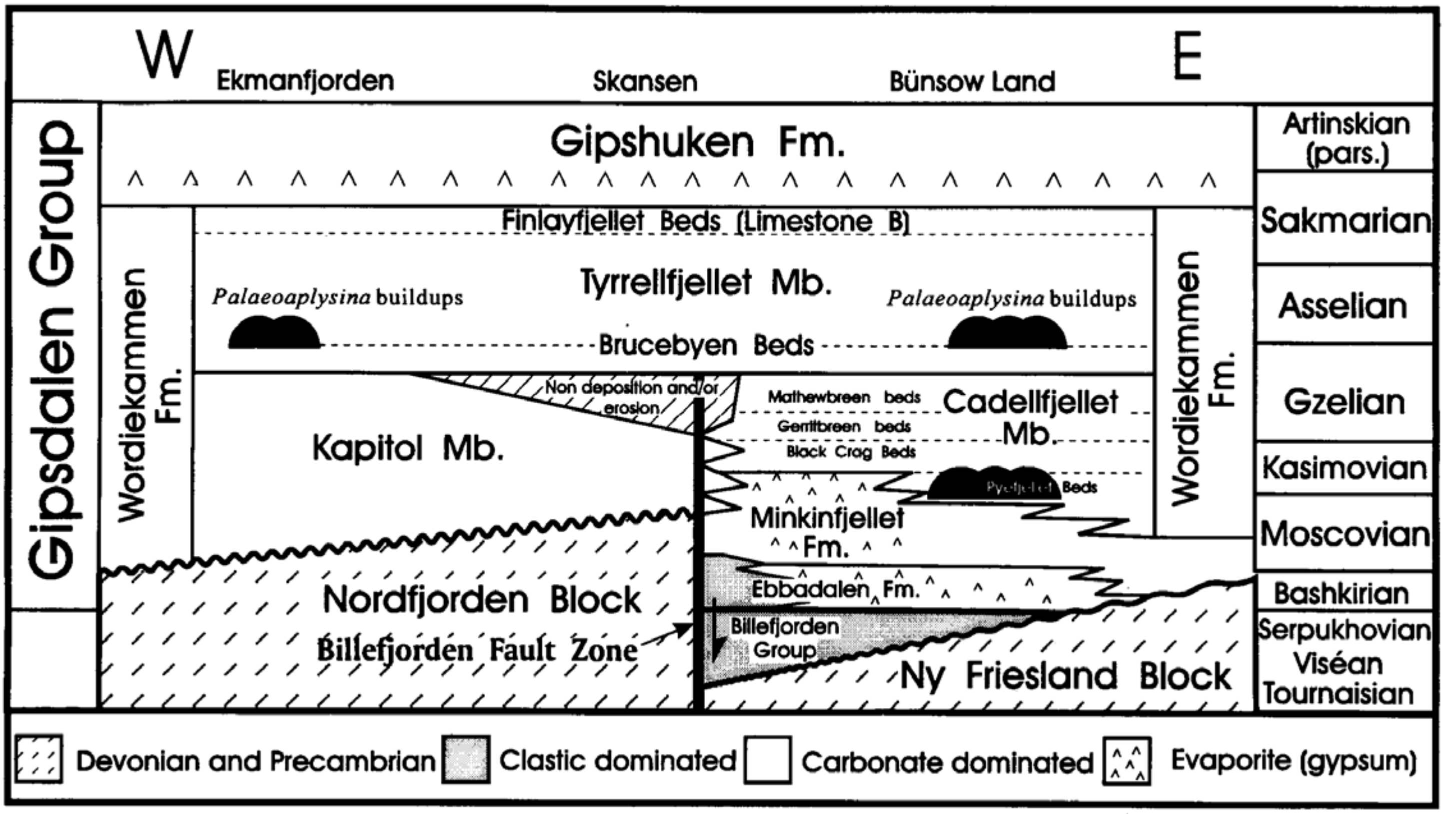


Fig. 2. Carboniferous and Early Permian lithostratigraphy of central Spitsbergen. See Fig. 3 for details of the relationship between the Minkinfjellet Formation and Cadellfjellet Member of the Wordiekammen Formation. Modified from Cutbill & Challinor (1965), Lønøy (1995) and Dallmann et al. (in press).

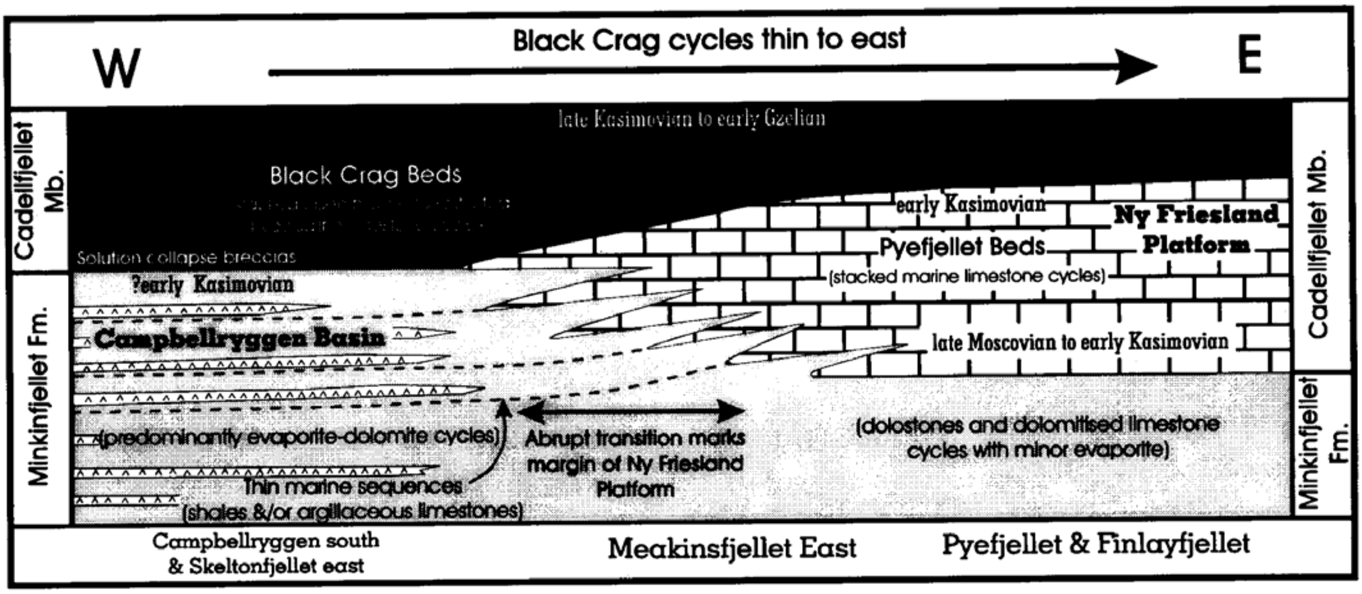


Fig. 3. Revised lithostratigraphic framework for the Minkinfjellet Formation-Cadellfjellet Member boundary, illustrating the relative position and stratigraphic relationships of the Pyefjellet Beds, Black Crag Beds and uppermost part of the Minkinfjellet Formation. The lateral transition between the Pyefjellet Beds and the Minkinfjellet Formation is considered to mark the margin of a late Moscovian–early Kasimovian platform margin. Note that the base of the Cadellfjellet Member, as defined here, becomes younger towards the west. See Fig. 5a for locations.

tion and an upper dolomitic and evaporitic Gipshuken Formation (Table 1, Fig. 2). However, Dallmann (1993) has recently proposed that the lowest member within the Nordenskiöldbreen Formation, the Minkinfjellet Member, should be raised to formation status. Dallmann's suggestion appears to be reasonable as the sediments which comprise the Minkinfjellet Member are restricted to the Billefjorden Trough (see Fig. 2). Furthermore, their lithological diversity (dolomites, evaporites, limestones, sandstones and rare shales) readily distinguishes them from the predominantly limestone units which overlie them. However, the ramifications from raising the Minkinfjellet Member to a Formation are far-reaching. For instance, the Nordenskiöldbreen Formation is invalidated (as it was originally defined as containing three members) and it is now proposed (Dallmann et al. in press) that the term 'Wordiekammen Formation' should supersede it (see Table 1). This nomenclature change resurrects the original term 'Wordiekammen' used by Gee et al. (1953). Moreover, several new Members are to be included in the Minkinfjellet Formation, of which the most important with respect to this study is the Fortet Member (Table 1) which has been assigned to a unit of angular breccias present in northwestern Bünsow Land and to the north of Billefjorden (see Dallmann 1993; Dallmann et al. in press). This newly proposed stratigraphic nomenclature is adopted here (Table 1), but the reader should be aware that it is still subject to confirmation by the Norwegian Stratigraphic Committee.

The successions discussed herein belong to the upper part of the newly defined Minkinfjellet Formation and the lower part of the Cadellfjellet Member (Wordiekammen Formation) (Figs. 2, 3). Problems arise, however, when trying to define the contact between these two units. The base of the Cadellfjellet Member has traditionally been placed at the base of the 'Black Crag' (a thick black to dark grey carbonate mudstone; Gee et al. 1953), or at the first appearance of fusulinids characteristic of the *Waeringella usvae* Zone (Cutbill & Challinor 1965). However, the usage of fusulinid foraminiferans to define the base of a lithostratigraphical unit is clearly unacceptable and is, more importantly, totally impractical in the field. It should be replaced by a purely lithostratigraphical definition.

In Cutbill & Challinor's original 1965 classification the Black Crag formed the lower part of the Gerritbreen Beds. Subsequently, Sundsbø (1982) separated the sequence of limestones containing 'Black Crag facies' into a distinct unit, the Black Crag Beds, which he correlated across northwest Bünsow Land. Previous studies have suggested that the Black Crag mudstones passed laterally eastwards into a series of phylloid algal banks (Sundsbø 1982; Dons 1983; Worsley et al. 1986). Consequently, in central and eastern Bünsow Land the base of the Cadellfjellet Member was placed at the base of the first phylloid algal bank (Sundsbø 1982; Dons 1983; Lønøy 1995).

Recent field mapping by the authors has shown that the Black Crag is *not* laterally equivalent to the phylloid algal banks but actually stratigraphically overlies the sequences in which they are developed (Figs. 3, 6). Moreover, this mapping has revealed that phylloid algal banks occur much lower in the stratigraphy than had hitherto been supposed, in strata normally assigned to the Minkinfjellet Formation. Confusion, therefore persists in how the boundary between the Minkinfjellet Formation and Cadellfjellet Member of the Wordiekammen Formation is defined. In order to clarify the nature of this boundary two newly defined lithostratigraphic units, the *Black Crag Beds* and *Pyefjellet Beds* (Tables 1, 2) are here used to define the base of the Cadellfjellet

Table 2. Lithological descriptions of the stratigraphic units within the Cadellfjellet Member of the Wordiekammen Formation and the uppermost part of the Minkinfjellet Formation (see Figs. 2, 3). Note that successively younger sediments within the Cadellfjellet Member indicate deposition in an increasingly near-shore setting, suggesting that the Cadellfjellet Member represents a long-term regressive rock succession.

Cadellfjellet Mb. (Wordiekammen Fm.)	Description	Age and thickness in Bünsow Land	Deposition setting
Mathewbreen beds	Very poorly exposed sequence of dolomites (often possessing moulds following the dissolution of gypsum) and thin intercalated gypsum beds. Thin carbonate mudstone and packstone beds are also present (Sundsbø 1982).	middle Gzelian 30–45 m	Restricted, shallow intertidal to supratidal inner shelf
Gerritbreen beds	Diverse lithologies including carbonate mudstones, packstones and locally relatively thick (ca. 5 m) cross-bedded sandy grainstone/calcareous sandstone units (Fig. 6). The Gerritbreen Beds originally included the Black Crag (Cutbill & Challinor 1965) but these beds are now considered to be a separate lithostratigraphic unit (see below).	early Gzelian ca. 20 m	Shallow, subtidal locally high-energy shelf
Black Crag Beds	A succession of limestones characterized by a series of distinctive massive carbonate mudstones (micrites) separated by bedded packstones and wackestones. The unit has a combined thickness of >60 m in western Bünsow Land but thins towards the east. The facies are arranged in a cyclic manner. A typical Black Crag cycle consists of well-bedded bioclastic (often fusulinid-rich) wackestones or packstones at the base which are overlain by massive black to dark grey carbonate mudstones (the Black Crag *sensu stricto*). The mudstones are generally massive or thickly bedded and are either sparsely fossiliferous or totally barren. Small moulds after gypsum crystals are locally present in the mudstones. Sedimentary breccias (debris flows and olistoliths) are locally present at the base of the first micrite unit. Subaerial exposure surfaces marked by minor karst development and locally by *in situ Microcodium* are present at the top of each cycle (Fig. 6). In western Bünsow Land and the Black Crag overlie evaporite-dolomite cycles of the uppermost Minkinfjellet Formation while in central and eastern Bünsow Land they are separated from the Minkinfjellet Formation by the Pyefjellet Beds (see Figs. 3, 4, 6).	early Kasimovian to late Kasimovian or possibly earliest Gzelian ca. 30–60 m	Open to partially restricted inner shelf setting (see Fig. 9c)
Pyefjellet Beds	A series of fossiliferous limestones whose constituent facies are cyclic; bedded bioclastic wackestones from the base of the cycles and are normally overlain by massive phylloid algal and/or *Palaeoaplysina* wackestones. Thin packstone or grainstone beds are commonly developed near the top of the cycles which are capped by subaerial exposure surfaces. The Pyefjellet Beds have a thickness of ca. 45 m in central Bünsow Land but thicken eastwards (reaching nearly 100 m thick at Ultunafjellet) and are transitional westwards into the predominantly evaporite-dolomite cycles of the uppermost part of the Minkinfjellet Formation (see Figs. 3, 6). The Pyefjellet Beds define a distinct carbonate platform that developed on the hanging wall of the Ny Friesland Block and which is here termed the Ny Friesland Platform.	late Moscovian to early Kasimovian 45–100 m	Fully marine open shelf sediments (see Fig. 8a, b)
Minkinfjellet Fm. (pars) [upper part, lateral equivalents to the Pyefjellet Beds]	On the west side of Meakinsfjellet and southern face of Campbellryggen the upper part of the Formation consists of thinly bedded dolomites, shales and gypsum beds. Further to the north (north side of Campbellryggen) gypsiferous strata are replaced by dolomite, sandstone and thin shale interbeds (Gee et al. 1953).	Moscovian–early Kasimovian	Predominantly shallow restricted hypersaline subtidal to supratidal setting with occasional open marine horizons

Member in Bünsow Land (see Table 2 and Fig. 3). The stratigraphical relationships of these units are outlined below and summarised in Figs. 2, 3 and 6.

Revised lithostratigraphic framework

The Black Crag Beds

Characteristics, age, distribution and thickness. – The term 'Black Crag' was first used by Gee et al. (1953) for '... one or several thick beds of cliff-forming porcellanous [micritic] limestone'. Up to five intervals of micrite have been recognized, each separated by fossiliferous limestone beds (see Fig. 6; Gee et al. 1953; Cutbill & Challinor 1965; Sundsbø 1982) and this package of rocks, varying from 30 to 60 m in total thickness, is here defined as the Black Crag Beds (Table 2). Fusulinids retrieved from the Black Crag Beds date them as early to late Kasimovian in age (see below).

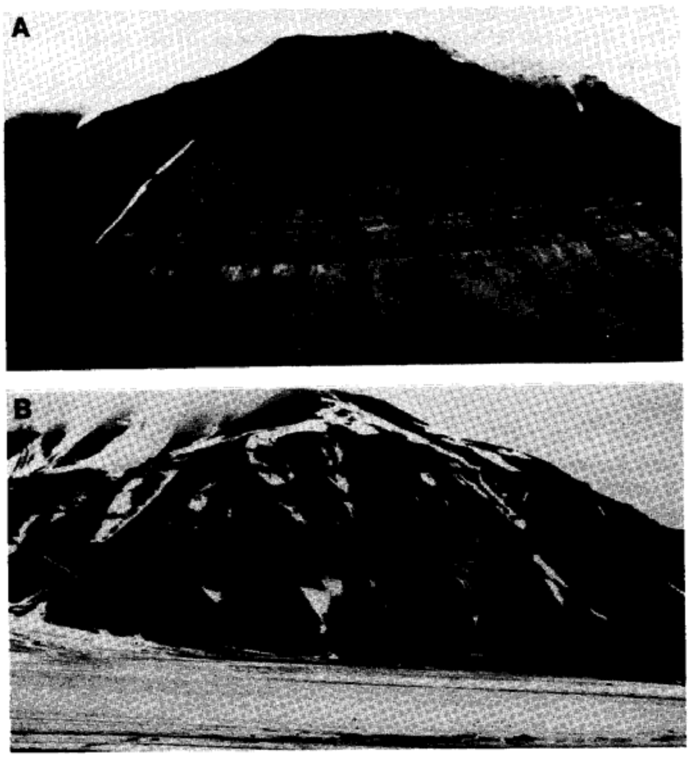


Fig. 4. Field photographs of the basal part of the Cadellfjellet Member in Bünsow Land. (A) Black Crag Beds (base arrowed) overlying a thick sequence of evaporitic strata (Minkinfjellet Formation). Note that the base of the Black Crag Beds is irregular due to the development of solifluction breccias during the last ice retreat. Small outcrops of evaporite occur within the scree-covered interval (small arrow) below the basal unit of Black Crag micrite (see Fig. 6). Southeastern corner of Campbellryggen, western Bünsow Land. Exposed rock succession is approximately 200 m thick. (B) Large arrows indicate the base of the Black Crag Beds on the north face of Pyefjellet in central Bünsow Land (Pyefjellet North locality, Fig. 6). Here the Black Crag Beds are underlain by a sequence of bedded limestones (the Pyefjellet Beds) which can be traced throughout central and eastern Bünsow Land. The lowermost, pale-looking unit (small arrow) is the thick phylloid bank developed at the top of the first Pyefjellet cycle (Py 1, see Fig. 6, Pyefjellet North) and is approximately 10 m thick.

As defined here the Black Crag Beds replace the lower part of Cutbill & Challinor's (1965) 'Gerritbreen Beds' (Table 1). It also amends slightly the informal definition of Sundsbø (1982). The term 'Gerritbreen Beds' is here reserved for the ca. 20 m of more diverse lithologies (Table 2) that overlie the Black Crag Beds (see Fig. 6; Cutbill & Challinor 1965; Sundsbø 1982).

Because the nature of the strata which underlie the Black Crag Beds differs in western and eastern Bünsow Land, two type localities are designated. The first is located on an eastern spur of Skeltonfjellet, which can be accessed via Stenhousebreen (a small valley on the western side of Gipsdalen), while the second is located on the north face of Pyefjellet, situated on the eastern side of Gipsdalen (Figs. 5a, 6). At both localities the base of the Black Crag Beds is taken at the base of the first thick, dark grey to black micrite unit. At Skeltonfjellet, and all localities to the west and south of Meankinsfjellet, the Black Crag Beds are underlain by intercalated gypsum and dolomite beds (see Fig. 6). As such, the base of the Black Crag Beds in these areas coincides with the base of the Cadellfjellet Member as originally defined by Cutbill & Challinor (1965) (Figs. 3, 4a, 6). However, in central and eastern Bünsow Land the Black Crag Beds are separated from the dolomitic sequences typical of the Minkinfjellet Formation by a succession of open marine limestones which contain phylloid algal and *Palaeoaplysina* buildups (Figs. 4b, 6). This succession of rocks was previously considered to be laterally equivalent to the Black Crag micrites (Sundsbø 1982; Dons 1983) but they are now known to be older and these marine limestones are here assigned to a new stratigraphical unit called the Pyefjellet Beds (Tables 1, 2, see below). The top of the Black Crag Beds is placed at the top of the fifth interval of dark grey to black micrite where there is a marked transition to a sedimentary succession containing units of thick cliff-forming sandy grainstones and calcareous sandstones (the Gerritbreen Beds, see Table 2 and Fig. 6).

The Black Crag Beds can be mapped throughout Bünsow Land (Figs. 3, 6; see also Gee et al. 1953, text figure 4) and show a drastic westwards thickening from ca. 30 m in eastern areas to in excess of 60 m on Skeltonfjellet. However, Black Crag micrites have not been recorded from the immediate vicinity of the Billefjorden Fault Zone and appear to be absent from the footwall of the Nordfjorden Block (Fig. 6). Nevertheless, thin intervals containing reworked clasts of black micrite are present in a small interval beneath a prominent sandstone horizon at Skansen (Fig. 6). Fusulinid datings from this interval indicate a late Kasimovian age, suggesting that this part of the Kapitol Member may indeed be laterally equivalent to the Black Crag Beds in the Billefjorden Trough (see discussion). Eastwards of the present study area outcrops are restricted to scattered nunataks in the Ny Friesland ice sheet and data are sparse. One exception is a logged succession on Malte Brunfjellet, where Kasimovian-aged rocks, though poorly exposed, are predominantly bioclastic limestones with abundant *in situ Microcodium* development (see Lønøy 1995).

In northwestern Bünsow Land (northern side of Campbellryggen) the base of the Black Crag Beds is often obscured by extensive brecciation (Figs. 4a, 5b). Several origins have been proposed for this breccia (see McWhae 1953 for discussion), but it is generally believed to have formed from collapse following the dissolution of evaporites in the upper part of the Minkinfjellet Formation (McWhae 1953; Lønøy 1995). However, recent field studies by two of the authors (NAHP & N-MH) on the southern side of Campbellryggen revealed the presence of both sedimentary breccias (debris flows and olistrostomes, see Fig. 6) as well as solifluction breccias within the basal Black Crag micrite. Collapse breccias were not observed even though they are extensive on the northern side of the same mountain (Dallmann 1993).

Lithologies and depositional environment. – Although a variety of lithologies are present in the Black Crag Beds, the most prominent is a sparse to non-fossiliferous dark

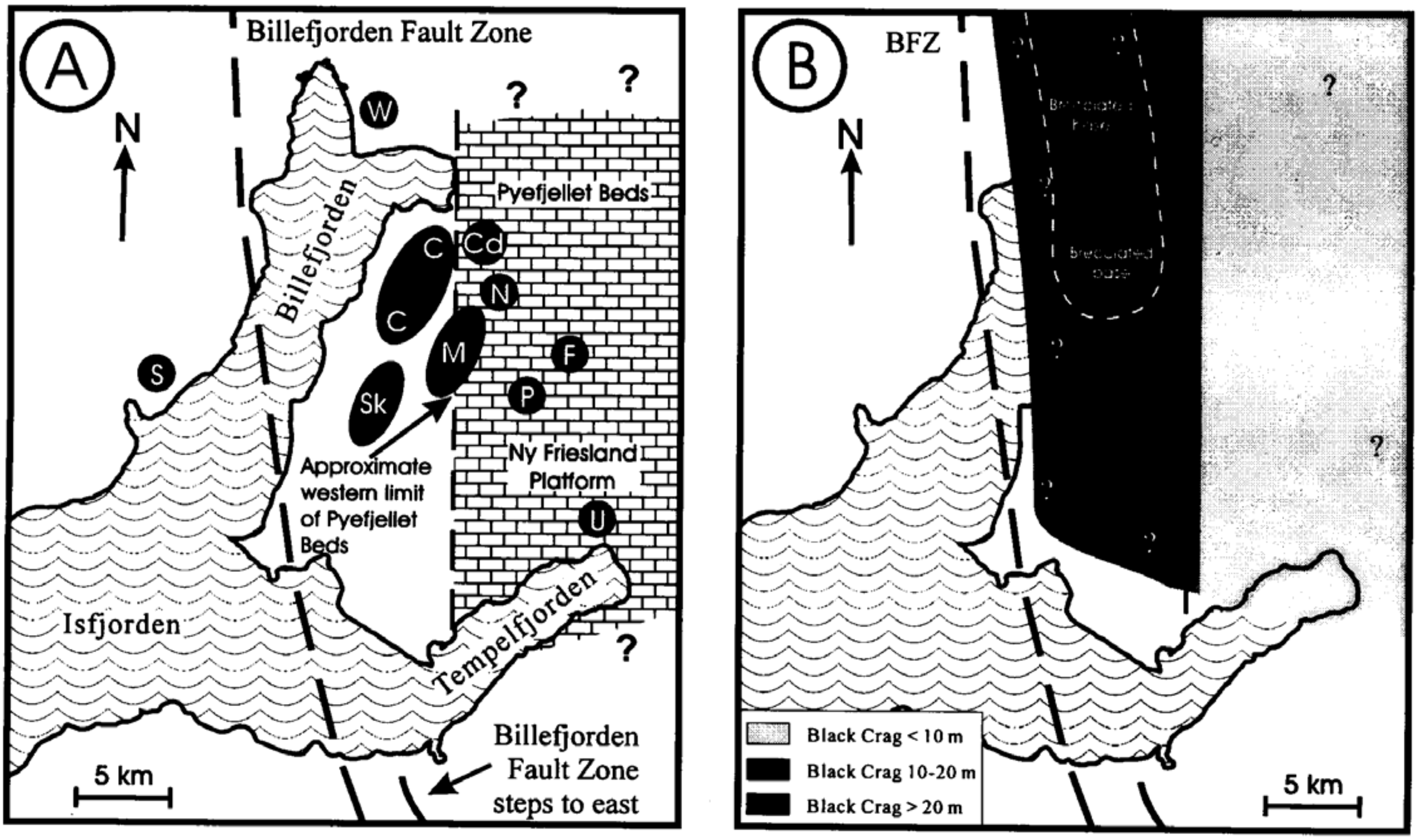


Fig. 5. (A) Sketch map of Bünsow Land illustrating the main localities discussed in the paper and the geographical extent of the Pyefjellet Beds. (B) Isopach map of the lowermost Black Crag cycle (BC1). The white dashed line shows the approximate extent of the solution collapse breccias developed at the base of this cycle (modified from McWhae 1953). Note the abrupt thinning of the first Black Crag cycle coincides with the western limit of the Pyefjellet Beds (see text for discussion). Localities, from west to east along line of cross section (Fig. 6): S – Skansen; C – Campbellryggen; Sk – Skeltonfjellet; M – Meakinsfjellet; N – Nordströmfjellet; P – Pyefjellet; F – Finlayfjellet; U – Ultunafjellet. Additional localities mentioned in the text, Cd – Cadellfjellet; W – Wordiekammen.

brown to black lime mudstone (micrite) which locally possesses gypsum crystals and/or lath-shaped moulds after gypsum. Sedimentary breccias (debris flows and olistoliths) are locally developed at the base of the first Black Crag micrite unit.

The micrite units that characterize the Black Crag Beds are typically massive and cliff forming whereas intervening fossiliferous limestones (packstones and wackestones) are generally well bedded and are often partly scree covered. Individual micrite units vary from 1.2 to nearly 30 m in thickness and each micrite systematically thickens westwards. This thickening can be abrupt and may have been controlled by topography developed on the underlying strata (Fig. 5b; see below).

Evidence of exposure, evinced through the development of *in situ Microcodium*, horizontal rhizocretions (root-mats) and local karstification, is common towards the top each micrite unit. Thin fossiliferous sandy grainstone beds (0.1–0.5 m thick) overlie the micrites. These grainstones contain a high proportion of detrital quartz and feldspar grains and typically possess a coarse basal lag of rounded pebble to cobble-sized clasts of lithified black mudstone, identical to the underlying micrite.

The facies present in the Black Crag Beds show a marked cyclicity and seven cycles have been identified, although not all are always present (see Fig. 6). A typical Black Crag cycle consists of sandy grainstones which directly overlie exposure surfaces. The grainstones pass upwards into fossiliferous wackestones and packstones indicative of deposition in an open marine environment. These in turn pass transitionally into the 'Black Crag' lime mudstones, considered to have been deposited in a restricted, hypersaline setting. Each cycle is capped by an exposure surface.

The Pyefjellet Beds

Characteristics, age, distribution and thickness. – The Pyefjellet Beds comprise a succession of fossiliferous limestones which stratigraphically underlie the Black Crag Beds in central and eastern Bünsow Land. They are readily distinguished from the Black Crag Beds by the absence of micrites and are named after a mountain in central Bünsow Land on which they are particularly well exposed (Figs. 4b, 5a). The type section is located on the north face of Pyefjellet, adjacent to the Methuenbreen glacier. West and south of Meakinsfjellet the Pyefjellet Beds are not present and the Black Crag Beds are underlain by a sequence of intercalated dolomites and evaporites which are considered to be the stratigraphic equivalents of the Pyefjellet Beds (see below, Figs. 2, 3, 4,

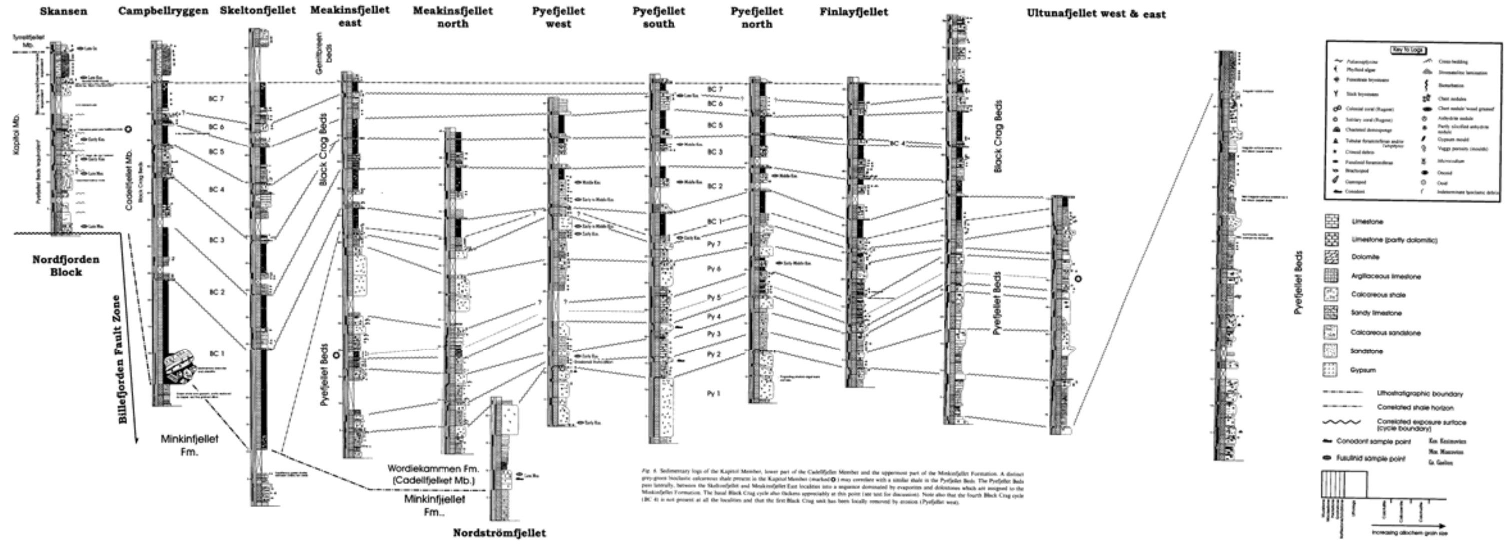


Fig. 6. Sedimentary logs of the Kapitol Member, lower part of the Cadellfjellet Member and the uppermost part of the Minkinfjellet Formation. A distinct grey-green bioclastic calcareous shale present in the Kapitol Member (marked ʘ) may correlate with a similar shale in the Pyefjellet Beds. The Pyefjellet Beds pass laterally, between the Skeltonfjellet and Meakinsfjellet East localities into a sequence dominated by evaporites and dolostones which are assigned to the Minkinfjellet Formation. The basal Black Crag cycle also thickens appreciably at this point (see text for discussion). Note also that the fourth Black Crag cycle (BC 4) is not present at all the localities and that the first Black Crag unit has been locally removed by erosion (Pyefjellet west).

6). The thickness of the Pyefjellet Beds increases from ca. 40 to 50 m in the vicinity of Gipsdalen, eastwards to nearly 100 m at Ultunafjellet (Fig. 6). Conodonts, sponges and fusulinid foraminiferans date the Pyefjellet Beds as late Moscovian to early Kasimovian in age (see below).

The top of the Pyefjellet Beds is defined by the base of the first thick, dark brown to black, sparsely to non-fossiliferous micrite of the overlying Black Crag Beds (see above), whereas the base is defined by the transition from bedded un- or sparsely-fossiliferous dolostones, typical of the underlying Minkinfjellet Formation, to undolomitized fossiliferous limestone beds (see Fig. 6). The basal contact is exposed on the southeastern corner of Nordströmfjellet where thickly bedded, coarse-grained crinoidal grainstones and packstones overlie thin to medium bedded, yellow to light brown, barren dolostones (Fig. 6). Elsewhere, the base of the unit is often difficult to define as the dolomitic upper part of the Minkinfjellet Formation is generally scree covered and the contact with the Pyefjellet Beds is rarely exposed. Nonetheless, it approximates to the base of the first major continuous cliffs (i.e. at the change from dolomite to limestone, Fig. 4b) exposed on the mountains in central Bünsow Land. Further east the contact between the Pyefjellet Beds and the Minkinfjellet Formation is even less clear. At Ultunafjellet bedded dolostones similar to those developed below the Pyefjellet Beds at Nordströmfjellet occur at several levels, intercalating with fossiliferous limestones which are often partly dolomitized (Fig. 6). Accordingly, the contact between the Cadellfjellet Member and the Minkinfjellet Formation appears to be more transitional in eastern areas.

Lithologies and depositional environment. – The Pyefjellet Beds consist of bedded fossiliferous limestones which display a variety of depositional textures. Thin to medium bedded wackestone and packstones predominate and alternate with thick to massive units of phylloid algal and/or *Palaeoaplysina* wackestone and bafflestone. The latter units form mappable lithosomes which possessed depositional relief on the sea floor and are hence termed 'carbonate buildups' (cf. Pickard 1992, p. 1083). Locally, beresellid-foraminiferal grainstones are developed in the Pyefjellet Beds. As with the overlying Black Crag Beds, the facies within the Pyefjellet Beds are arranged in a cyclic manner and seven cycles are recognized (Py 1–7, Fig. 6). Each cycle records an overall shallowing of the depositional environment; bioclastic wackestones and packstones form the base of the cycles and are succeeded by phylloid algal and/or *Palaeoaplysina* buildup facies (Figs. 6, 7). Beresellid grainstones

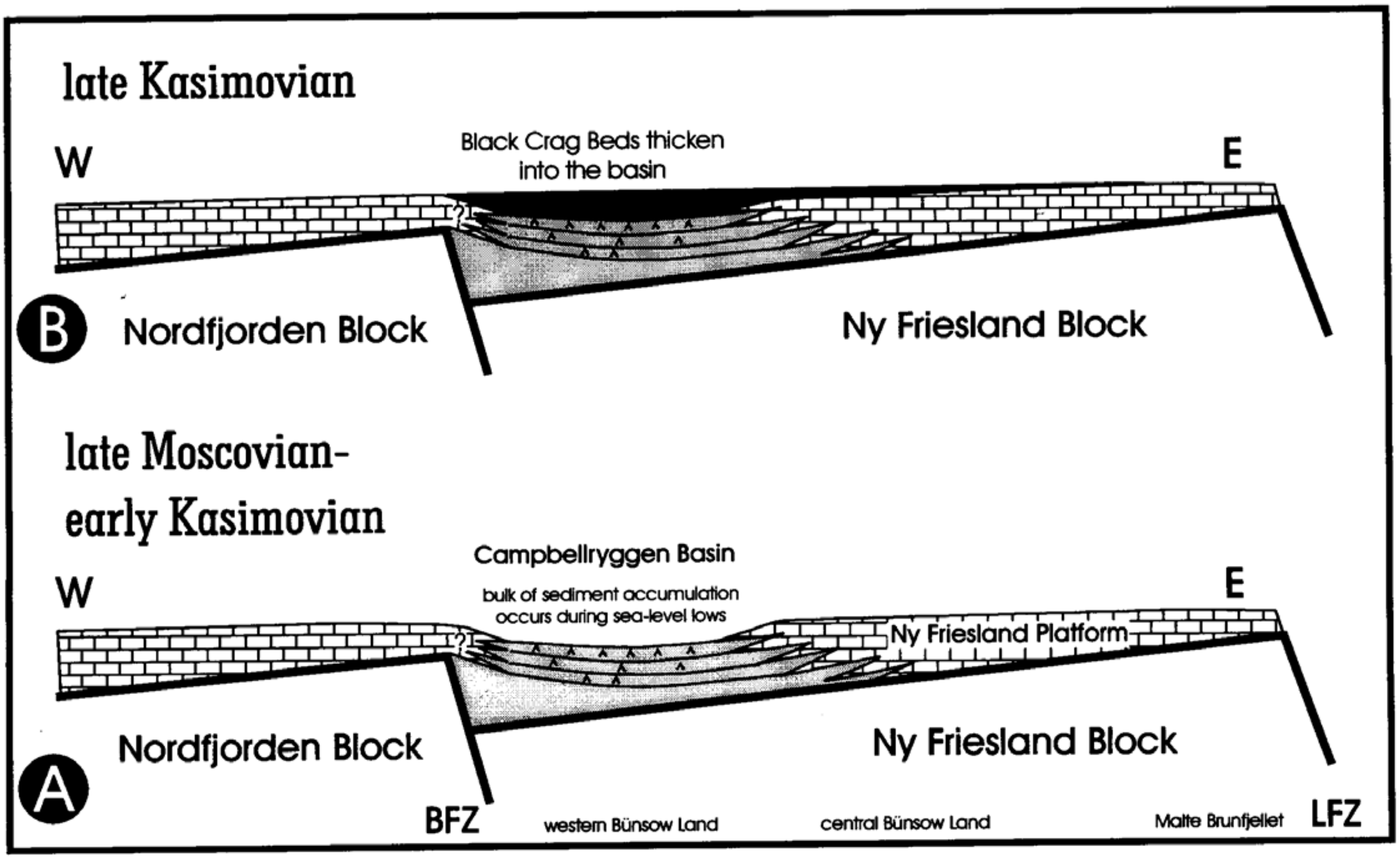


Fig. 7. Schematic sections across the Ny Friesland and Nordfjorden Blocks illustrating the development of the Ny Friesland Platform and the contemporary Campbellryggen Basin during: (A) late Moscovian–early Kasimovian time with the deposition of the Pyefjellet Beds (Cadellfjellet Member) and uppermost part of the Minkinfjellet Formation; (B) late Kasimovian time when the basin was 'in-filled' by the deposition of the Black Crag Beds. See also Fig. 8. NB. For simplicity, rocks older than late Moscovian have been omitted from the Ny Friesland Block. BFZ – Billefjorden Fault Zone; LFZ – Lomfjorden Fault Zone.

locally cap the cycles. Features typical of subaerial exposure are generally developed in the upper part of each cycle, these include *in situ Microcodium*, local preservation of silty and clay rich paleosols and hummocky karst surfaces.

Discussion. The succession of limestones, which represents the Pyefjellet Beds, was first noted by Singleton (reported in Gee et al. 1953, pp. 340–341) from Ultunafjellet on the eastern margin of Bünsow Land (Fig. 5a). Gee et al. (1953) recognised the stratigraphical relationship of these limestones with respect to the overlying Black Crag and suggested that they were laterally equivalent to the uppermost part of their 'Passage Beds' (the upper part of the Minkinfjellet Formation) in northwestern Bünsow Land (see Table 1). Recent mapping by the authors has confirmed this relationship (see Figs. 3, 6). However, on lithological grounds the Pyefjellet Beds should be assigned to the Cadellfjellet Member rather than the Minkinfjellet Formation ('Passage Beds') in which they were formerly included by Gee et al. (1953, see Table 1). As such, the base of the Pyefjellet Beds forms the base of the Cadellfjellet Member (and hence the newly defined Wordiekammen Formation; Dallmann et al. in press) in central and eastern Bünsow Land. Several points arise from this assignment:

1. The boundary between the Wordiekammen and Minkinfjellet Formations is diachronous, becoming younger westwards, towards the Billefjorden Fault Zone (Figs. 2, 3, 6).
2. As pointed out above, several authors (Sundsbø 1982; Dons 1983) have suggested that the base of the Cadellfjellet Member should be placed at the base of the first phylloid algal bank. Despite this being based on an erroneous assumption, i.e. that the phylloid algal banks were laterally equivalent to the Black Crag, phylloid banks are in fact developed near the base of the Pyefjellet Beds (Fig. 6), and owing to their massive nature, they often form the lowest outcrops of the Pyefjellet Beds (Fig. 4b). However, caution must be applied when using the phylloid algal buildups to define the base of the Cadellfjellet Member in central and eastern Bünsow Land because:- (i) they are not always developed in the first marine cycle of the Pyefjellet Beds (the buildups pass laterally westwards into crinoidal-rich wackestones and packstones); (ii) the base of any individual phylloid algal bank may be diachronous; bank facies developed simultaneously at several sites on the sea floor prior to amalgamation and the development of sheet-like buildup geometries (unpublished data); (iii) dolomitized phylloid algal banks are present in the upper part of the Minkinfjellet Formation on the southeastern and southwestern corner of Nordströmfjellet and Pyefjellet respectively (unpublished data).

Biostratigraphy

Conodont and fusulinid samples, together with corals were collected to date the measured sections. Previous palaeogeographical reconstructions and depositional models have indicated that the Nordfjorden Block remained a positive feature throughout most of late Carboniferous time and was not transgressed until the late Gzelian (Sundsbø 1982; Dons 1983; Worsley et al. 1986). However, Nilsson (1988, 1993) demonstrated that late Moscovian strata are present on the footwall of the Nordfjorden Block at Skansen (Figs. 1, 5a, 6) and Somerville (1995) has recorded late Moscovian ceriod rugose corals from near the base of the Kapitol Member at Ekmanfjorden (Fig. 2). Clearly, the block was 'drowned' much earlier than had previously been recognized and it is important to determine the equivalents of the Skansen section within the Billefjorden Trough, before any palaeogeographical reconstructions and depositional models can be attempted.

As discussed earlier, the base of the Cadellfjellet Member was originally considered by Cutbill & Challinor (1965) to be placed below 'Black Crag' or at the first appearance of the *Waeringella* (i.e. *Pseudofusulinella*) *usvae* fusulinid Zone of Gzelian age. However, Cutbill & Challinor's assemblage is now considered to consist of fusulinids typical of both the Kasimovian and Gzelian and it has been superseded by Nilsson's (1993) early-, middle- and late Kasimovian assemblages as well as her early Gzelian fusulinid assemblage.

Fusulinids from the topmost beds of the Cadellfjellet Member indicate a middle Gzelian age (Nilsson 1993), while conodonts and fusulinids from the base of the member (i.e. the base of the Pyefjellet Beds, see below and Fig. 6) suggest a late Moscovian age. As such the Cadellfjellet Member contains strata which are directly time equivalent to strata in the Kapitol Member developed on the footwall of the Nordfjorden Block where late Moscovian to late Kasimovian fusulinid datings have been recovered (Figs. 2, 6; Nilsson 1988, 1993).

Pyefjellet Beds

Conodonts recovered from the base of the Pyefjellet Beds on Nordströmfjellet (Fig. 6) yielded a fauna consisting of *Streptognathodus cancellosus* (Gunnell), *Idiognathodus delicatus* Gunnell, *I.* cf. *podolskiensis* Goreva, *I.* cf. *sinuosus* (Ellison & Graves) and *Neognathodus* cf. *medexultimus* Merrill. The stratigraphic ranges of these species are well known from North America (Sutherland & Grayson 1992), the Canadian Arctic (Bender 1980; Beauchamp et al. 1989a, Henderson et al. 1995) and Novaya Zemlya (Sobolev & Nakrem in press) as well as other areas in Russia (Barskov et al. 1984) and they indicate a late early to late Moscovian (Kashirskian to Myachkovskian) age.

Higher in the succession, the conodont *Diplognathodus coloradoensis* (Murray & Chronic) has been retrieved from the second cycle in the Pyefjellet Beds at Pyefjellet South (Py 2, see Fig. 6) while *Idiognathodus incurvus* Dunn has been recorded from the fourth cycle (Py 4, Fig. 6). Both of these conodonts have previously been recovered from Moscovian strata in North America and the Canadian Arctic (Bender 1980; von Bitter & Merrill 1990; Henderson et al. 1995).

Fusulinids recovered from the basal part of the Pyefjellet Beds on Nordströmfjellet (Fig. 6) have yielded *Wedekindellina dutkevichi* (Rauser-Chernousova), *Fusulinella* aff. *eopulchra* (Rauser-Chernousova), *Ozawainella* sp. and *Quasifusulinoides*? spp. suggesting a late Moscovian age, which is in close agreement with the conodont data. However, fusulinids retrieved from higher in the first cycle and from the third Pyefjellet cycle (Py 1 & 3, Fig. 6, Pyefjellet West) include *Protriticites* spp., *Quasifusulinoides* sp., *Obsoletes* sp. and *Ozawainella* sp. indicating an earliest Kasimovian age. Consequently, the Moscovian–Kasimovian boundary appears to lie within the first Pyefjellet cycle in the Gipsdalen vicinity.

Only randomly orientated thin sections were available from the upper part of the Pyefjellet Beds (Fig. 6, Pyefjellet North and West), but they contain tests of *Protriticites* sp. and *Obsoletes* sp. Both of these are common in lower Kasimovian strata but they also range into the middle Kasimovian (Bensh 1972). One sample from below the *Palaeoaplysina* buildup in cycle Py 7 at Pyefjellet West yielded *Pseudofusulinella*?, *Fusulinella eopulchra* (Rauser-Chernousova) and *Pseudoendothyra* sp., which are indicative of an age no younger than early Kasimovian. Furthermore, from a sample just below the top of the Pyefjellet Beds (Fig. 6, Pyefjellet South) Nilsson (1993) recovered a diverse assemblage which included *Protriticites variabilis* Bensh, *P. subovatus* Bensh, *P. sphaericus* Volozhaniniae, *P. ovoides* Putrya, *P. pseudomontiparus* Putrya, *P. globulus* Putrya and *P. inflatus* Bensh. This faunal assembly is considered to belong to her early Kasimovian *Protriticites pseudomontiparus-Obsoletes obsoletus* Zone.

Rare chaetetid demosponges are present at the top of the first cycle at Pyefjellet West, but have not been recorded higher in the succession. Chaetetids are, however, relatively common in the Pyefjellet Beds at Ultunafjellet (Fig. 6). They have also been recovered from the underlying Minkinfjellet Formation in Gipsdalen (Nordströmfjellet & Finlayfjellet) and from the lower part of the Kapitol Member at Ekmanfjorden (located on the Nordfjorden Block, see Figs. 1, 2; Somerville 1995) where, in both cases, the strata are of undoubted Moscovian age. Several authors have noted that the abundance of chaetetids decreases dramatically between the Moscovian and Kasimovian (Fedorowski 1981; West & Kershaw 1991; West 1992), an observation which is consistent with the stratigraphic distribution of these organisms in central Spitsbergen.

In conclusion, fusulinid, conodont and sponge fossils retrieved from the Pyefjellet Beds indicate a mainly early Kasimovian age for these strata in the vicinity of Gipsdalen, although the base does extend down into the late Moscovian and a thicker succession of late Moscovian age is present further to the east at Ultunafjellet and Malte Brunfjellet (Lønøy 1995).

Black Crag Beds

No conodonts have been recovered from Black Crag strata. However, one sample from just above the Black Crag Beds (at the base of the Gerritbreen Beds) at the Pyefjellet South locality has yielded *Idiognathodus magnificus* Stauffer & Plummer, which characterizes the Gzelian in the Urals (Barskov et al. 1984).

Fusulinid foraminiferans are generally abundant in the wackestone and packstone beds which form the base of the Black Crag cycles. The second and third cycles at Pyefjellet South (Fig. 6) include fusulinids such as *Montiparus montiparus* (Ehrenberg *sensu* Moeller), *M. rhombiformis* Rosovskaya, *M.* sp. A, *Quasifusulina* sp. and *Pseudofusulinella pulchra* (Rauser-Chernousova). This assemblage is correlated to the middle Kasimovian *Montiparus montiparus* Zone of the Russian Platform and Urals (Rosovskaya 1958; Rauser-Chernousova et al. 1979). However, the sixth cycle (BC6, Fig. 6) at Pyefjellet South yielded a fauna consisting of *Rauserites simplex* (Schellwien), *R. panteleevi* (Rosovskaya), *R. whitei* (Rauser-Chernousova & Belyaev), *R. morkvashensis* (Rosovskaya), *R. petschoricus* (Rauser-Chernousova), *R. umbus* Rosovskaya, *Quasifusulina* sp. and *Pseudofusulinella usvae* (Dutkevich) and is considered to belong to the late Kasimovian *Rauserites quasiarcticus* Zone of Nilsson (1993).

Although rugose corals are relatively sparse in the Black Crag Beds, large caniniids, *Caninia* aff. *verneuili* (Stuckenberg) and tabulate corals, *Syringopora*, have been recovered from packstones at the base of the first Black Crag cycle (BC 1) at Pyefjellet South and also from the basal part of the first Black Crag micrite. Moreover, loose blocks of Black Crag micrite have yielded hundreds of abraded caniniids (*Caninia* sp.) concentrated as storm lags within the micrites. Rare colonial rugose corals, including *Fomichevella* cf. *kiaeri major* (Heritsch), have been recorded from this interval. Unfortunately, none of these corals are age diagnostic, each being long-ranging forms.

Based primarily on the fusulinid foraminiferans the Black Crag Beds appear to range in age from the early to late Kasimovian. Nevertheless, the possibility exists that the top of the unit is early Gzelian in age.

Discussion

Several points arise from the revision of the Late Carboniferous stratigraphy of Bünsow Land. These are discussed below, before a new depositional model is presented.

Lithostratigraphic vs. cycle boundaries

The lithostratigraphic boundary between the Pyefjellet and Black Crag Beds is placed at the incoming of a very distinct facies, namely thick homogeneous micrites which are either non-fossiliferous or contain a very sparse fauna. It is important to note that this stratigraphic boundary does not coincide with a cycle boundary, rather it lies within the middle of a typical 'Black Crag' cycle (Fig. 6). Consequently, no break in sedimentation occurs between the Pyefjellet and Black Crag Beds.

Pyefjellet Beds – Minkinfjellet Member: lateral transition (Figs. 3, 6)

The Pyefjellet Beds can be traced throughout central and eastern Bünsow Land (Fig. 5a), but pass westward into a series of evaporites, dolomites and thin shales. This lateral transition is relatively rapid, occurring over a distance of several hundred metres. It also coincides with an abrupt thickening of the overlying Black Crag Beds (Figs. 3, 5b, 6). Thickening of the Black Crag cycles is best observed between the Meakinsfjellet east and Skeltonfjellet sections (Fig. 6). It may be seen in the field on the southeastern face of Meakinsfjellet where the first Black Crag micrite thickens dramatically from ca. 5 m to nearly 20 m over a distance of approximately 200 m. West of this point the limestone cycles of the Pyefjellet Beds are replaced by poorly exposed dolomite–gypsum cycles (Fig. 6) representing the uppermost part of Lønøy's (1995) upper unit in the Minkinfjellet Formation.

A review of previous literature (Sundsbø 1982; Dons 1983) suggests that a similar transition occurs further north between the northeastern corner of Campbellryggen and Cadellfjellet (see Fig. 5a for position of localities). Here, the thick basal unit of Black Crag mudstone exposed on Campbellryggen was considered by Sundsbø (1982) to pass laterally into a phylloid algal bank which crops out on Cadellfjellet. However, this basal mudstone may simply thin between these two mountains (as observed on Meakinsfjellet) and actually overlie the phylloid-bearing strata on Cadellfjellet. Such a hypothesis would not contradict the data presented by Sundsbø (1982, his figure 4.7a).

The upper part of the Minkinfjellet Formation is dominated by alternating thin-bedded cherty dolomites, evaporites (gypsum beds), conglomerates, micritic limestones and rare fossiliferous limestones (Gee et al. 1953, p. 340). Marked lateral facies changes have been recorded in the formation from exposures on Campbellryggen, west of Meakinsfjellet (Fig. 5a). From the northern to southern side of Campbellryggen (a distance of 7 km) thick gypsum beds (up to 10 m thick) occur at successively higher stratigraphic levels within the Minkinfjellet Member so that only ca. 40 m of upper Minkinfjellet sediments separate the predominantly gypsiferous strata from the base of the Black Crag Beds on the southeastern face of Campbellryggen (Figs. 4a, 6; Gee et al. 1953, text figures 8, 9; Lønøy 1995). Indeed, thinner gypsum beds can be observed even higher in the Minkinfjellet Formation at this locality (Figs. 4a, 6) and are also present on the eastern spur of Skeltonfjellet where they have been recorded less than 5 m below the base of the Black Crag Beds (Fig. 6, Skeltonfjellet). These beds are considered to be laterally equivalent to the Pyefjellet Beds. Further to the north, on the northern side of Campbellryggen, extensive solution collapse breccias are present at the top of the Minkinfjellet Formation. The collapse breccias extend across much of northwest Bünsow Land and also north of Billefjorden (see Fig. 5b), suggesting that gypsiferous strata were formerly even more extensive at this stratigraphic level. Dissolution of gypsum at the top of the Minkinfjellet Formation may have occurred during any one, or indeed all, of the exposure periods represented by subaerial exposure surfaces now recognized in the Black Crag Beds.

The lateral transition between the Pyefjellet Beds and the Minkinfjellet Formation is considered to mark the margin of a distinct carbonate platform (the Ny Friesland Platform) defined by the Pyefjellet Beds, with the uppermost Minkinfjellet sediments representing the off-platform 'basin fill' (see below and Figs. 3, 6). The abrupt thickening of the Black Crag Beds across this platform margin may therefore be partly attributable to relict topographic relief.

Correlation between the Cadellfjellet and Kapitol Members

One of the crucial factors in developing a depositional model for the Upper Carboniferous rocks of central Spitsbergen is the correlation between the rocks in the Billefjorden Trough (Minkinfjellet Formation and Cadellfjellet Member) with those present on the Nordfjorden Block (Kapitol Member, see Figs. 2, 6). Recent fusulinid datings have established that the strata comprising the lower part of the Kapitol Member at Skansen are time equivalent to the Pyefjellet Beds in central and eastern Bünsow Land, and by inference (see above), to the upper part of the Minkinfjellet Formation in western Bünsow Land (Figs. 2, 6). Although the base of the Kapitol Member is extensively dolomitized at Skansen (Fig. 6), it displays a similar cyclicity to that developed in the Pyefjellet Beds. Indeed, at least 10 cycles have been recorded in the Kapitol Member which is, nonetheless, significantly thinner than the Cadellfjellet Member in the Billefjorden Trough (Fig. 6). Phylloid algal buildups are present in the succession which otherwise possesses rocks indicative of deposition in a relatively shallow water setting (predominantly grainstones and packstones). A distinctive calcareous grey-green shale, rich in bioclastic debris is also present in the succession at Skansen. A similar shale horizon has been recorded in the Pyefjellet

Beds where it can be correlated across central and eastern Bünsow Land (Fig. 6). This shale, of probable early Kasimovian age, may prove to be an important marker horizon between the Kapitol and Cadellfjellet Members (Fig. 6).

Typical Black Crag micrites are missing from the Kapitol Member at Skansen. Nevertheless, a thin micrite unit containing *Microcodium* is present near the top of the succession where it is overlain by a distinctive conglomerate containing pebbles of micrite. A late Kasimovian age for the immediately overlying strata (Nilsson 1993) indicates that these beds are time equivalent to the uppermost part of the Black Crag Beds.

Traditionally, the top of the Kapitol Member has been placed at the base of a thick calcareous sandstone (Dons 1983; Stemmerik et al. 1995). However, several factors suggest that this unit ought to be included in the Kapitol Member, with the boundary between the Kapitol and Tyrrellfjellet Members being moved to the top of the sandstone (Fig. 6). Firstly, extensive *in situ Microcodium* occurs throughout the sandstone, suggesting that prolonged exposure and pedogenesis occurred after its deposition. This would be inconsistent with the generally transgressive sequences that mark the basal part of the Tyrrellfjellet Member. Secondly, the calcareous sandstone is lithologically similar to those present in the Gerritbreen Beds (Fig. 6). Indeed, thick sandstones have not been recorded from the base of the Tyrrellfjellet Member in other areas, although they are relatively common towards the top of the member (Lønøy 1982; Dons 1983; Johansen 1994). Consequently, the sandstone is here correlated with the Gerritbreen Beds of the Cadellfjellet Member. Importantly, strata equivalent to the Mathewbreen Beds were either not deposited on the footwall of the Nordfjorden Block, or were removed by erosion, prior to the regional late Gzelian transgression which marks the base of the Tyrrellfjellet Member (Fig. 2).

Depositional setting

Two palaeogeographical features appear to have controlled the distribution of Upper Carboniferous sediments in the Billefjorden Trough, and hence the Upper Carboniferous lithostratigraphic framework of Bünsow Land. The first is a late Moscovian–early Kasimovian carbonate platform defined by the Pyefjellet Beds of the Cadellfjellet Member. This platform developed on the hanging wall of the Ny Friesland Block (Figs. 7, 8) and is here defined as the Ny Friesland Platform. The second palaeogeographical element was a relatively shallow-water basin, termed here the Campbellryggen Basin, which was located between the western margin of the Ny Friesland Platform and the footwall of the Nordfjorden Block (Figs. 3, 7, 8). From variations in thickness across the margin of the Ny Friesland Platform (obtained primarily from the abrupt thickening of the Black Crag Beds, see Figs. 3, 5b, 6) this basin is not likely to have been very deep, probably in the order of tens of metres deeper than the platform during the deposition of the Pyefjellet Beds.

The margin of the Ny Friesland Platform is marked by westward thinning of the Pyefjellet Beds and concomitant interfingering of the Pyefjellet marine cycles with evaporites and barren dolostones of the uppermost part of the Minkinfjellet Formation (Figs. 3, 8). The latter, basin-fill sediments, are indicative of deposition in an arid, restricted, shallow subtidal to supratidal setting (Table 2). Clearly a dichotomy exists here. Any model for the distribution of Upper Carboniferous strata in Bünsow Land needs to explain (i) the development of an Upper Carboniferous platform comprised of stacked open marine cycles, and (ii) an age-equivalent basin filled predominantly by sediments typical of deposition in a shallow and periodically hypersaline environment. Basin geometry and the development of cyclicity are considered to be the main controls on this sediment distribution.

Basin geometry. – The location of the late Carboniferous Campbellryggen Basin coincides with the thickest developments of mid-Carboniferous strata (Ebbadalen Formation) in the Billefjorden Trough (Johannessen & Steel 1992). Indeed, antecedent topography created during Serpukhovian–Bashkirian aged extension may have controlled the location of this Late Carboniferous (Moscovian–Kasimovian) palaeogeographic feature. Alternatively, movement may have continued along the bounding faults into late Carboniferous time. Johannessen & Steel (1992) and Nøttvedt et al. (1993) noted that the thickness of the mid-Carboniferous strata in the Billefjorden Trough decreased to the south, where unpublished seismic data indicate that the Billefjorden Fault Zone steps towards the east (Fig. 5a), and they suggested that the mid-Carboniferous basin possibly closed in that direction. Could the Late Carboniferous carbonate-evaporite basin have also closed to the south? Partial closure of this basin, in combination with an arid climate would have aided the development of a restricted hypersaline environment during falls in sea level (see below).

Progradation and aggradation of the Ny Friesland Platform on the hanging-wall dip-slope of the Ny Friesland Block would have accentuated any antecedent topography present on the hanging-wall closer to the Billefjorden Fault Zone, thereby helping to both create and maintain basin topography (Fig. 8a). Evidence for progradation of the Ny Friesland Platform down the hanging-wall dip-slope of the block comes from two sources. Firstly, the eastward thickening of the Pyefjellet Beds suggests that 'platform' sedimentation was initiated earlier to the east. This is collaborated by a logged section on Malte Brunfjellet (see Fig. 1), located some 16 km further east of Bünsow Land (Lønøy 1995). Here a relatively thick sequence (ca. 40 m) of late Moscovian strata was recorded at the base of the Cadellfjellet Member which includes several phylloid algal and *Palaeoaplysina* buildups (Lønøy 1995). The rock succes-

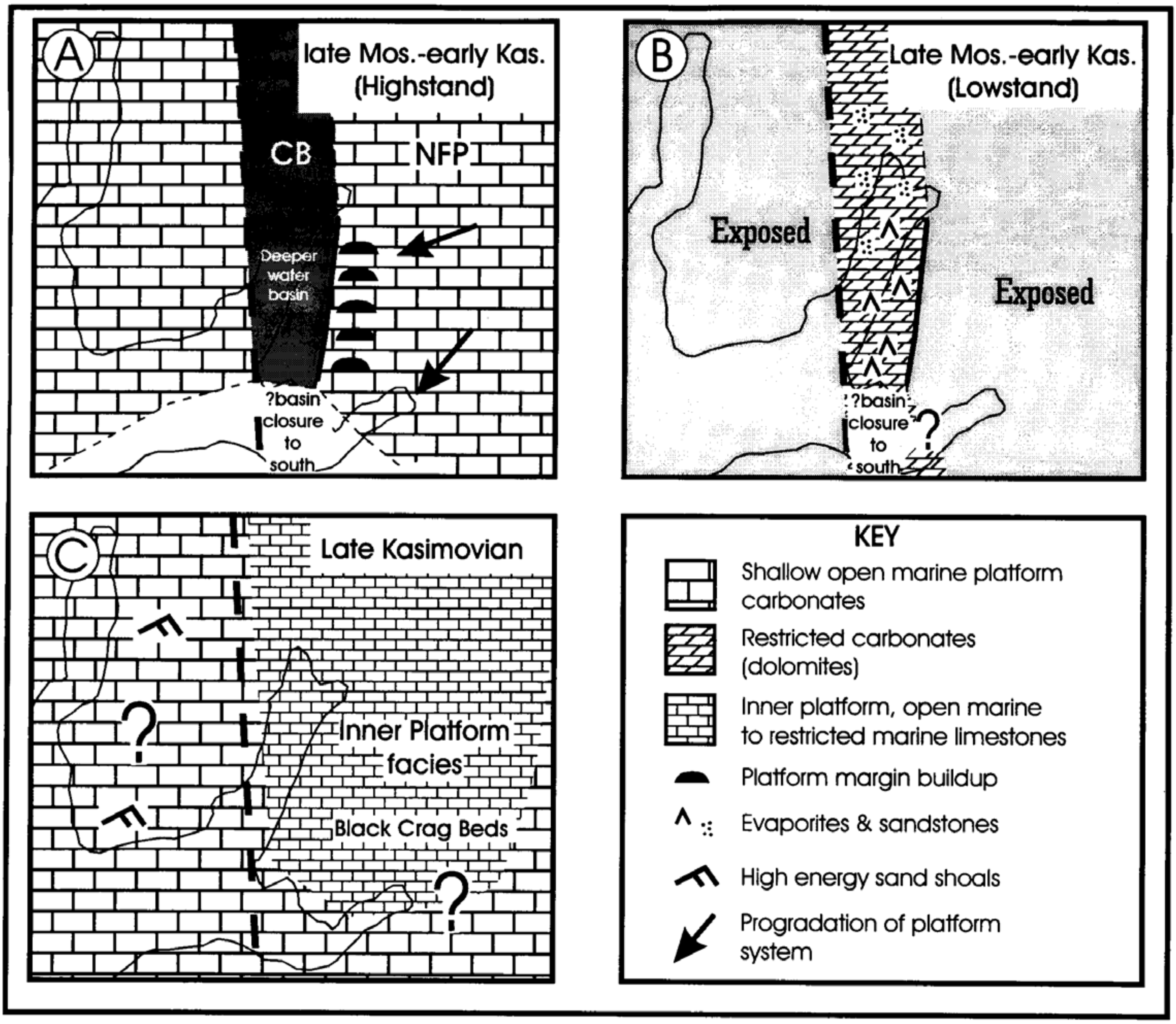


Fig. 8. Palaeogeographic maps for central Spitsbergen during Late Carboniferous (late Moscovian to late Kasimovian) time. Platform deposition occurred during sea-level highstands when phylloid algae and/or *Palaeoaplysina* buildups formed at the margin of the Ny Friesland Platform (A). Evidence for platform progradation is twofold: (i) the dip of the limestone beds close to the inferred platform margin steepens slightly, to the west against the southerly regional dip; (ii) from prograding phylloid algae and/or *Palaeoaplysina* buildups. During relative sea-level falls (B) the Ny Friesland Platform was exposed and lowstand sequences are restricted to the Campbellryggen Basin, located between the western margin of the Ny Friesland Platform and the footwall of the Nordfjorden Block. Here deposition was dominated by dolomites and evaporites in the basin centre and dolomites and sandstone further to the north (Gee et al. 1953). The mid- to late-Kasimovian-aged Black Crag Beds are considered to represent deposition on the inner part of a much more extensive carbonate platform (C) which covered the whole of central Spitsbergen. See also Fig. 7 and text for discussion. CB – Campbellryggen Basin; NFP – Ny Friesland Platform.

sion recorded by Lønøy (1995) is very similar to the predominantly Kasimovian-aged Pyefjellet Beds in central Bünsow Land (Fig. 6) and suggests that platform initiation commenced earlier on the up-dip part of the hanging-wall dip-slope. Moreover, the succession of dated Kasimovian strata at Malte Brunfjellet is much thinner than that in the Gipsdalen area, indicating that westward progradation of the platform sediments, as opposed to vertical aggradation, was relatively more important during Kasimovian time.

Prograding and aggrading carbonate platforms, developed on the hanging-wall dip-slopes of major fault blocks are a relatively common geological phenomenon and have been recorded from Carboniferous sequences in Britain and Ireland (Gawthorpe et al. 1989; Pickard et al. 1994), Cretaceous of Spain (Rosales et al. 1994) and from the Miocene of the Red Sea (Haddad et al. 1984; Aïssaoui et al. 1986; Jackson et al. 1988).

Cyclicity. – Both the Pyefjellet and Black Crag Beds are composed of a series of limestone cycles which are separated by subaerial exposure surfaces (Table 1; Fig. 6). Late Carboniferous cyclicity appears to be a world-wide phenomenon. It has been recorded from Arctic Canada (Beauchamp et al. 1989a, b), Greenland (Stemmerik & Elvebakk 1993), the Barents Sea (Stemmerik et al. 1995) and the USA (Goldhammer et al. 1991, 1994; Youle et al. 1994; Soreghan 1994) and has been linked with global sea-level changes (Ross & Ross 1985). Controls on sea level fluctuations are much debated, but high-amplitude short-term changes are commonly associated with the presence of polar ice caps (icehouse times) such as existed in Late Carboniferous and Early Permian time (Veevers & Powell 1987). During icehouse periods rapid, high-amplitude changes in sea-level are considered to arise from changes in ice volume driven by Milankovitch rhythms and can produce changes of up to 100 m (Tucker et al. 1993).

Despite the general agreement that the Late Carboniferous was an icehouse period, and thus a time of rapid sea-level changes, possible local tectonic influences on relative sea-level change must also be assessed. In sedimentary basins that have been subjected to later tectonic events, including inversion, evidence for synsedimentary tectonism is generally indirect and must be retrieved from the sedimentary record itself (cf. Gawthorpe et al. 1989). Several features of the Upper Carboniferous strata in central Spitsbergen suggest that tectonic movements persisted throughout Late Carboniferous (late Moscovian–Kasimovian) time. The first and most obvious is the pronounced thinning of late Moscovian and Kasimovian-aged strata across the Billefjorden Fault Zone and on to the footwall of the Nordfjorden Block (Fig. 6). Part of this thinning is the result of either non-deposition or erosion of strata equivalent in age to the uppermost part of the Cadellfjellet Member in the Billefjorden Trough (e.g. the Black Crag, Gerritbreen and Mathewbreen Beds, Fig. 6). The extensive development of *Microcodium* in the sandstone capping the Kapitol Member at Skansen is certainly indicative of one (or more) period(s) of subaerial exposure. Localized unconformities and extended periods of exposure are a feature common to sedimentary sequences developed close to the footwall of active normal fault systems (cf. Rosales et al. 1994). Perhaps the most convincing evidence for synsedimentary tectonism during the deposition of the Upper Carboniferous succession is the presence of sedimentary breccias at the base of the first Black Crag micrite. The breccias are restricted to the Campbellryggen Basin and most of the blocks appear to have been derived from the Pyefjellet Beds (or their equivalents on the Nordfjorden Block). Submarine sedimentary breccias, while having several possible origins, are commonly associated with periods of enhanced tectonic activity (cf. Gawthorpe 1986; Gawthorpe et al. 1989; Pickard et al. 1994). Indeed, tectonically induced collapse of platform margins has been documented in seismically active areas of the Caribbean (Mullins & Hine 1989; Mullins et al. 1991; Hine et al. 1992).

Dallmann (1993) described a series of subvertical fissures filled with angular breccias from the Black Crag Beds at Wordiekammen (situated at the head of Billefjorden, see Fig. 5a) which he suggested could have formed as a result of earthquake activity. However, in view of the subaerial exposure surfaces developed at the top of each cycle in the Black Crag Beds, Dallmann's 'earthquake breccias' could well represent large-scale karst features. Indeed, these breccias could be intimately related to the dissolution of evaporites and the development of the collapse breccias (the Fortet Member) which underlie the Black Crag Beds in this area (Figs. 4a, 5b). Consequently, the actual origin of Dallmann's (1993) breccias remains equivocal. Despite this, evidence suggests that active extension along the boundary faults (Billefjorden Fault Zone) continued into Late Carboniferous time and may have influenced some of the cyclicity observed in the Cadellfjellet Member.

Towards a depositional model

Periods of sea-level highs would have resulted in flooding of both the Campbellryggen Basin and Ny Friesland Platform leading to deposition of open marine sediments across the whole area (Figs. 7a, 8a). Sea-level falls, if of sufficient magnitude, would result in exposure of the platform and concomitant deposition of shallow-water facies in the basin (Figs. 7a, 8b). Correlatable subaerial exposure surfaces in the Pyefjellet Beds attest to periods of platform exposure (Fig. 6). Partial closure of the basin in conjunction with an arid climate, such as existed on the northern margin of Pangaea during Late Carboniferous time (Beauchamp et al. 1989a, b; Beauchamp 1994), would favour deposition of evaporites and dolomitic sediments while siliciclastic sediments bypassing the exposed platform would also accumulate in proximal parts of the basin (Fig. 8b). Indeed, the north-to-south transition of dolomites and sandstones, to evaporite-dominated sequences recorded in the uppermost part of the Minkinfjellet Formation on Campbellryggen, probably reflects a proximal-distal trend in the basin. Gee et al. (1953) and McWhae (1953) certainly considered that the southern part of Campbellryggen formed the depositional centre of their 'Passage Beds' basin (Table 1).

In sequence stratigraphic terms, the off-platform Minkinfjellet sediments are therefore represented primarily by lowstand sequences (Figs. 7, 8) and they are thus considered to be time-equivalent to the exposure surfaces in the platform strata of the Pyefjellet Beds. Similar lowstand basin-fill sequences are well documented from the Upper Carboniferous and Permian sequences of central USA (Sarg 1988; Goldhammer et al. 1991, 1994; Sonnenfeld & Cross 1993; Stafleu & Sonnenfeld 1994). During sea-level lows, siliciclastics bypassed exposed carbonate platforms and accumulated as wedges at the base of the platforms which bordered the Delaware and Central Basins of Texas and New Mexico (Sarg 1988; Garber et al. 1989). In the Paradox basin of Utah and Colorado sea-level falls resulted in the deposition of thick halite deposits in the basin centre, whereas gypsum (now anhydrite) and siliciclastics accumulated at the margins of the basin, adjacent to exposed carbonate platforms (Goldhammer et al. 1991, 1994). In each of the preceding examples platform development and progradation was essentially a sea-level high phenomenon and a similar relationship is suggested here for the Upper Carboniferous rock succession of Bünsow Land (Figs. 7, 8).

The Cadellfjellet Member: a single regressive rock succession

The transition from the Pyefjellet Beds (and contemporary Minkinfjellet sediments) to the Black Crag Beds represents a major change in circulation patterns and/or regional geography (Figs. 7, 8). The open marine cycles present in the Pyefjellet Beds are succeeded by inner platform, open marine to restricted hypersaline sediments of the Black Crag Beds. These Black Crag cycles are developed across both the late Moscovian–early Kasimovian Ny Friesland Platform and the Campbellryggen Basin. Indeed, individual Black Crag cycles thicken into the basin and filled any relict topography across the platform margin (see Figs. 5b, 6, 7, 8) and by late Kasimovian time a more extensive carbonate platform appears to have developed across the whole of central Spitsbergen (Fig. 8c). Flooding of this extensive late Kasimovian platform, recorded by the basal beds of each Black Crag cycle, led to the development of open marine conditions across the whole platform. However, subsequent sedimentation led to localized restriction and deposition of the 'Black Crag' mudstone facies in Bünsow Land. Grainstone facies dominate the tops of cycles in equivalent strata at Ekmanfjorden on the Nordfjorden Block (unpublished data).

The Mathewbreen Beds which form the uppermost part of the Cadellfjellet Member contain evaporites and dolomites (Table 1) and appear to represent deposition in an intertidal to supratidal setting (Sundsbø 1982). An increasingly restricted, nearshore depositional setting is therefore shown by successively younger units in the Cadellfjellet Member and the member appears to represent a single late Moscovian to middle Gzelian regressive succession. Regressive successions of similar magnitude, and spanning the same time interval, have also been documented in Arctic Canada, Greenland and the Barents Sea (Beauchamp et al. 1989b; Henderson et al. 1995) suggesting that a regional relative fall in sea-level affecting the northernpart of Pangaea may have been the predominant control on the development of the Cadellfjellet Member.

Conclusions

1. Two formal units (the Pyefjellet and Black Crag Beds) are used to define the base of the Cadellfjellet Member in Bünsow Land. The Pyefjellet Beds are restricted to central and eastern areas while the Black Crag Beds can be traced throughout Bünsow Land and also further north (Gee et al. 1953). Mapping of the Pyefjellet Beds suggests that they grade laterally into evaporites and dolomites which represent the upper part of the Minkinfjellet Formation in western Bünsow Land.
2. The Pyefjellet Beds are considered to represent a late Moscovian–early Kasimovian carbonate platform (the Ny Friesland Platform) which developed on the hanging-wall of the Ny Friesland Block. A distinct basin, the Campbellryggen Basin, formed between the western margin of the Ny Friesland Platform and the footwall of the Nordfjorden Block. This basin was filled largely by Minkinfjellet Formation sediments indicative of deposition in a shallow restricted environment and the lateral transition between the Pyefjellet Beds and Minkinfjellet Formation is considered to represent a platform margin.
3. The rock strata represented by the uppermost part of the Minkinfjellet Formation are considered to have been primarily deposited during sea-level lows when the Ny Friesland Platform was exposed. Platform sedimentation and progradation was a sea-level high phenomenon and resulted in the deposition of the Pyefjellet Beds.
4. The transition from Pyefjellet to Black Crag Beds probably reflects a large-scale change in circulation patterns across the central Spitsbergen carbonate province. The Black Crag cycles are considered to represent deposition on the inner part of a much more extensive carbonate platform, which covered the whole of central Spitsbergen (Figs. 7, 8). The Black Crag Beds drape across the margin of the Ny Friesland Platform and together with the succeeding Gerritbreen and Mathewbreen Beds they filled relict topography in the Campbellryggen Basin.

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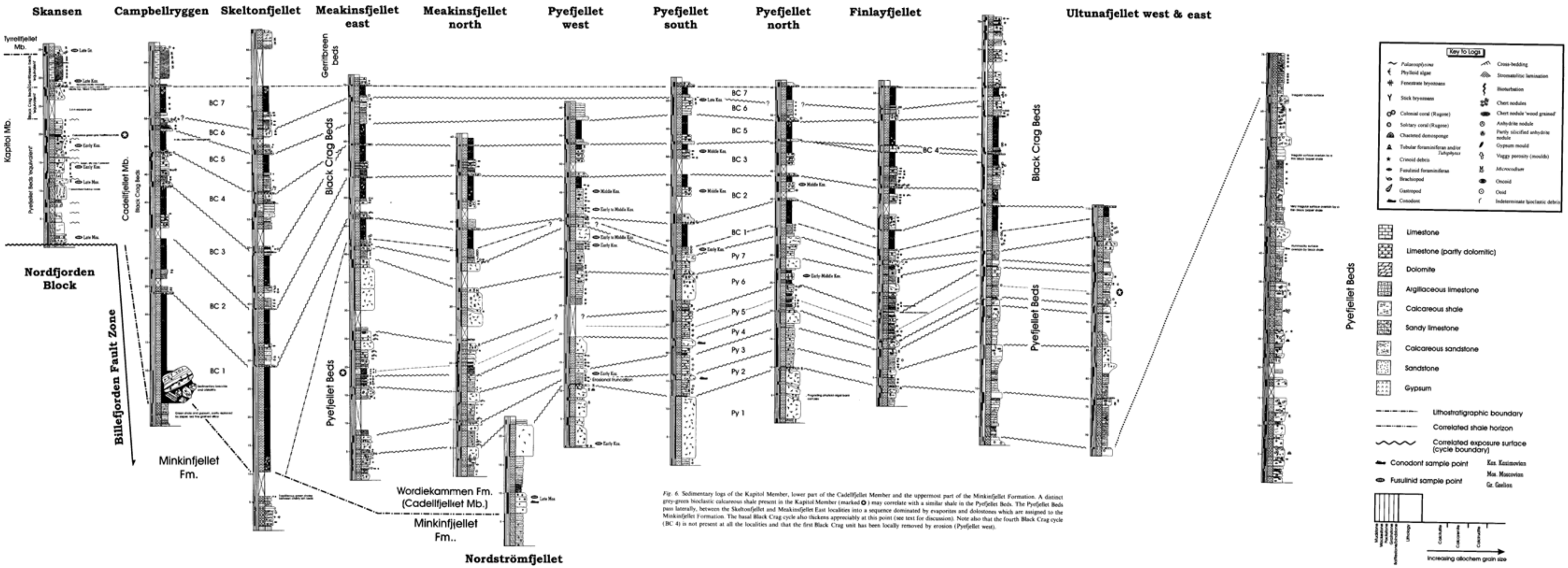

Fig. 6. Sedimentary logs of the Kapitol Member, lower part of the Cadellfjellet Member and the uppermost part of the Minkinfjellet Formation. A distinct grey-green bioclastic calcareous shale present in the Kapitol Member (marked ✪) may correlate with a similar shale in the Pyefjellet Beds. The Pyefjellet Beds pass laterally, between the Skeltonfjellet and Meakinsfjellet East localities into a sequence dominated by evaporites and dolostones which are assigned to the Minkinfjellet Formation. The basal Black Crag cycle also thickens appreciably at this point (see text for discussion). Note also that the fourth Black Crag cycle (BC 4) is not present at all the localities and that the first Black Crag unit has been locally removed by erosion (Pyefjellet west).