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# Type section of the Bravaisberget Formation (Middle Triassic) at Bravaisberget, western Nathorst Land, Spitsbergen, Svalbard

Krzysztof P. KRAJEWSKI[1*], Przemysław KARCZ[1], Ewa WOŹNY[1] and Atle MØRK[2]

[1] *Instytut Nauk Geologicznych PAN, Twarda 51/55, 00-818 Warszawa, Poland*
*<kpkraj@twarda.pan.pl> <pkarcz@twarda.pan.pl> <ew_ja@wp.pl>*

[2] *SINTEF Petroleum Research, NO-7465 Trondheim, Norway & Department of Geology and Mineral Resources Engeneering, NTNU, Norwegian University of Sciences and Technology, NO-7491, Trondheim, Norway <Atle.Mork@iku.sintef.no>*

**Abstract**: The Bravaisberget Formation in Spitsbergen embraces an organic carbon-rich, clastic sequence that reflects a general shallow shelf development of the Middle Triassic depositional system in Svalbard. New observations and measurements of the type section of the formation at Bravaisberget in western Nathorst Land allow to present detailed lithostratigraphical subdivision of the formation, and aid to reconstruct its depositional history. The subdivision of the formation (209 m thick at type section) into the Passhatten, Somovbreen, and Van Keulenfjorden members is sustained after Mørk *et al.* (1999), though with new position of the boundary between the Passhatten and Somovbreen mbs. The Passhatten Mb is defined to embrace the black shale-dominated sequence that forms the lower and middle parts of the formation (160 m thick). The Somovbreen Mb (20 m thick) is confined to the overlying, calcite-cemented sequence of marine sandstones. The Van Keulenfjorden Mb (29 m thick) forms the topmost part of the formation composed of siliceous and dolomitic sandstones. The formation is subdivided into twelve informal units, out of which eight is defined in the Passhatten Mb (units 1 to 8), two in the Somovbreen Mb (units 9 and 10), and also two in the Van Keulenfjorden Mb (units 11 and 12). Units 1, 3, 5, 7 and 9 contain noticeable to abundant phosphorite, and are interspaced by four black shale sequences (units 2, 4, 6, and 8). Unit 9 passes upwards gradually into the main sandstone sequence (unit 10) of the Somovbreen Mb. The base of the Van Keulenfjorden Mb is a discontinuity surface covered by thin phosphorite lag. The Van Keulenfjorden Mb consists of two superimposed sandstone units (units 11 and 12) that form indistinct coarsening-upward sequences. The Bravaisberget Fm records two consequent transgressive pulses that introduced high biological productivity conditions to the shelf basin. The Passhatten Mb shows pronounced repetition of sediment types resulting from interplay between organic-prone, fine-grained environments, and clastic bar environments that focused phosphogenesis. The lower part of the member (units 1 to 5) contains well-developed bar top sequences with abundant nodular phosphorite, which are under- and overlain by the bar side sequences grading into silt- to mud-shale. The upper part of the member (units 6 to 8) is dominated by

[*] *Corresponding author*

mud-shale, showing the bar top to side sequence with recurrent phosphatic grainstones in its middle part. Maximum stagnation and deep-water conditions occurred during deposition of the topmost shale sequence (unit 8). Rapid shallowing trend terminated organic-rich environments of the Passhatten Mb, and was associated with enhanced phosphogenesis at base of the Somovbreen Mb (unit 9). Bioturbated sandstones of the Somovbreen Mb (unit 10) record progradation of shallow-marine clastic environments. The sequence of the Van Keulenfjorden Mb (units 11 and 12) was deposited in brackish environments reflecting closure of the Middle Triassic basin in western Svalbard.

Key words: Arctic, Spitsbergen, Middle Triassic, Bravaisberget Formation, stratotype, lithostratigraphy, facies, phosphogenesis.

## Introduction

Excellent exposures of rocks in Svalbard give insight into the geological structure and evolution of the western Barents Sea Shelf (Birkenmajer 1981; Faleide *et al.* 1996; Harland 1997). The lithostratigraphic scheme developed on land has been extended into offshore areas, providing a framework in which to precise future exploration targets in the region (Dallmann *et al.* 1999; Mørk *et al.* 1999; Dallmann *et al.* 2002; Larssen *et al.* 2002). The Middle Triassic sedimentary sequence exposed in Svalbard is thought to be one of the best potential petroleum source units, because it is prominently rich in organic carbon, contains mostly oil-prone kerogen, and extends into wide underwater area of the shelf (Forsberg and Bjorøy 1983; Mørk and Bjorøy 1984; Leith *et al.* 1992; Mørk *et al.* 1993, 1999; Mørk and Elvebakk 1999).

This paper presents detailed description of section of the Middle Triassic organic carbon-rich sequence at Bravaisberget in western Nathorst Land, Spitsbergen. The section was first described by Buchan *et al.* (1965), and measured in more detail by Mørk *et al*. (1982). It has been defined as the stratotype for the Bravaisberget Formation, and hypostratotype for two of its members (the Passhatten and Somovbreen mbs) in the *Lithostratigraphic Lexicon of Svalbard* (Mørk *et al*. 1999: section M-19/20b/22b), in accordance with the stratigraphical nomenclature of Nystuen (1989). New observations and measurements allow to present detailed lithostratigraphical subdivision of the formation, and aid to reconstruct its depositional history. Revised position of the boundary between the Passhatten and Somovbreen mbs is based on improved lithological correlations with their type sections at Treskelen in Hornsund (Krajewski 2000e: pl. 1). The amendments of the hypostratotypes have been approved by the Norwegian Committee on Stratigraphy.

## Geological background

The Middle Triassic sedimentary sequence in Svalbard crops out in Spitsbergen, SW Nordaustlandet, Barentsøya, and Edgeøya (Fig. 1). The sequence is overmature

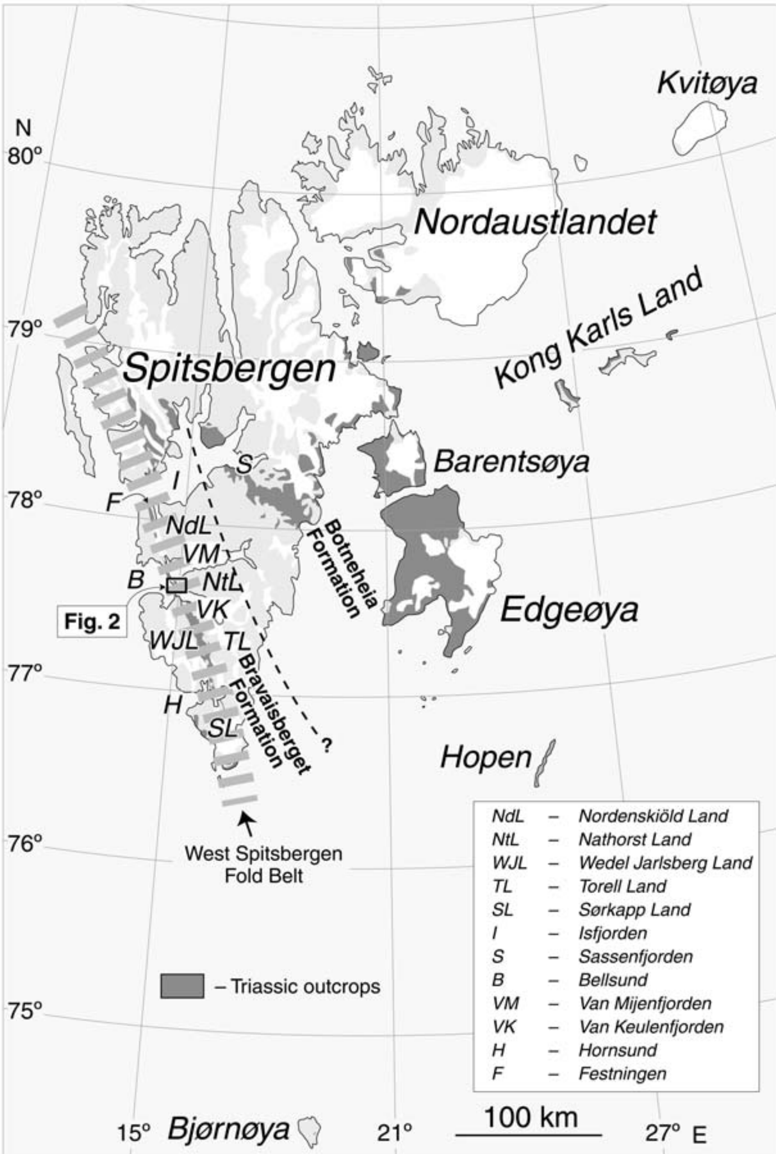



Fig. 1. Sketch map of the Svalbard archipelago showing location of stratotype for the Bravaisberget Fm at Bravaisberget in western Nathorst Land in Spitsbergen (rectangle enlarged in Fig. 2). Grey is ice-free area, and white is ice cover.

with respect to oil generation in the Cenozoic West Spitsbergen Fold Belt, and mature to early mature in the remainder of the islands, except local contacts with Late Mesozoic dolerite sills and dykes (Mørk and Bjorøy 1984; Abdullah 1999; Krajewski 2000d, e). It was deposited in a broad shelf basin that was bordered by delta-dominated land located west and southwest of the present western coast of

Spitsbergen (Mørk *et al.* 1982; Krajewski 2000a). The sediments in western and southern Spitsbergen contain in general more coarse-grained clastics, compared to the shale-dominated sediments in central and eastern Svalbard (Buchan *et al.* 1965; Pčelina 1965a, b, 1967; Flood *et al.* 1971; Birkenmajer 1977; Lock *et al.* 1978; Worsley and Mørk 1978; Mørk *et al.* 1982). These two developments are classified into the Bravaisberget and Botneheia formations, respectively (Mørk *et al.* 1999). The association of organic carbon, mineral phosphorus, and siliceous biotas suggests high biological productivity during the Middle Triassic in Svalbard, though complex facies patterns and poorly reconstructed paleogeography make it difficult to conclude about exact mechanisms of basin nutrification (Worsley 1986; Weitschat and Bandel 1991; Krajewski 2000a–e, 2005, in press; Embry *et al.* 2002).

The Bravaisberget and Botneheia fms are included in the upper part of the Early–Middle Triassic Sassendalen Group, which embraces several transgressive-regressive cycles (Mørk *et al.* 1982, 1993; Egorov and Mørk 2000). Distinct sequence boundaries in the group are interpreted to represent major sea level changes in the Boreal Ocean (Embry 1988, 1989; Mørk *et al.* 1989; Egorov and Mørk 2000; Embry and Mørk in press). The bottom of the Bravaisberget and Botneheia fms is marked by regional transgression in Early Anisian, and the top by regional regression in Late Ladinian, with possible emersion or non-depositional episode at boundary towards the overlying Late Triassic–Middle Jurassic Kapp Toscana Group (Buchan *et al.* 1965; Flood *et al.* 1971; Korchinskaya 1972; Weitschat and Lehmann 1983; Weitschat 1986; Weitschat and Dagys 1989). In most outcrop areas, the succession is dominated by black, organic carbon-rich shale containing varying amounts of phosphorite (Krajewski 2000a–c, in press). This shale forms bulk of the Botneheia Fm in central and eastern Spitsbergen, and on eastern islands of the archipelago. The upper part of this sequence, represented by very organic-rich, phosphatic mudrock with abundant thin-shelled pelecypods (*Daonella*), is distinguished as the Blanknuten Member (Mørk *et al.* 1982, 1999). The Anisian/Ladinian boundary is situated in the middle of this member (Weitschat and Lehmann 1983). Black shale dominates the lower and middle parts of the Bravaisberget Fm in western Spitsbergen (Birkenmajer 1977; Krajewski 2000a). The shale-dominated sequence is here classified into the Passhatten Member (Birkenmajer 1977; Mørk *et al.* 1982, 1999), which is roughly Anisian in age (Tozer and Parker 1968; Korchinakaya 1972). It contains varying number of siltstone to sandstone beds with abundant nodular phosphorite and, at places, also phosphatic grainstones and phosphatic crust horizons. The upper part of the formation usually shows two superimposed siltstone/sandstone sequences, which are classified into the Somovbreen and Van Keulenfjorden members (Mørk *et al.* 1999). The Somovbreen Mb encompasses marine siltstones and sandstones with changing amounts of nodular phosphorite that are cemented mostly by calcite (Krajewski 2000e). The Van Keulenfjorden Mb encompasses siltstones and sandstones deposited in brackish environments that show siliceous and dolomitic cements (Pčelina 1983). The sandstone facies of the Somovbreen Mb thickens southwards and southwestwards in Spitsbergen at the expense of the Passhatten shale, reflecting shallowing of the environment and proximity of land (Krajewski 2000a). This shallowing trend is associated with a general thinning of the Bravaisberget Fm that results from deposition on the Hornsund-Sørkapp High, a positive tectonic block in the southernmost Spitsbergen (Worsley and Mørk 1978; Dallmann *et al.* 1993b; Winsnes *et al.* 1993; Harland 1997). In this area, medium- to coarse-grained, cross-bedded sandstone sequences with plant detritus form lenses in the lower and middle parts of the formation. They represent distributary channels of delta top facies that prograded into the shallow shelf depositional area. These lenses are discerned as the Karentoppen Member (Mørk *et al.* 1982, 1999). The Somovbreen and Van Keulenfjorden mbs are generally considered to be of Ladinian age, though biostratigraphic relations are poorly constrained and the member boundaries are diachronous.

## Bravaisberget Formation in western Nathorst Land

The Bravaisberget Fm in western Nathorst Land forms a 10-km long belt stretching NNW–SSE between Van Mijenfjorden and Van Keulenfjorden (Fig. 2). The formation occurs at eastern margin of the West Spitsbergen Fold Belt, being involved in a wide monoclinal structure that dips eastwards (Fig. 3A). Major tectonic deformations of the Fold Belt are exposed at Midterhuken peninsula (Hjelle *et al.* 1986; Dallmann *et al.* 1990), where they are dominated by isoclinal folds and imbricate thrusts (Maher 1984, 1988; Maher *et al.* 1986; Ringset 1988). The monoclinal structure to the east shows second-order folds, thrusts and thrust faults (Dallmann *et al.* 1993a). The latter are surrounded by intensely folded zones developed mostly in shale-dominated sedimentary sequences. Such zones occur in the shale-dominated Passhatten Mb throughout the outcrop belt in Nathorst Land. One of them is exposed in a rocky gully at SE margin of Bravaisberget (Fig. 3B). It extends down to the shore of Van Keulenfjorden, and is associated with abrupt change of dip of the Somovbreen and Van Keulenfjorden mbs.

The Bravaisberget Fm in western Nathorst Land overlies a thick sequence of the Vardebukta and Tvillingodden formations (Early Triassic), which in the Bravaisberget section exceeds 400 m (Fig. 3B). The two formations embrace four coarsening-upward units, out of which the lower (and the thickest one) is attributed to the Vardebukta Fm, and the succeeding three to the Tvillingodden Fm (Fig. 4A; see also Mørk *et al.* 1999: fig. 3-13; Egorov and Mørk 2000: fig. 9). The Bravaisberget Fm is overlain by a sequence of shales, mudstones, and cross-bedded and massive sandstones with recurrent horizons of diagenetic carbonate bodies, which is classified into the Kapp Toscana Group (Late Triassic–Middle Jurassic) (Mørk *et al.* 1999). In spite of the fact that there are excellent sections of the group along the coasts of Van Mijenfjorden and Van Keulenfjorden, it remains

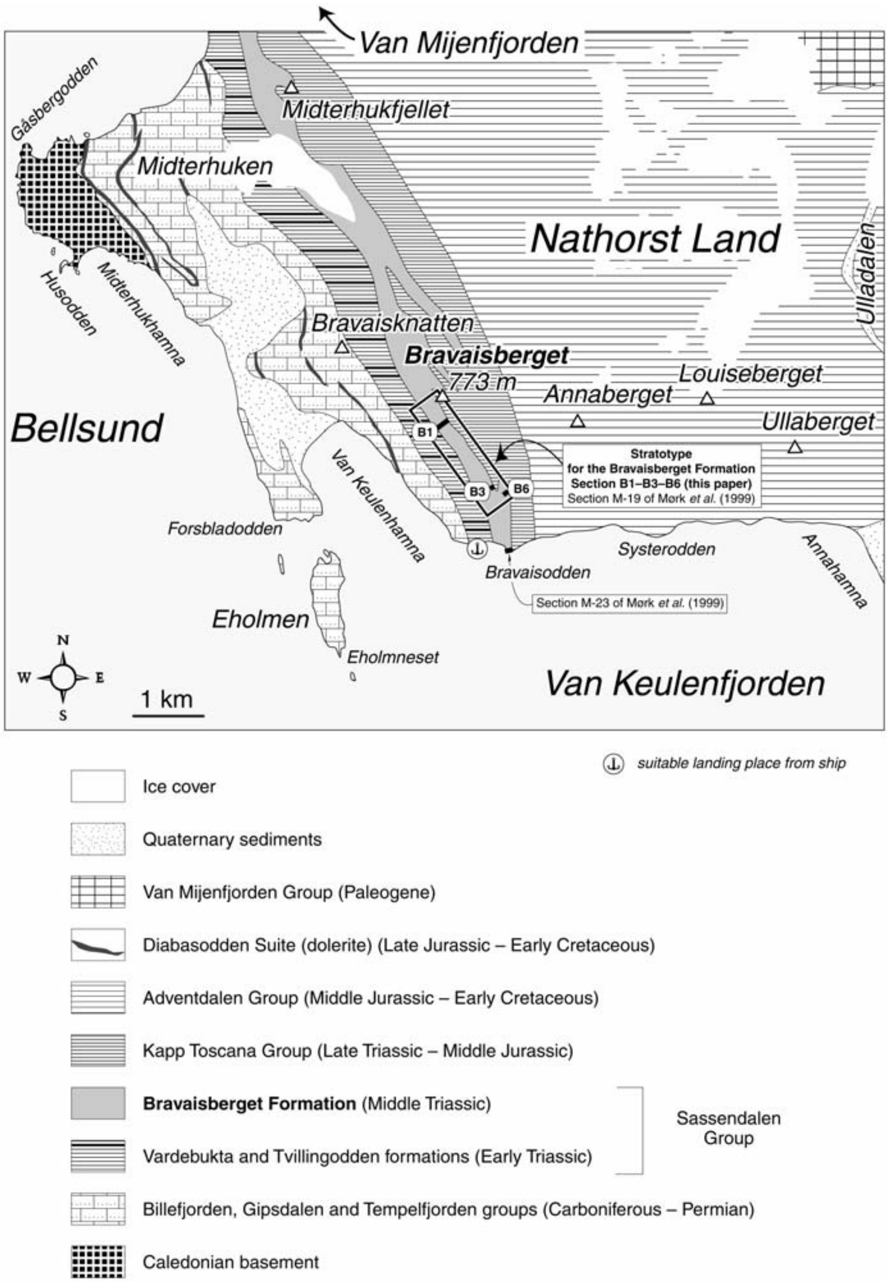



Fig. 2. Geological map of the western part of Nathorst Land. Stratotype for the Bravaisberget Fm is the SW slope of Bravaisberget (mountain) exposed towards Van Keulenfjorden. The section presented in this paper is composite section B1–B3–B6. The section M-19 of Mørk *et al.* (1999) has been referred to represent a general section of the Middle Triassic sequence at Bravaisberget (rectangle). The section M-23 of Mørk *et al.* (1999) at Bravaisodden is stratotype for the Van Keulenfjorden Mb (topmost member) of the Bravaisberget Fm. Geology after Dallmann *et al.* (1990), simplified.

poorly studied in the area. Our observations suggest that the sequence directly overlying the Bravaisberget Fm belongs to the De Geerdalen Formation, with the Tschermakfjellet Formation widely missing in western Nathorst Land.

The outcrop belt of the Bravaisberget Fm in western Nathorst Land has a continuation to the south (Wedel Jarlsberg Land and Torell Land) and to the north (Nordenskiöld Land) in Spitsbergen (Różycki 1959; Mørk *et al.* 1982; Hjelle *et al.* 1985; Dallmann *et al.* 1990). The formation occurring north of Van Mijenfjorden (Fridtjovbreen) shows in general similar tectonic position to the one observed in western Nathorst Land, though the outcrops are poor and isolated. At the northern margin of Wedel Jarlsberg Land, the formation occurs in two major parts of the Berzeliustinden thrust structure, with the Reinodden section representing the lower limb, and the Sterneckøya–Bourbonhamna–Foldaksla sections representing the upper limb (Różycki 1959; Harland 1997). Tectonic deformations are far stronger than those observed at Bravaisberget, though the outcrops provide excellent sections of parts of the formation.

The Bravaisberget Fm at Bravaisberget shows clear-cut lower and upper boundaries accentuated by different erosional resistance of the adjoining rock complexes (Fig. 3B). The formation exceeds 200 m in thickness. It is subdivided into three successive members: (1) the Passhatten Mb; (2) the Somovbreen Mb; and (3) the Van Keulenfjorden Mb (Fig. 4A, B). The formation is dominated by black shale sequence of the Passhatten Mb (lower and middle parts of the formation), which is overlain by three yellow-weathering siltstone/sandstone sequences. The lower siltstone/sandstone sequence forms intensely coloured yellow belt on the SW slope, and is classified into the Somovbreen Mb. The upper two weather yellowish-grey, and form a steep rocky wall (up to 30 m high) in the upper part of the SW slope. They are classified into the Van Keulenfjorden Mb. There is observed an increase in thickness of the Somovbreen Mb southeastwards along the outcrop belt at Bravaisberget. The Passhatten and Van Keulenfjorden mbs seem to have fairly constant thickness within the limits of examined outcrops, though the sequence of the Passhatten Mb is at places strongly tectonically disrupted.

The type section of the Bravaisberget Fm is located on the SW slope of Bravaisberget exposed towards Van Keulenfjorden (Van Keulenhamna) (Figs 2, 3B). This slope shows four distinct rocky ribs separated by steep gullies, which are referred to as Ribs I, II, III, and IV in this paper (Fig. 4A). The Ribs I to III show excellent and strikingly similar outcrop of the formation, though the Rib III is relatively easy to access. The Rib IV is the easiest to access, but some intervals of black shale sequence are covered by scree. The recommended approach on foot is along indistinct bench at top of the Tvillingodden Formation, starting from a raised beach beneath the eastern part of the slope (Fig. 4B). Excellent outcrop at Rib I continues northwestwards to the summit crest of Bravaisberget. Outcrops located southeast of the Rib IV become poor and increasingly more and more covered by scree. The Van Keulenfjorden Mb and at places also the upper part of the Somov-

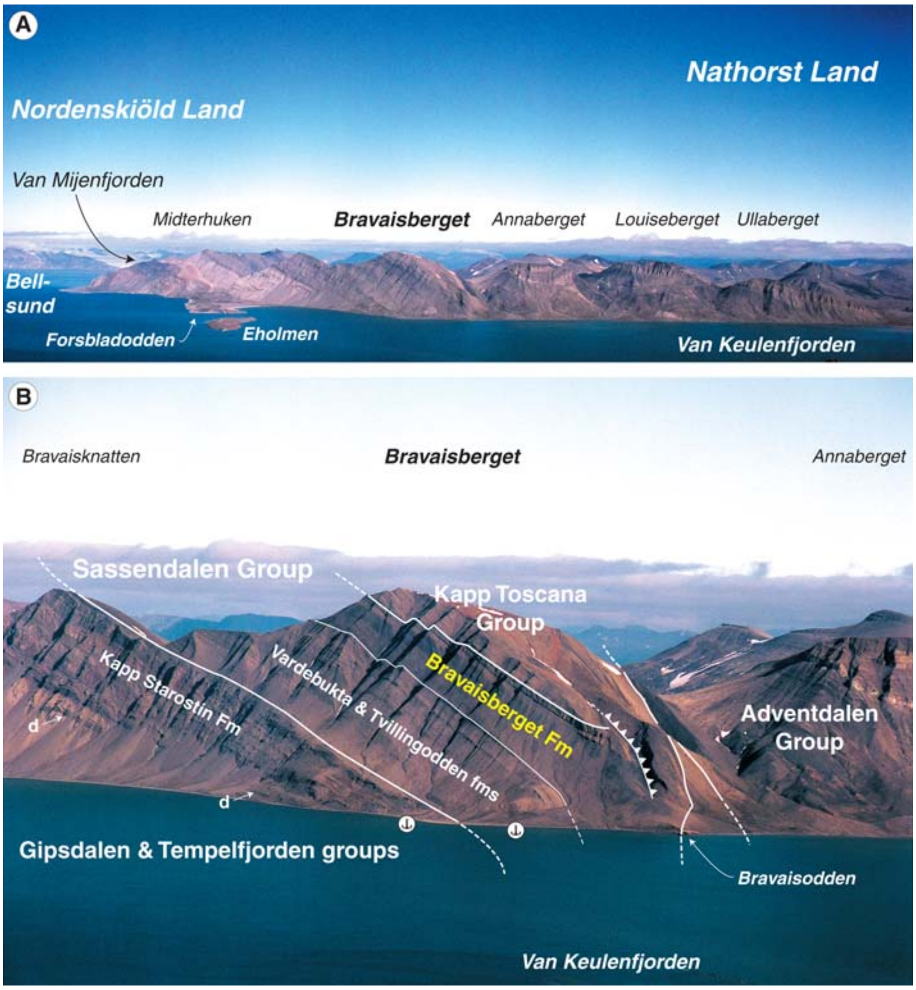



Fig. 3. **A**. Panoramic view of the western part of Nathorst Land seen from the south (photo taken from the summit of Berzeliustinden, 1205 m at northern margin of Wedel Jarlsberg Land). Complex tectonic deformations of the West Spitsbergen Fold Belt at Midterhuken fade eastwards, passing into a general monoclinal alignment of Late Paleozoic and Mesozoic strata between Bravaisberget and Ullaberget. The synclinal structure at Annaberget is accompanied by small-scale thrusts at Bravaisberget and Louiseberget-Ullaberget. **B**. Monoclinal alignment of Late Paleozoic (Gipsdalen and Tempelfjorden gps) and Mesozoic (Sassendalen, Kapp Toscana and Adventdalen gps) strata between Bravaisknatten and Annaberget. The steep rocky wall of Bravaisknatten exposed towards Van Keulenfjorden is built of the Kapp Starostin Fm (Permian). The Triassic Sassendalen Gp builds the SW slope of Bravaisberget. The lower part of the slope is built of the Vardebukta and Tvillingodden fms (Early Triassic).The middle, black-coloured part of the slope is built of the Bravaisberget Fm (Middle Triassic). The uppermost part of the slope and the top of Bravaisberget are built of the Kapp Toscana Gp (Late Triassic–Middle Jurassic). The lower part of the SE slope of Bravaisberget as well as Annaberget are built of the Adventdalen Gp (Middle Jurassic–Early Cretaceous). A thrust fault is exposed in rocky gully at SE flank of Bravaisberget (indicated). Dolerite sill (*d*) of the Diabasodden Suite (Late Jurassic–Early Cretaceous) cuts the Gipshuken Fm (Early Permian) at foot of the Bravaisknatten rocky wall. Anchor signs indicate suitable landing places from ship.

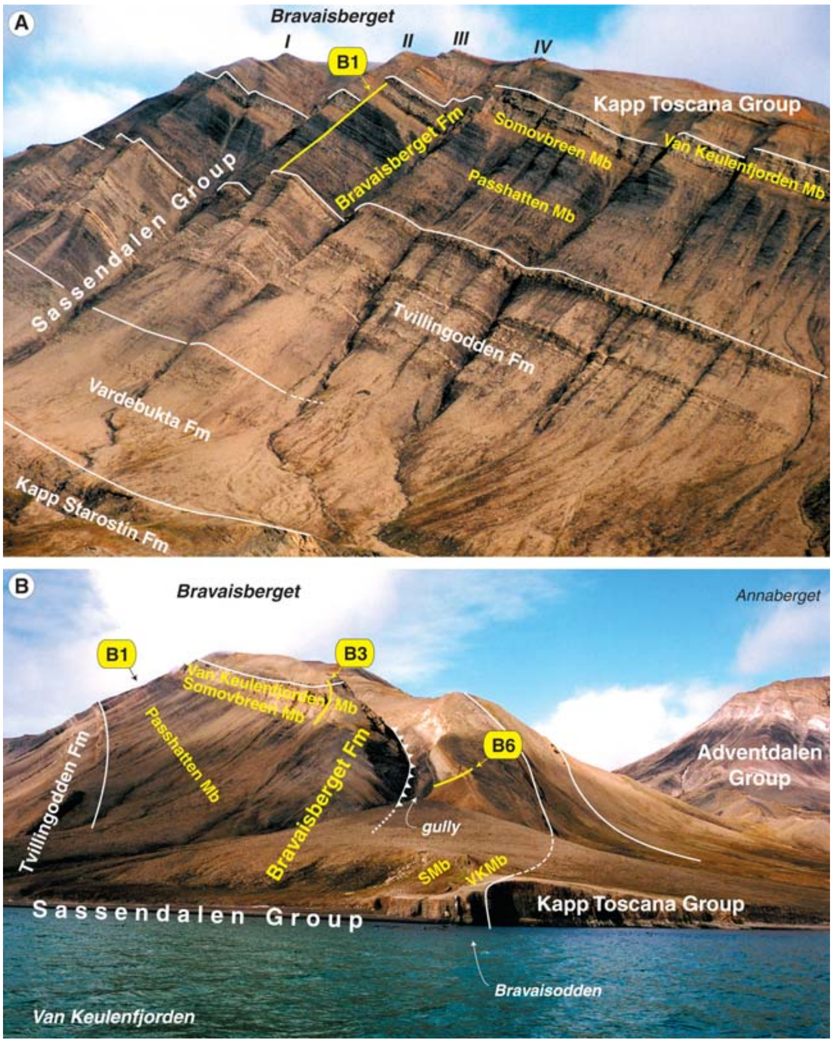



Fig. 4. Type section of the Bravaisberget Fm at Bravaisberget seen from Van Keulenfjorden. **A**. The foot of the SW slope of Bravaisberget is a morphological bench developed at the top of resistant Kapp Starostin Fm. The lower part of the slope is built of the Vardebukta (first coarsening-upward unit) and Tvillingodden (subsequent three coarsening-upward units) fms (Early Triassic). The middle part of the slope is built of the Bravaisberget Fm (Middle Triassic). The formation is dominated by black shale sequence of the Passhatten Mb, which is overlain by two sandstone sequences of the Somovbreen and Van Keulenfjorden mbs. The upper part of the slope and the summit of Bravaisberget are built of the lower part of the Kapp Toscana Gp (Late Triassic). There are four distinct ribs on the SW slope (*I*, *II*, *III*, and *IV*) that provide excellent sections of the Bravaisberget Fm. Detailed measurements of the formation were done along the Rib *III* (section *B1*). **B**. Supplementary measurements of the Somovbreen and Van Keulenfjorden mbs were done along the western (section *B3*) and eastern (section *B6*) sides of a rocky gully at SE flank of Bravaisberget. Detailed section of the Van Keulenfjorden Mb at Bravaisodden (see also Figs 2, 3), *i.e.* approximately 700 m to the south from section *B6*, is the stratotype for the member in Svalbard (Mørk *et al*. 1999; section M-23). *SMb* – Somovbreen Mb; *VKMb* – Van Keulenfjorden Mb.

breen Mb are difficult to access on the SW slope. This part of the formation can easily be accessed at Bravaisodden (Fig. 4B), where stratotype for the Van Keulenfjorden Mb has been established (Mørk *et al.* 1999). Also both sides of a rocky gully located at SE flank of Bravaisberget provide good insight into this part of the formation.

## Materials and methods

Field observations of the Bravaisberget Fm were collected along the outcrop belt at Bravaisberget, and supported by examination of outcrops located further north in western Nathorst Land (Midterhukfjellet), in southern Nordenskiöld Land (Fridtjovbreen), and in northern Wedel Jarlsberg Land (Reinodden, Sterneckøya, Bourbonhamna, Foldaksla). Detailed measurements and sampling of the formation were taken along the Rib III on the SW slope of Bravaisberget (Fig. 4A). This section is hereafter referred to as section B1. Supplementary measurements and sampling of the Somovbreen and Van Keulenfjorden mbs were taken along the western and eastern sides of a rocky gully at the SE flank of Bravaisberget. These sections are referred to as sections B3 and B6, respectively.

174 samples were collected along the composite section B1–B3–B6: 152, 14, and 8 from the Passhatten, Somovbreen, and Van Keulenfjorden mbs, respectively. Samples collected along sections B1, B3, and B6 are numbered B1-.., B3-.., and B6-.., respectively. The samples are housed at the Institute of Geological Sciences, Polish Academy of Sciences in Warsaw, Poland.

All the samples were analyzed for dominant detrital fraction using binocular microscope. Selected samples (86) were cut with a diamond saw, and their sections were analyzed in detail. 48 thin sections representing all the discerned lithologies and lithostratigraphic units were analyzed under transmitted (TLM) and reflected light microscopy (RLM). Classifications of detrital rocks after Folk (1974) and phosphate rocks after Föllmi *et al.* (1990) have been followed for the description of discerned lithologies.

Mineral composition of bulk samples and separated phosphorite was analyzed by X-ray diffraction (XRD). Samples were ground to <63 μm fraction. Diffraction patterns were recorded on a SIGMA 2070 diffractometer using a curved position sensitive detector in the range 2–120° 2θ with CoKα radiation and 20 hour analysis time. DIFFRACTIONEL software v. 03/93 was used to process the obtained data. The content of carbon dioxide in the crystal lattice of carbonate fluorapatite (francolite) was calculated from XRD data using the equations of Gulbrandsen (1970) and Shuffert *et al.* (1990).

Quantitative EDS analyses of carbonate cements and pyrite were obtained using a JEOL JSM-840A scanning electron microscope equipped with a THERMO NORAN VANTAGE EDS system. Operating conditions were a 15 kV acceleration voltage, 1 to 5 μm beam diameter, and 100-s counting time. Detection limits of the analyzed elements (Ca, Mg, Fe, Mn, Co, Ni, Cu, Cd, and Zn) were better than 0.05 wt %. To facilitate comparison among samples, the EDS data for calcite and dolomite were recalculated as cation mole fractions.

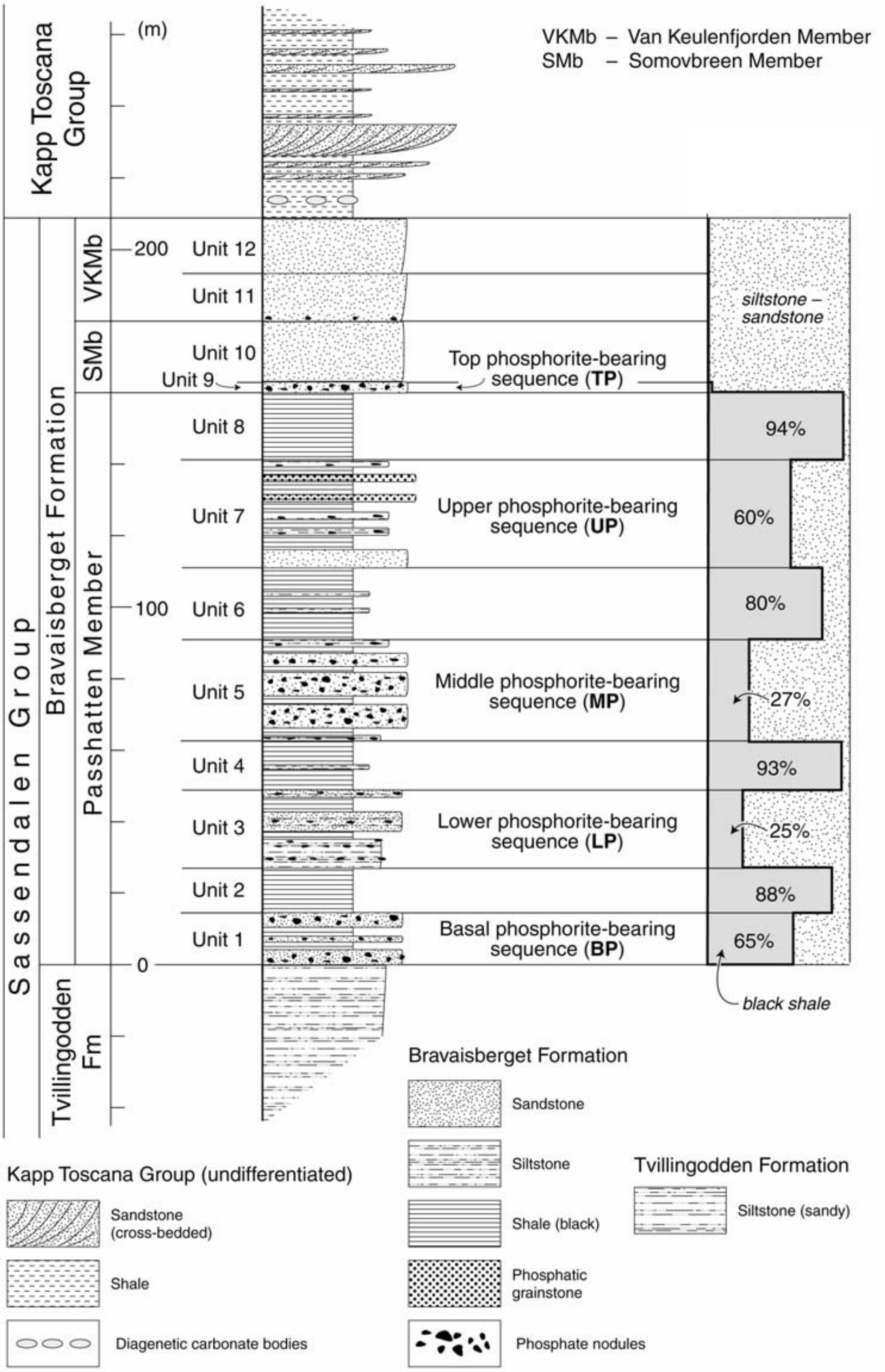
## Type section of the Bravaisberget Formation

### Lithostratigraphic subdivision

The Bravaisberget Fm at Bravaisberget is here subdivided into twelve informal lithostratigraphic units (units 1 to 12). Eight units are discerned in the Passhatten Mb, two in the Somovbreen Mb, and also two in the Van Keulenfjorden Mb (Table 1, Fig 5). This subdivision is based on three criteria: (1) the units are easily discernible in the field; (2) they form mappable rock horizons; and (3) a threshold of 80% by volume of black, organic carbon-rich, fissile rock (black shale) has been accepted to discriminate between the shaly and the composite units of the Passhatten Mb (Fig. 6). These criteria were formerly applied to subdivide the Bravaisberget Fm along the Creek IV section at Treskelen, Hornsund (Krajewski 2000e), which is the stratotype for the Passhatten and Somovbreen mbs in Svalbard (Mørk *et al*. 1999).

Detailed thickness of the Bravaisberget Fm measured along section B1 (209 m) is identical with the value reported by Mørk *et al*. (1999) for the general section at Bravaisberget (Table 1).

Units 1, 3, 5, 7, and 9 contain noticeable to abundant phosphorite that is concentrated in siltstone and sandstone beds. They are referred to as the basal (BP), lower (LP), middle (MP), upper (UP), and top (TP) phosphorite-bearing sequences, respectively (Fig. 5). The Passhatten Member embraces four phosphorite-bearing sequences (BP, LP, MP, and UP) interspaced by four black shale sequences (units 2, 4, 6, and 8). The shale sequences contain varying number of coarser-grained interbeds that are usually dark grey to black in colour, and contain at places phosphorite horizons. The lower and upper boundaries of the middle phosphorite-bearing sequence (unit 5) as well as the lower boundaries of the upper and top phosphorite-bearing sequences (units 7 and 9) are clear-cut and associated with abrupt change of dominant lithology. The other unit boundaries in the Passhatten Mb are gradational, though the units are easily discernible in the field (Fig. 6). The phosphorite-bearing sequences in the Passhatten Mb show sets of yellow-weathering siltstone to sandstone beds. They can be traced in the black shale sequence in western Nathorst Land (*e.g.* in a major décollement fold at Midterhukfjellet), and throughout the outcrops in northern Wedel Jarlsberg Land and northern Torell Land (Różycki 1959; Pčelina 1965a, b). The most prominent is the middle phosphorite-bearing sequence (unit 5) that concentrates thick siltstone and sandstone beds.



Kapp Toscana Group
(m)
VKMb – Van Keulenfjorden Member
SMb – Somovbreen Member
Sassendalen Group
Bravaisberget Formation
VKMb
SMb
Passhatten Member
Tvillingodden Fm
200
100
0
Unit 12
Unit 11
Unit 10
Unit 9
Unit 8
Unit 7
Unit 6
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1
Top phosphorite-bearing sequence (TP)
Upper phosphorite-bearing sequence (UP)
Middle phosphorite-bearing sequence (MP)
Lower phosphorite-bearing sequence (LP)
Basal phosphorite-bearing sequence (BP)
siltstone – sandstone
94%
60%
80%
27%
93%
25%
88%
65%
black shale
Bravaisberget Formation
Sandstone
Siltstone
Shale (black)
Phosphatic grainstone
Phosphate nodules
Tvillingodden Formation
Siltstone (sandy)
Kapp Toscana Group (undifferentiated)
Sandstone (cross-bedded)
Shale
Diagenetic carbonate bodies

Table 1

Lithostratigraphic subdivision and thickness of the Bravaisberget Fm at type section (section B1), SW slope of Bravaisberget, western Nathorst Land, Spitsbergen.

| *Fm* | *Mb* | *Informal units* | | *(phosphorite content)* |
|---|---|---|---|---|
| Bravaisberget Formation 209.2 m | Van Keulenfjorden Member 29.0 m | Unit 12 | 15.6 m | |
| | | Unit 11 | 13.4 m | ← at places basal phosphorite lag |
| | Somovbreen Member 20.4 m | Unit 10 | 17.3 m | |
| | | Unit 9 | 3.1 m | Top phosphorite-bearing sequence (**TP**) |
| | Passhatten Member 159.8 m | Unit 8 | 18.1 m | |
| | | Unit 7 | 31.0 m | Upper phosphorite-bearing sequence (**UP**) |
| | | Unit 6 | 20.1 m | |
| | | Unit 5 | 28.4 m | Middle phosphorite-bearing sequence (**MP**) |
| | | Unit 4 | 13.8 m | subordinate phosphorite-bearing beds |
| | | Unit 3 | 21.6 m | Lower phosphorite-bearing sequence (**LP**) |
| | | Unit 2 | 12.5 m | |
| | | Unit 1 | 14.3 m | Basal phosphorite-bearing sequence (**BP**) |

Detailed comparison of the Bravaisberget section presented in the *Lithostratigraphic Lexicon of Svalbard* (Mørk *et al*. 1999) and in the source publication (Mørk *et al*. 1982) with the section presented in this paper suggests that the boundary between the Passhatten and Somovbreen mbs has been placed by these authors at base of here defined unit 5. This confined the Passhatten Mb to only lower part of organic-rich, black shale sequence, which is 76 m thick according to these authors, and 62 m thick using our measurements (units 1 to 4). The boundary be-

← Fig. 5. Type section of the Bravaisberget Fm at Bravaisberget (composite section B1–B3–B6; see Figs 3, 4) showing its detailed lithostratigraphic subdivision and new position of boundary between the Passhatten and Somovbreen mbs. The formation is subdivided into three successive members (Passhatten, Somovbreen, and Van Keulenfjorden mbs) and twelve informal lithostratigraphic units (units *1* to *12*). Units *1*, *3*, *5*, *7*, and *9* are referred to as the basal (*BP*), lower (*LP*), middle (*MP*), upper (*UP*), and top (*TP*) phosphorite-bearing sequences, respectively. The Passhatten Mb embraces four phosphorite-bearing sequences interspaced by four black shale sequences (units *2*, *4*, *6*, and *8*). The shale sequences are defined to contain no less than 80% by volume of black, organic carbon-rich, fissile rock (mud- to silt-shale). The top phosphorite-bearing sequence (unit *9* – *TP*) forms the base of the sandstone sequence of the Somovbreen Mb (unit *10*). The Van Keulenfjorden Mb embraces two superimposed sandstone sequences (units *11* and *12*), and contains a thin, discontinuous phosphorite lag horizon at base. For detailed thickness of the lithostratigraphic units see Table 1.

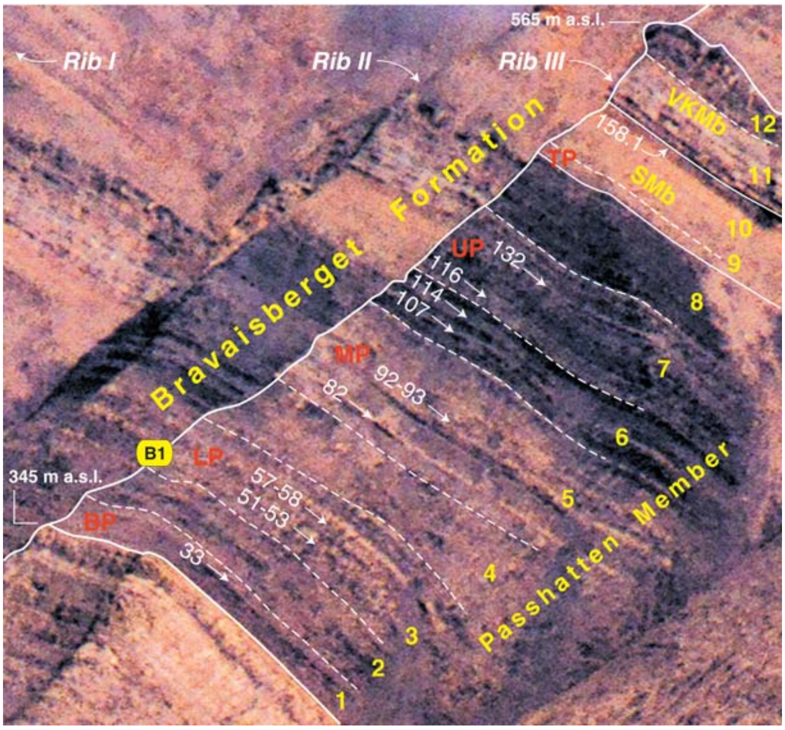



Fig. 6. Section of the Bravaisberget Fm along the *Rib III* on the SW slope of Bravaisberget (section *B1*) showing its formal (Passhatten, Somovbreen, and Van Keulenfjorden mbs) and informal lithostratigraphic units (units *1–12*). Units *1*, *3*, *5*, *7*, and *9* are referred to as the basal (*BP*), lower (*LP*), middle (*MP*), upper (*UP*), and top (*TP*) phosphorite-bearing sequences, respectively. Numbers and arrows (*33–158.1*) show position of some distinct beds in the sequence (for detailed bed numbering see Fig. 7). The altitudes (in metres above see level) of the bottom and top of the formation along the *Rib III* are altimeter values.

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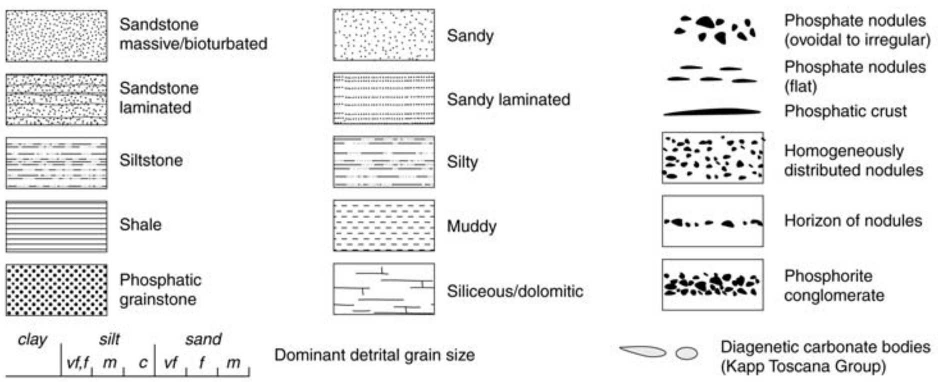
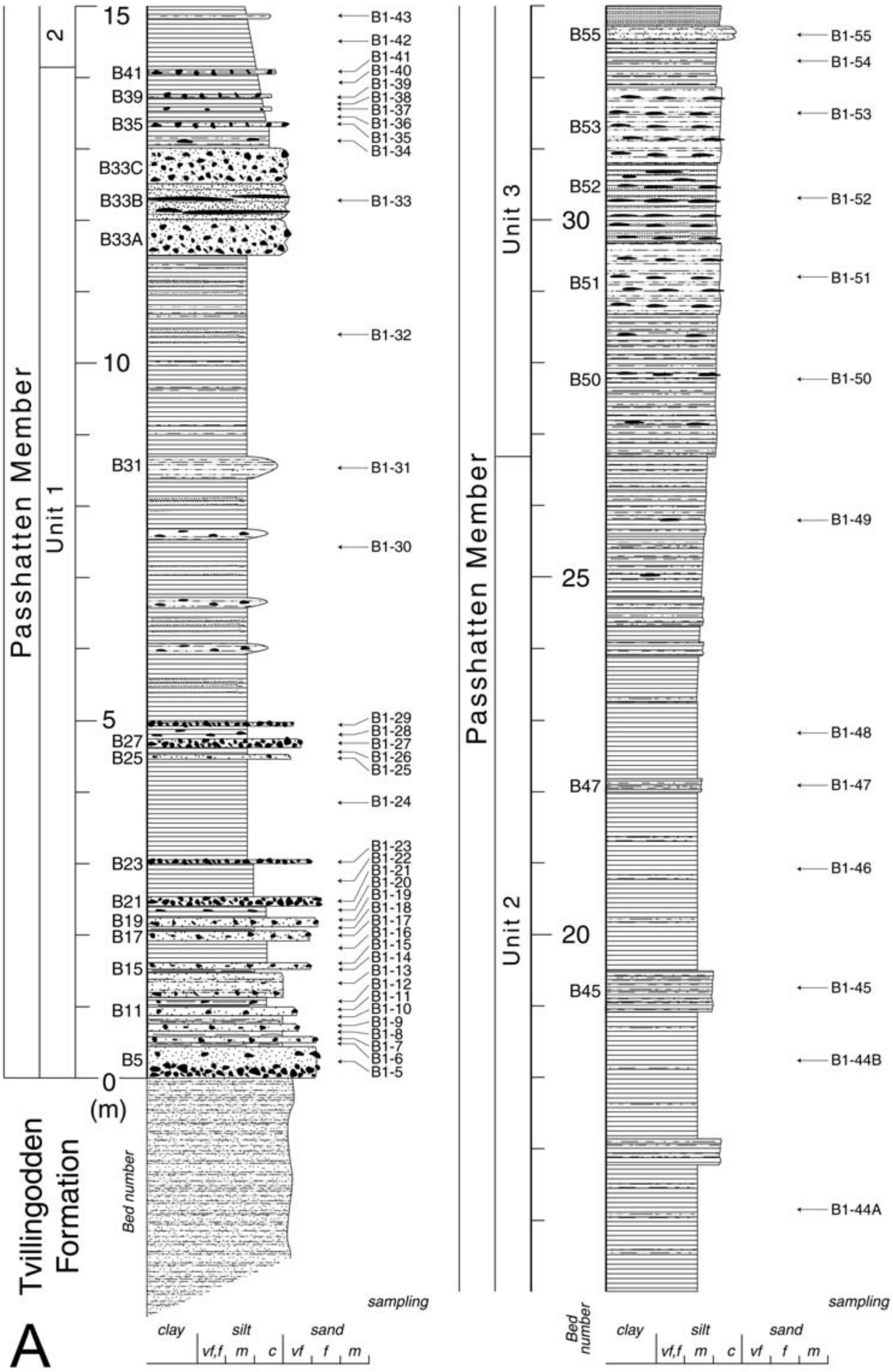
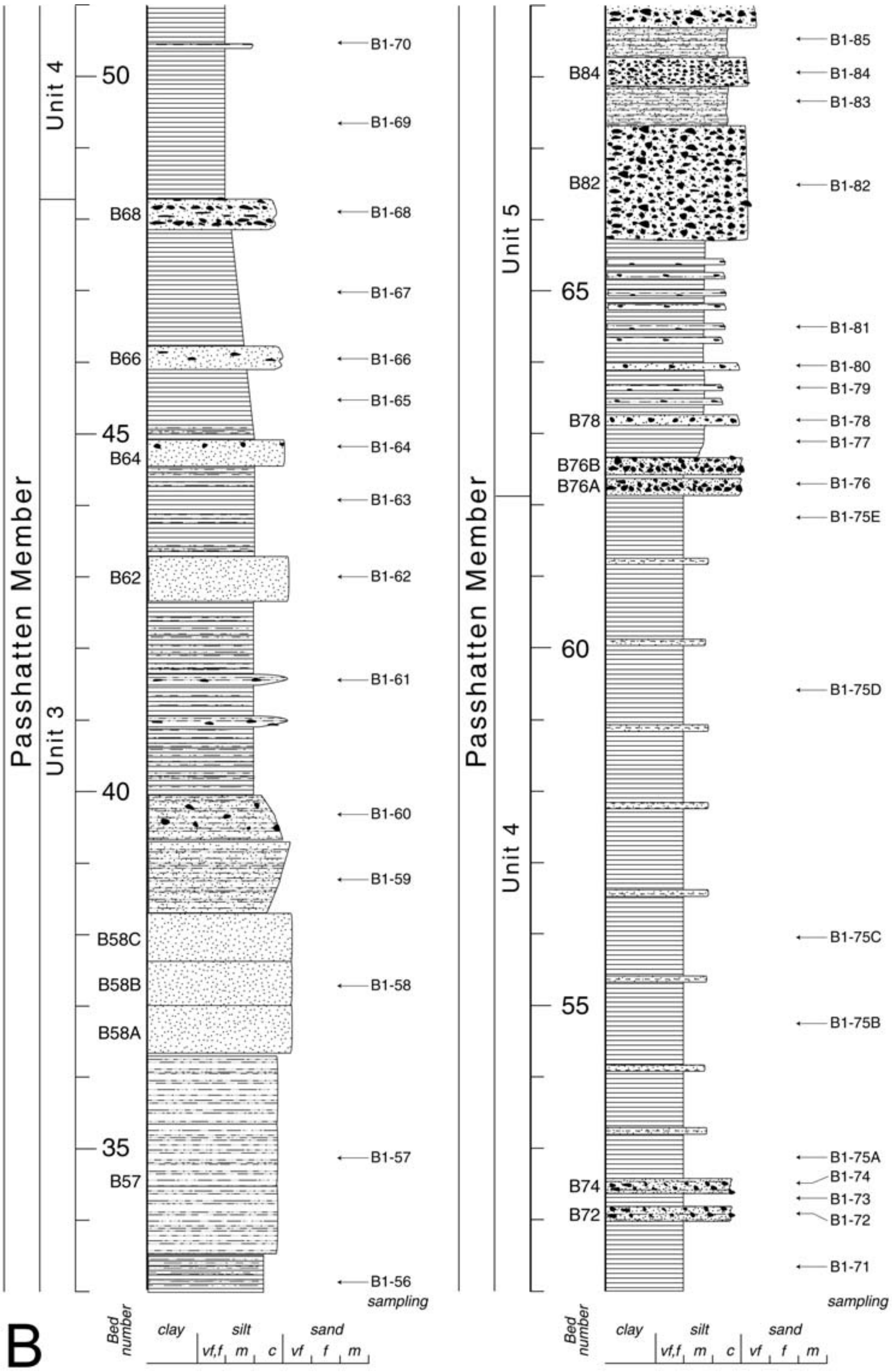
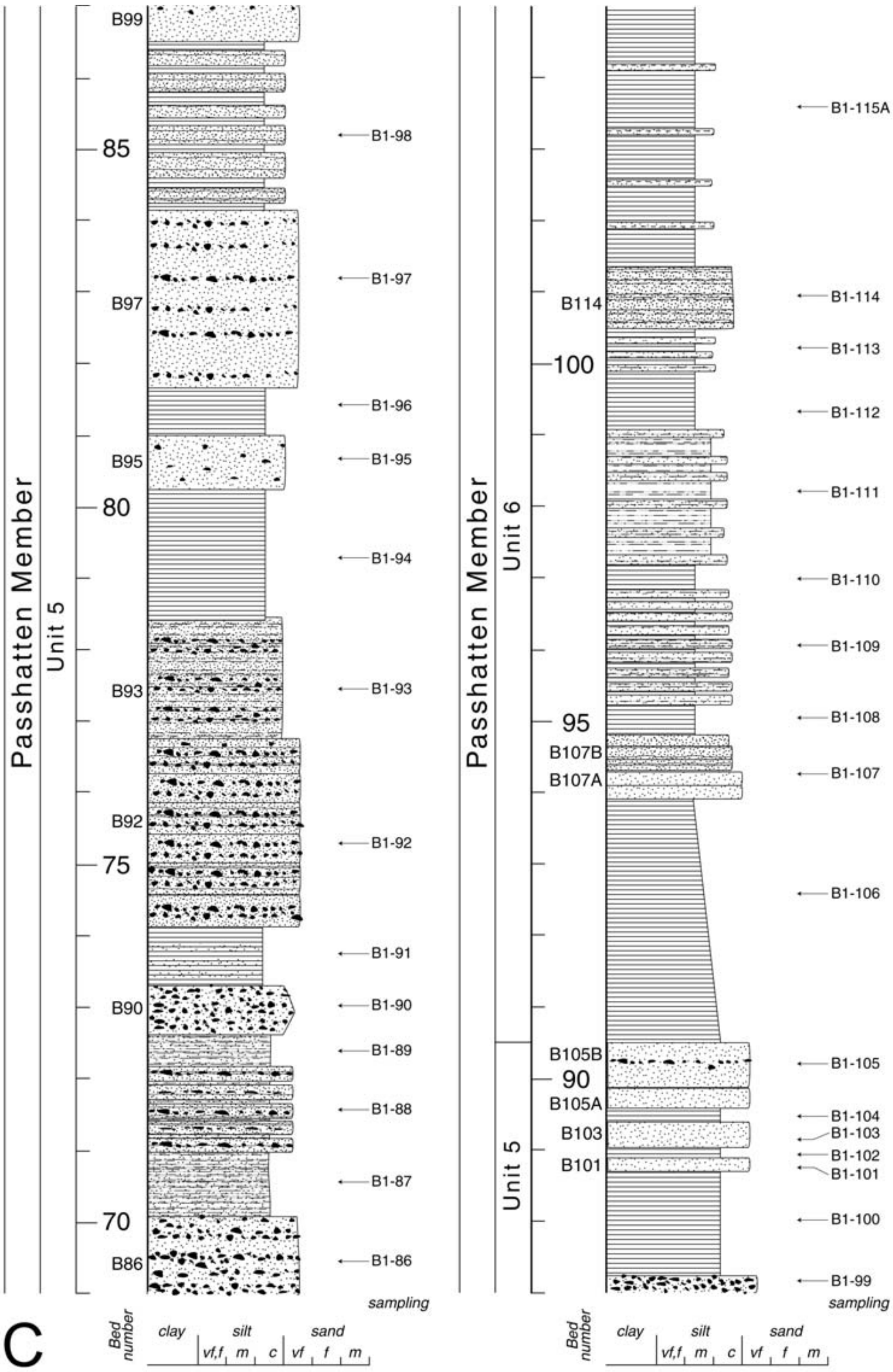
Fig. 7**A**–**F**. Detailed section (composite section B1–B3–B6; see Figs 4, 6) of the Bravaisberget Fm at Bravaisberget. This is the stratotype for the Bravaisberget Fm and hypostratotype for the Passhatten and Somovbreen mbs in Svalbard. →

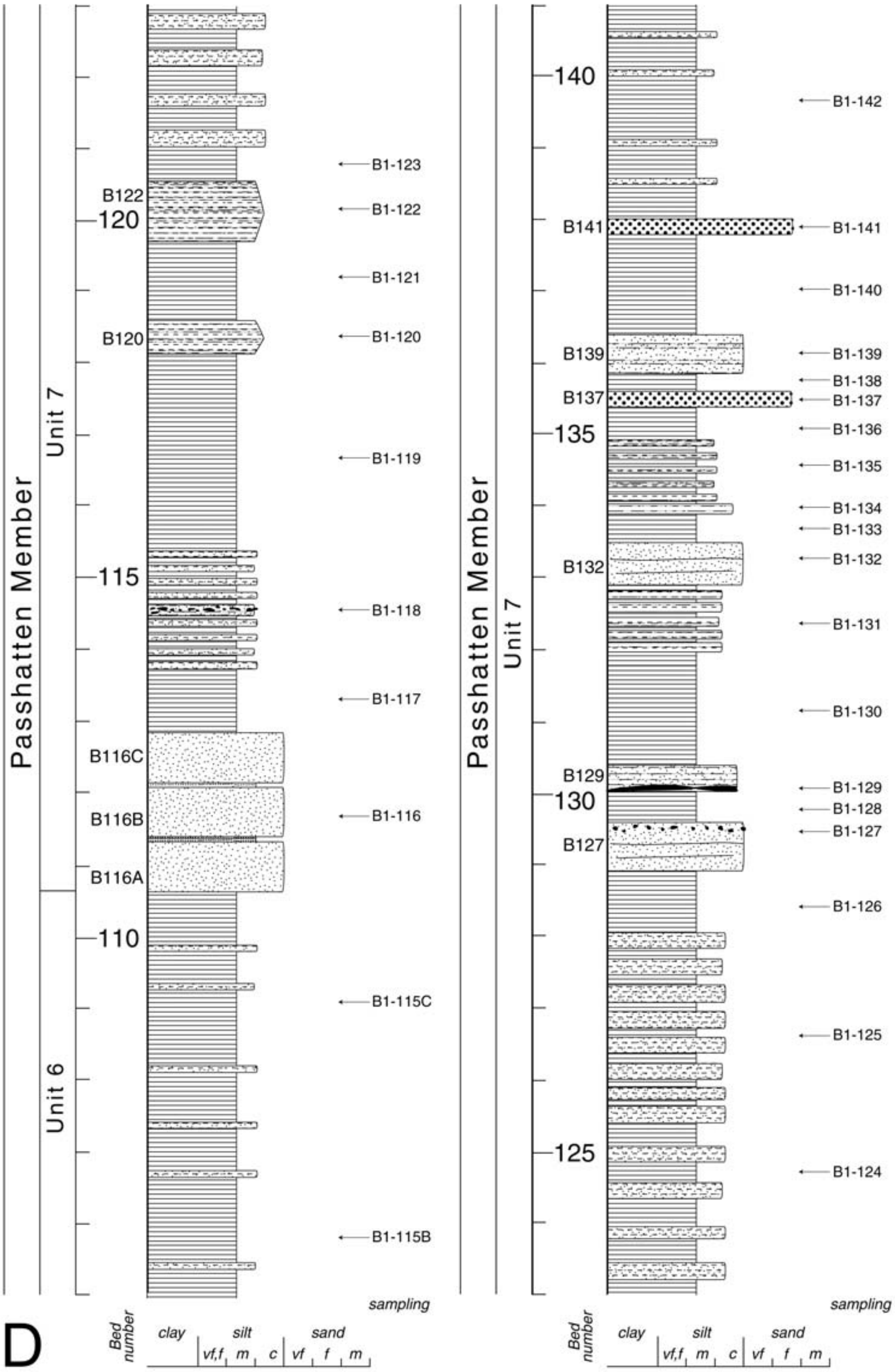


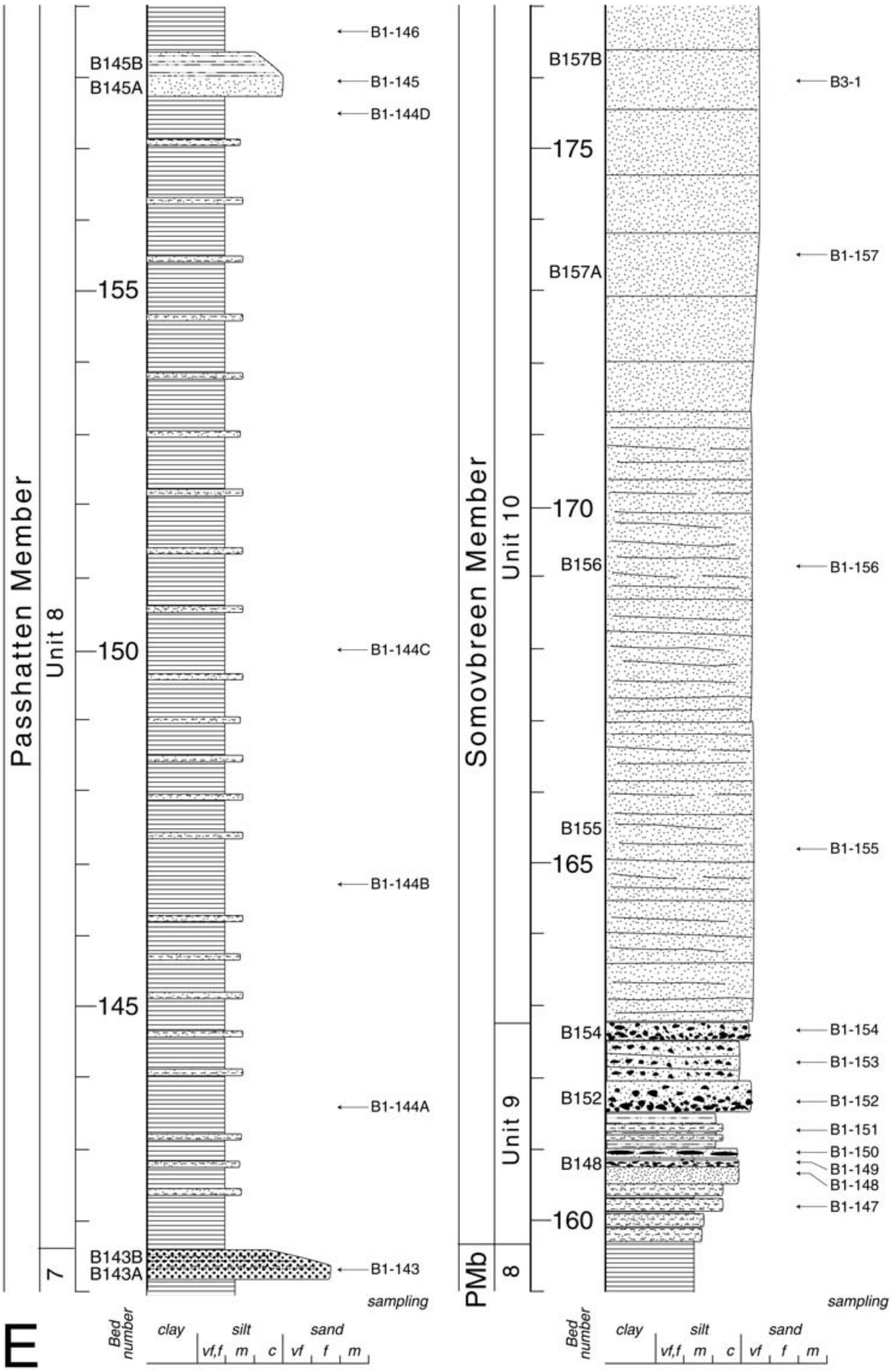

Passhatten Member
Unit 1
2
Tvillingodden Formation
15
10
5
0
(m)
Bed number
B41
B39
B35
B33C
B33B
B33A
B31
B27
B25
B23
B21
B19
B17
B15
B11
B5
B1-43
B1-42
B1-41
B1-40
B1-39
B1-38
B1-37
B1-36
B1-35
B1-34
B1-33
B1-32
B1-31
B1-30
B1-29
B1-28
B1-27
B1-26
B1-25
B1-24
B1-23
B1-22
B1-21
B1-20
B1-19
B1-18
B1-17
B1-16
B1-15
B1-14
B1-13
B1-12
B1-11
B1-10
B1-9
B1-8
B1-7
B1-6
B1-5
sampling
clay
silt
sand
vf,f m c vf f m
A
Passhatten Member
Unit 3
Unit 2
30
25
20
B55
B53
B52
B51
B50
B47
B45
B1-55
B1-54
B1-53
B1-52
B1-51
B1-50
B1-49
B1-48
B1-47
B1-46
B1-45
B1-44B
B1-44A
Bed number
sampling
clay
silt
sand
vf,f m c vf f m

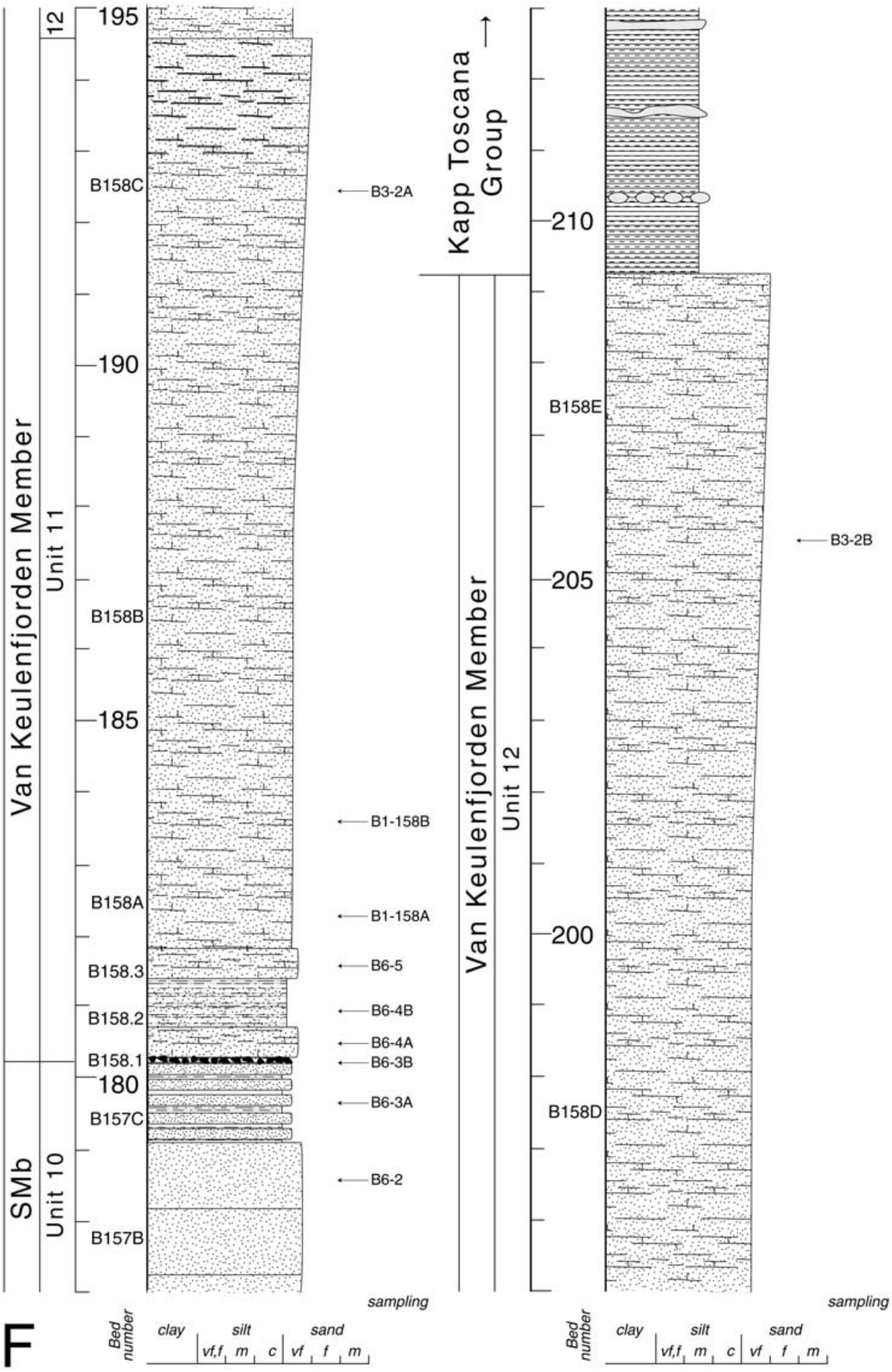


B
Passhatten Member
Unit 3
Unit 4
Unit 5
35
40
45
50
55
60
65
B57
B58A
B58B
B58C
B62
B64
B66
B68
B72
B74
B76A
B76B
B78
B82
B84
B1-56
B1-57
B1-58
B1-59
B1-60
B1-61
B1-62
B1-63
B1-64
B1-65
B1-66
B1-67
B1-68
B1-69
B1-70
B1-71
B1-72
B1-73
B1-74
B1-75A
B1-75B
B1-75C
B1-75D
B1-75E
B1-76
B1-77
B1-78
B1-79
B1-80
B1-81
B1-82
B1-83
B1-84
B1-85
sampling
Bed number
clay
silt
sand
vf,f
m
c
vf
f
m


Passhatten Member
Unit 5
B99
85
B1-98
B1-97
B97
B1-96
B95
B1-95
80
B1-94
B93
B1-93
B92
B1-92
75
B1-91
B90
B1-90
B1-89
B1-88
B1-87
70
B86
B1-86
sampling
C
Bed number
clay
silt
sand
vf,f m c vf f m
Passhatten Member
Unit 6
Unit 5
B1-115A
B114
B1-114
100
B1-113
B1-112
B1-111
B1-110
B1-109
95
B1-108
B107B
B107A
B1-107
B1-106
B105B
B1-105
90
B105A
B1-104
B103
B1-103
B1-102
B101
B1-101
B1-100
B1-99
sampling
Bed number
clay
silt
sand
vf,f m c vf f m


Passhatten Member
Unit 7
Unit 6
B122
B120
B116C
B116B
B116A
120
115
110
B1-123
B1-122
B1-121
B1-120
B1-119
B1-118
B1-117
B1-116
B1-115C
B1-115B
sampling
D
Bed number
clay
silt
sand
vf,f m c vf f m
140
135
130
125
B141
B139
B137
B132
B129
B127
B1-142
B1-141
B1-140
B1-139
B1-138
B1-137
B1-136
B1-135
B1-134
B1-133
B1-132
B1-131
B1-130
B1-129
B1-128
B1-127
B1-126
B1-125
B1-124


Passhatten Member
Unit 8
7
B145B
B145A
B143B
B143A
155
150
145
B1-146
B1-145
B1-144D
B1-144C
B1-144B
B1-144A
B1-143
sampling
E
Bed number
clay
silt
sand
vf,f
m
c
vf
f
m
Somovbreen Member
Unit 10
Unit 9
PMb
8
B157B
B157A
B156
B155
B154
B152
B148
175
170
165
160
B3-1
B1-157
B1-156
B1-155
B1-154
B1-153
B1-152
B1-151
B1-150
B1-149
B1-148
B1-147


Van Keulenfjorden Member
SMb
12
Unit 11
Unit 10
195
190
185
180
B158C
B158B
B158A
B158.3
B158.2
B158.1
B157C
B157B
B3-2A
B1-158B
B1-158A
B6-5
B6-4B
B6-4A
B6-3B
B6-3A
B6-2
sampling
Bed number
clay
silt
sand
vf,f
m
c
vf
f
m
Kapp Toscana Group
Van Keulenfjorden Member
Unit 12
210
205
200
B158E
B158D
B3-2B
sampling
Bed number
clay
silt
sand
vf,f
m
c
vf
f
m
F

tween the Passhatten and Somovbreen mbs is here redefined, and placed at top of the black shale-dominated sequence, *i.e.* at top of unit 8 (Fig. 6), a definition correlating better with the type section at Treskelen (Birkenmajer 1977; Mørk *et al.* 1982, 1999; Krajewski 2000e). According to this new definition, the Passhatten Mb is 160 m thick along section B1 (Table 1).

Unit 9 (top phosphorite-bearing sequence) is here classified at base of the Somovbreen Mb, in accordance with its definition at Treskelen (Krajewski 2000e). It encompasses a pile of yellow-weathering sandstone beds that contain abundant phosphorite, and are separated by thin shaly layers. This sequence passes upwards gradually into the main sequence of yellow-weathering sandstones (unit 10) of the Somovbreen Mb. The top phosphorite-bearing sequence thins southeastwards and its phosphorite and shale contents decrease along with a consequent thickening of unit 10 on the SW slope of Bravaisberget. The uppermost part of unit 10 contains a few interbeds of sandy shale. The upper boundary of the Somovbreen Mb (and also the upper boundary of unit 10) is a discontinuity surface that at places shows traces of intraformational reworking. It is covered by a thin (up to 5 cm thick), discontinuous phosphorite lag, which is here regarded as the base of the Van Keulenfjorden Mb. This lag horizon is well developed at the eastern side of rocky gully at SE flank of Bravaisberget (section B6), and also at some places along the SW slope. It seems to be missing in the type section of the member at Bravaisodden. The Van Keulenfjorden Mb consists of two superimposed sandstone units (units 11 and 12) that form indistinct coarsening-upward sequences. The lowermost part of unit 11 shows two beds of reddish-weathering sandstone separated by sandy shale. This reddish horizon can be traced along the SW slope of Bravaisberget, where it marks foot of the steep rocky wall of the member. The boundary between units 11 and 12 is clear-cut, and also well visible along the rocky wall.

Detailed section of the Bravaisberget Fm at Bravaisberget is presented in Fig. 7. This section combines data collected from sections B1, B3, and B6, though sections B3 and B6 provided supplementary information and samples only for the two upper members. Thickness values used in the construction of Fig. 7 represent measurements taken along section B1 (see also Table 1). The position of samples taken at sections B3 and B6 has been marked at a corresponding bed position in section B1.The beds and sediment intervals discerned along the section are consequently numbered from B/5 (base of the formation) to B/158E (top of the formation). Unit 1 encompasses beds B/5–B/41; unit 2: beds B/42–B/49; unit 3: beds B/50–B/68; unit 4: beds B/69–B/75; unit 5: beds B/76–B/105; unit 6: beds B/106–B/115; unit 7: beds B/116–B/143; unit 8: beds B/144–B/146; unit 9: beds B/147–B/154; unit 10: beds B/155–B/157C; unit 11: beds B/158.1–158C; and unit 12: beds B/158D and B/158E. The beds B/33, B/51–53 and B/57–58, and B/82 and B/92–93 are well-visible marker horizons in the basal, lower, and middle phosphorite-bearing sequences (units 1, 3, and 5) of the Passhatten Mb, respectively (Fig. 6).

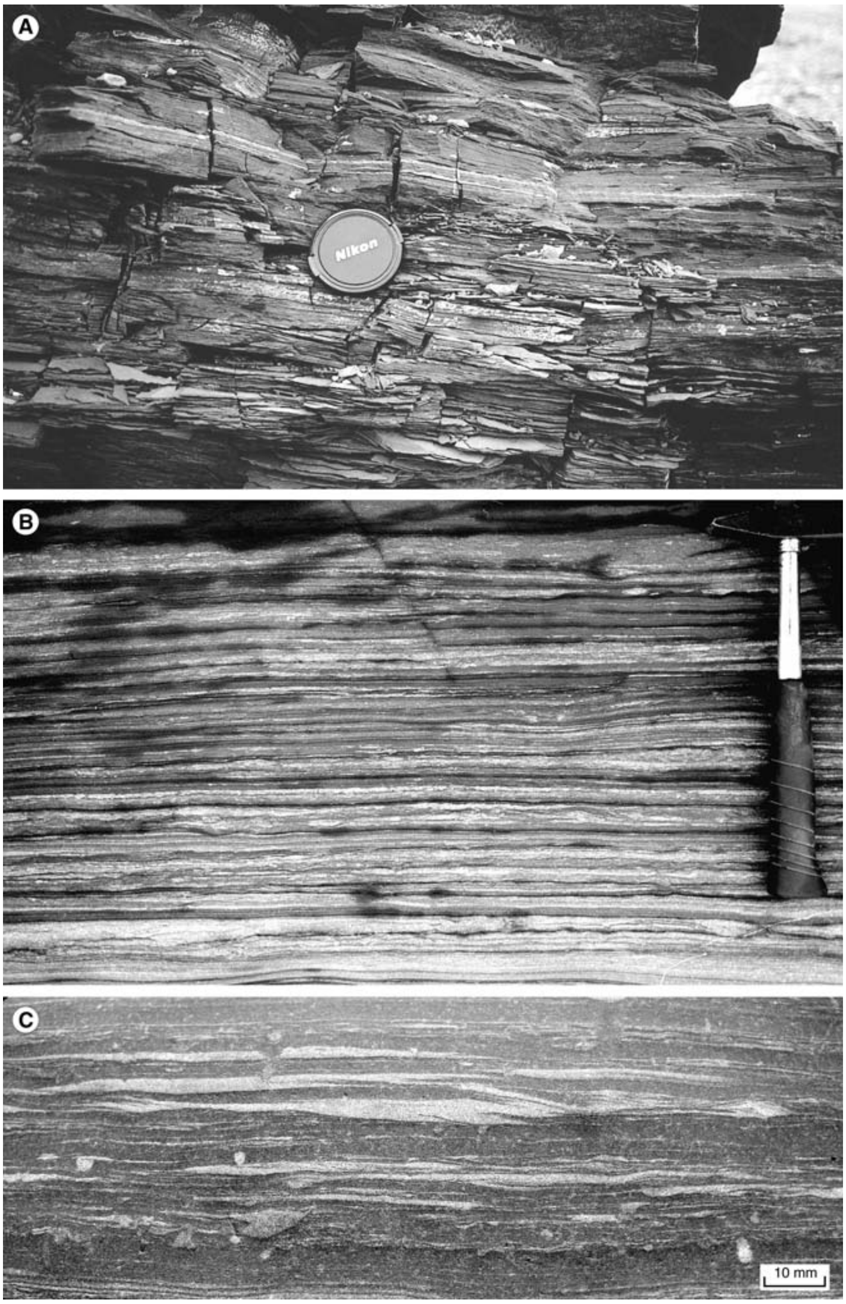



Fig. 8. Black shale of the Passhatten Mb (I). **A**. Black, organic-rich fissile mud-shale in the upper part of the member (unit 8) shows rare, thin pale layers enriched in fine silt material. **B**. Striped silty mudstone in the middle part of the member (unit 6) shows common silt-dominated layers that alternate with black layers of organic-rich mudstone. Note irregular, current-defined shapes of the pale laminae. **C**. Low-angle cross to ripple lamination in a striped silty mudstone in the middle part of the member (unit 6). A–C – field photos.

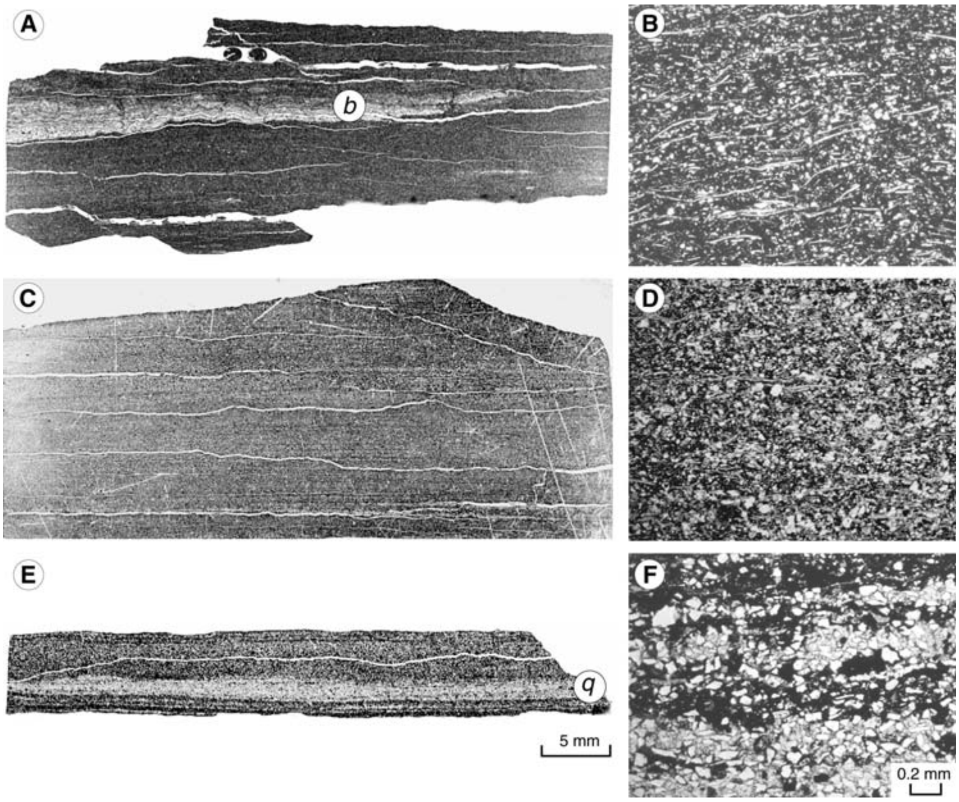



Fig. 9. Black shale of the Passhatten Mb (II). **A**. Laminated clay-shale in the upper part of the member (unit 8). Note a discontinuous pale lamina dominated by thin-shelled pelecypods (*b*). **B**. The shale matrix is organic-rich and shows parallel-oriented debris of thin-shelled pelecypods. **C**. Fissile, non-laminated mud-shale in the upper part of the member (unit 7). **D**. The shale matrix is organic-rich and shows quartz grains in the fine to medium silt fraction. **E**. Laminated sandy mud-shale in the middle part of the member (unit 6). Note a 2 mm thick pale lamina dominated by quartz silt (*q*). **F**. The shale matrix is enriched in quartz grains in the coarse silt to very fine sand fraction. A, C, E – photographs of thin sections; B, D, F – TLM photomicrographs, normal light. The scale in E and F is for A, C, E and B, D, F, respectively.

## Facies development

The Bravaisberget Fm at Bravaisberget consists of fine-grained clastics that in general do not exceed the fine sand fraction. Four clastic facies can be discerned: (1) the black shale facies, which is widely confined to the Passhatten Mb; (2) siltstone-sandstone beds forming composite sequences in the black shale; (3) massive sandstone facies forming the main sequence of the Somovbreen Mb; and (4) massive sandstone facies forming bulk of the Van Keulenfjorden Mb. Superimposed on the former three facies is (5) sedimentary phosphorite, which forms authigenic deposits showing various reworking and redeposition features.

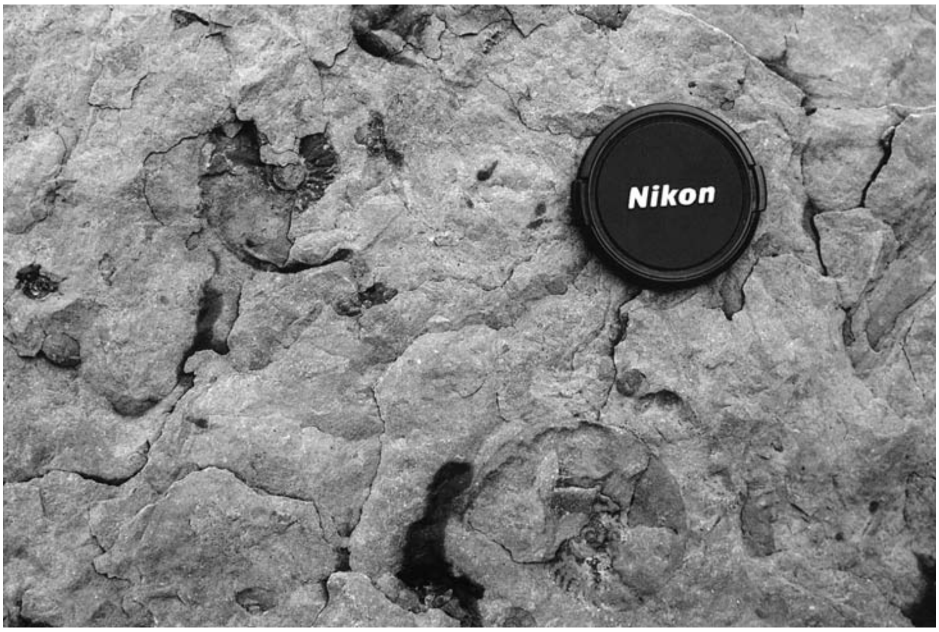
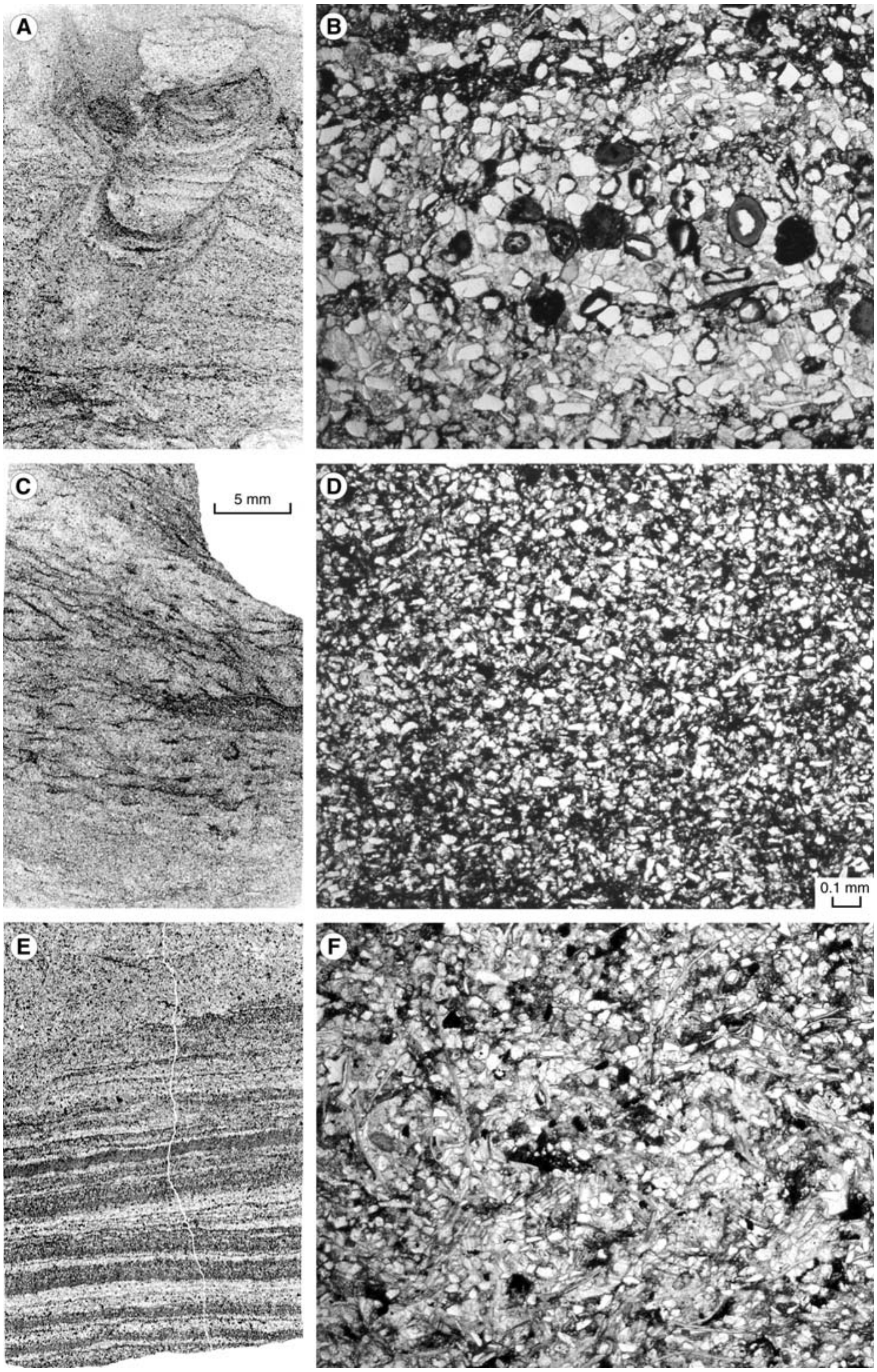



Fig. 10. Siltstone–sandstone of the Passhatten Mb (I). Silty sandstone bed showing flattened moulds of ammonoids (unit 3). The bed is calcareous due to the presence of inter-particle calcitic cement. Field photo of broken surface planar to the bedding.

**Black shale of the Passhatten Mb.** — The black shale facies embraces a variety of petrographic rock types that show common appearance in the field: they are black in colour due to high content of organic matter; and they are fissile as a rule (Fig. 8). These rock types cover a spectrum from sandy silt-shale with weakly developed fissility, through silt-shale and mud-shale, to very fissile clay-shale (Fig. 9). The dominant lithology is illite-dominated mud-shale with varying admixture of quartz grains in the very fine to coarse silt fraction. Feldspar constitutes subordinate detrital component. Organic matter is mostly amorphous, forming organo-clay aggregates and seams and clusters in the matrix, though herbaceous and woody components are recognized. Sedimentary pyrite occurs in the form of microcrystals and their aggregates as well as in the form of (poly)framboids. The

Fig. 11. Siltstone–sandstone of the Passhatten Mb (II). **A**. Very fine- to fine-grained sandstone in the middle part of the member (unit 5) showing finely bioturbated matrix disturbed by a vertical burrow. **B**. The sandstone is dominated by quartz grains and shows the presence of phosphatic peloids and coated grains (dark grey to black). Inter-particle pore space is replaced by calcitic cement. **C**. Finely bioturbated siltstone in the lower part of the member (unit 1). **D**. The siltstone shows homogeneous structure resulted from intense bioturbational mixing of the sediment. **E**. Laminated siltstone overlain with erosional surface by bioturbated sandy siltstone in the upper part of the member (unit 6). **F**. The siltstone shows noticeable admixture of fragments of thin-shelled pelecypods. A, C, E – photographs of thin sections; B, D, F – TLM photomicrographs, normal light. The scale in C and D is for A, C, E and B, D, F, respectively. →


A
B
C
5 mm
D
0.1 mm
E
F

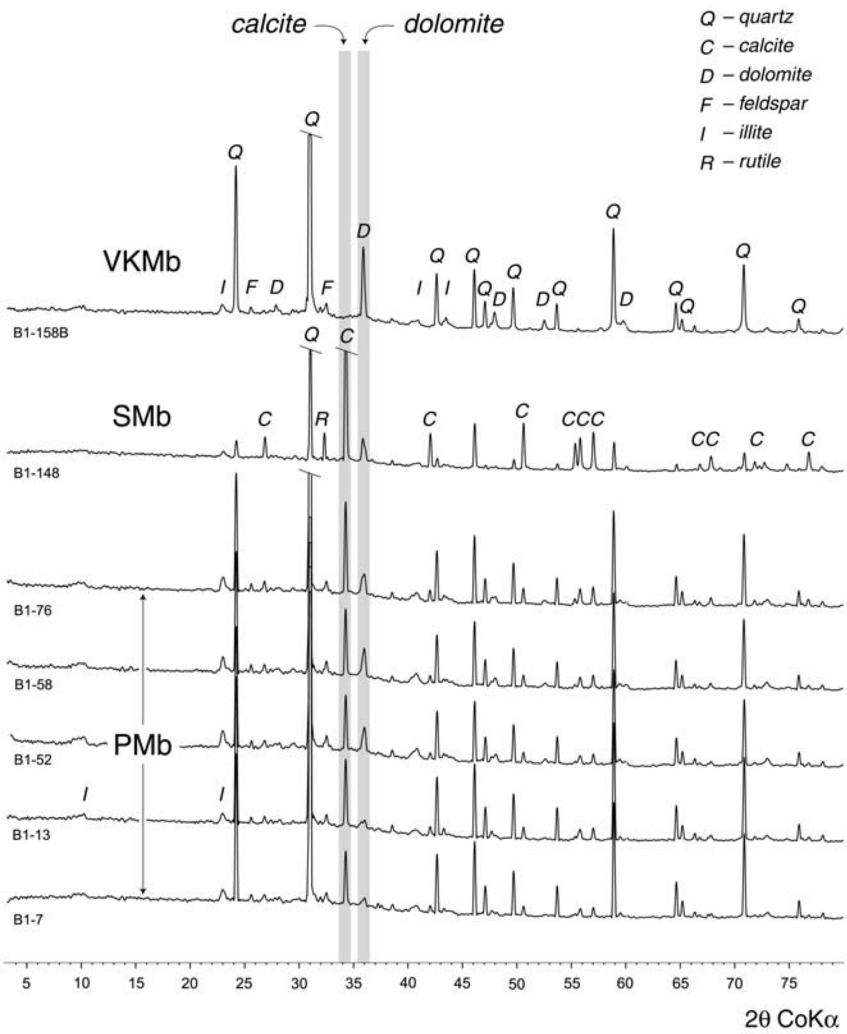



Fig. 12. X-ray diffraction patterns of siltstone to sandstone in the Bravaisberget Fm along section B1 showing increasing-upwards content of dolomite. *PMb* – Passhatten Mb; *SMb* – Somovbreen Mb; *VKMb* – Van Keulenfjorden Mb.

shale is locally enriched in biogenic debris represented mostly by fragments of thin-shelled pelecypods. Fragments of vertebrate bones and teeth are noted. Diagenetic cement is a negligible rock component, except layers and lenses enriched in coarser-grained material. It is dominated by calcitic micrite to microspar.

The black shale varies from non-laminated, solid black sediment to densely laminated, striped sediment (Fig. 8). The paler laminae are 0.1 to 2 cm thick, and vary from continuous laminae to discontinuous rows of seams and lenses. They are coarser-grained (usually silt-dominated) than the interspacing black mudstone, frequently showing undulated boundaries, and low-angle cross-laminated and ripple-laminated internal structure. These sedimentary structures are indicative of frequent activity of bottom currents in the black shale depositional environment.

There is a huge vertical variation of the structure and texture of black shale in intervals that appear homogeneous in the field (Fig. 7). In general, the most fine-grained sediment occurs in units 4 and 8. However, it also forms intervals in other units of the Passhatten Mb. These intervals interspace with sharp boundaries coarser-grained beds or are involved in small-scale coarsening- and/or fining-upward depositional cycles. Indistinct traces of sediment bioturbation occur at several levels in the shale. A general absence of bioturbations seems to define the upper parts of units 4 and 6 as well as the bulk of unit 8. The sedimentary features observed in black shale suggest fluctuating dynamics of bottom environment, which overlapped on delicate changes of depositional rate and changing dysaerobic to anaerobic conditions.

**Siltstone-sandstone of the Passhatten Mb**. — Piles of siltstone to fine-grained sandstone beds (5 cm up to 2.9 m thick) occur recurrently in the Passhatten Mb (Fig. 7). Many of these beds are fossiliferous, yielding ammonoids that might be helpful in detailed biostratigraphic subdivision of the Bravaisberget Fm (Fig. 10). They cover a spectrum of petrographic rock types, from immature to mature quartzarenites, showing fluctuating content of detrital feldspar. Biogenic components embrace mostly debris of thin-shelled pelecypods. Proportional contribution of biogenic components tends to increase in the upper part of the Passhatten Mb. The dominant detrital size fraction and the content of clay-dominated matrix vary between individual beds and within the beds themselves. This is reflected in complex representation of lithology, embracing sandstone, muddy and silty sandstone, sandy siltstone and siltstone (Fig. 11). Individual beds may have sharp boundaries or gradational transitions towards the under- and/or overlying black shale. Gradual or abrupt decrease in the content of clay-dominated matrix in the siltstone to sandstone beds is usually compensated by a corresponding increase of the content of diagenetic carbonate cement that replaces pore space between detrital grains. The cement is dominated by calcite microspar containing up to 5 mol % $FeCO_3$, with increasing contribution of dolomite upwards in the Passhatten Mb (Fig. 12). The dolomite occurs in the form of scattered rhombs that at many places show zoned internal structure. Their chemical composition is a subject of wide variation, from nearly pure dolomite, through ferroan dolomite, to ankerite (0 to 20 mol % $FeCO_3$). The content of clay-dominated matrix versus carbonate cement is reflected in weathering colour of the siltstone to sandstone beds, with yellow and dark grey colours corresponding to maximum cement and maximum matrix, respectively.

Most of the siltstone to sandstone beds in the Passhatten Mb show traces of more or less intense bioturbation of sediment. Gradations of finely laminated into finely bioturbated sediment are observed at transitional margins of the beds. Thicker sandstone beds are heavily bioturbated as a rule, though the bioturbations form shallow structures and usually oblique to the bedding. Rare vertical burrows

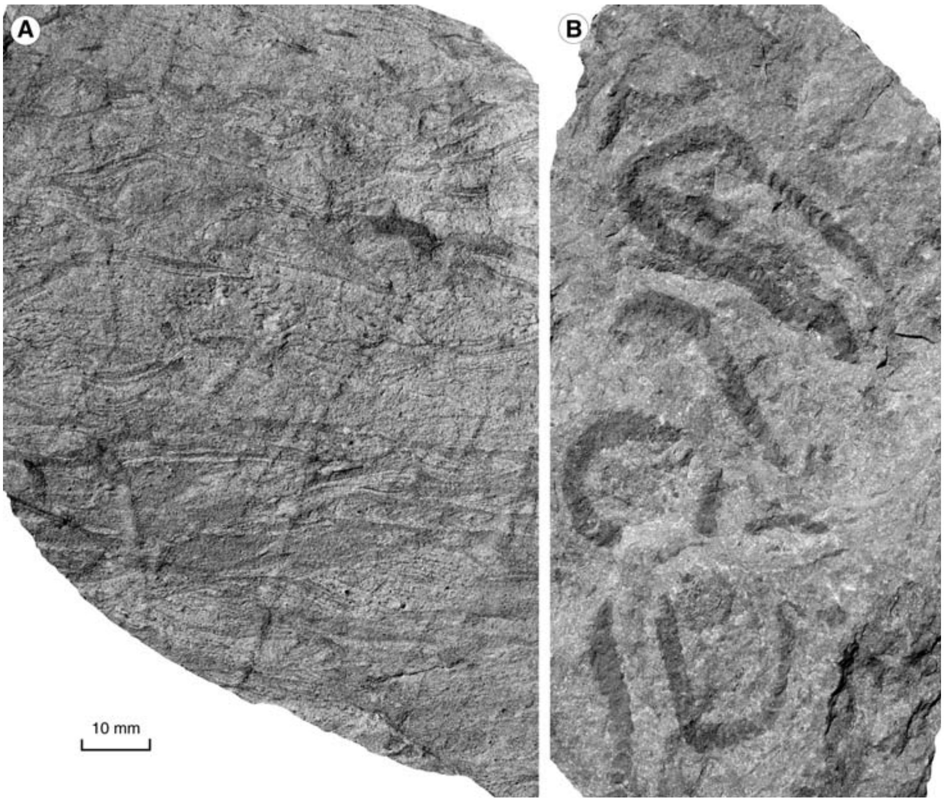



Fig. 13. Sandstone of the Somovbreen Mb (I). **A**. Patchy weathered surface of finely bioturbated silty sandstone in the lower part of the member (lower part of unit 10). The section is normal to the bedding. **B**. *Taenidium* is the dominant trace fossil in the lower part of the member. Broken surface planar to the bedding. The scale is for both photos.

penetrate the sediment at distances of a few centimetres. The bioturbations contain animal traces that are usually enriched in mud sediment and organic matter. This results in a patchy structure of the siltstone to sandstone beds, which is well visible on weathered surfaces and on rock sections (Fig. 11). Trace fossils are dominated by *Taenidium* (see also Mørk and Bromley in press). Bioturbation of the siltstone to sandstone beds, coupled with the presence of skeletal remains of benthic animals (siliceous sponges, brachiopods), suggests recurrent development of aerobic bottom conditions during the deposition of the Passhatten Mb.

The observed sedimentary features of the siltstone to sandstone beds suggest that they originated as a result of two contrasted mechanisms: (1) winnowing and reworking of the black shale sediment; (2) progradation of coarser-grained sediment bodies onto the muddy bottom. The first mechanism required recurrent increase of activity of bottom dynamic agents, and is consistent with sedimentary features observed in the shale. The second mechanism suggests deposition on morphological slopes, and agrees well with the observed phosphorite slumps and rede-

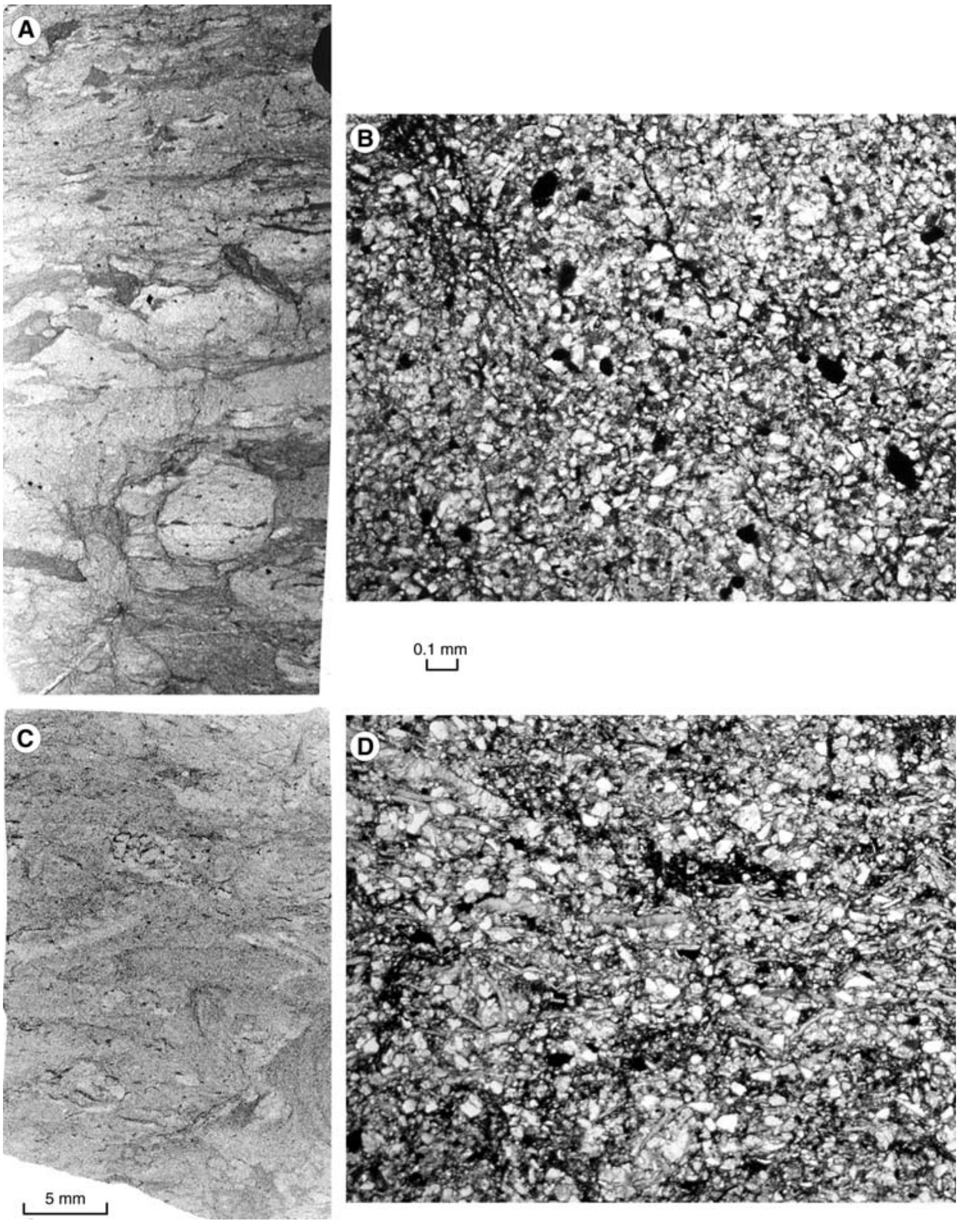



Fig. 14. Sandstone of the Somovbreen Mb (II). **A**. Heavily bioturbated, very fine-grained silty sandstone in the upper part of the member (upper part of unit 10). **B**. The sandstone is dominated by quartz grains and contains common woody detritus (black). Inter-particle pore space is replaced by calcitic cement with subordinate dolomite. **C**. Very fine-grained silty sandstone in the lower part of the member (lower part of unit 10) showing finely bioturbated matrix. **D**. The sandstone is dominated by quartz grains and shows common fragments of thin-shelled pelecypods and fine woody detritus (black). A, C – photographs of thin sections; B, D – TLM photomicrographs, normal light. The scale in C and D is for A, C and B, D, respectively.

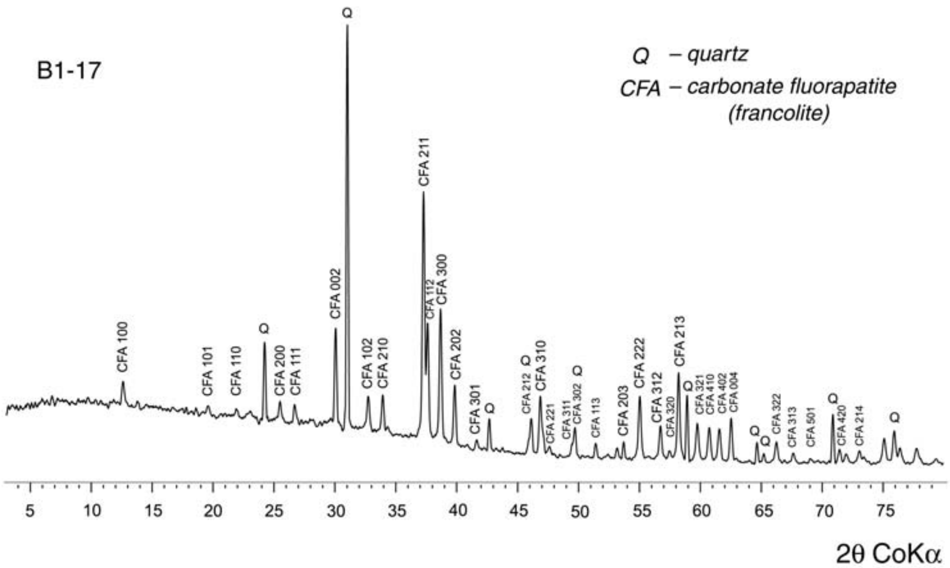



Fig. 15. X-ray diffraction pattern of a phosphate nodule from the lower part of the Passhatten Mb (unit 1).

posited horizons in the Passhatten Mb (see below). Complex sequences of some thicker beds suggest interplay between the two mechanisms, enhanced during periods of non-deposition and prolonged exposure of the sediment at sea bottom.

**Sandstone of the Somovbreen Mb**. — The sequence of the Somovbreen Mb embraces very fine- to fine-grained silty sandstones and sandy siltstones. These rocks are dominated by submature quartzarenites with noticeable content of detrital feldspar, and elevated content of detrital rutile at some levels (Fig. 12). They are bioturbated throughout the sequence (Fig. 13A). Lower part of the sequence is usually finely bioturbated, with *Taenidium* being the dominant trace fossil (Fig. 13B). This part contains common debris of thin-shelled pelecypods, which decrease in abundance and disappear upward in the sequence. Contribution of vertical burrows increases upwards, though the material analyzed at Bravaisberget does not allow to recognize ichnogenera of the corresponding trace fossils. *Polykladichnus* has been reported by Mørk and Bromley (in press) to dominate ichnofacies of the uppermost part of the Bravaisberget Fm.

The inter-particle pore space of sandstones and siltstones of the Somovbreen Mb is replaced by diagenetic carbonate cement, which is strikingly similar to the one observed in siltstone–sandstone beds of the Passhatten Mb (Fig. 14). Calcite microspar dominates, and (ferroan) dolomite occurs in the form of scattered rhombs. Disseminated pyrite forms microcrystals and rare framboids. Organic matter is dominated by woody fraction. The woody fragments are often pyritized, suggesting input of fresh, land-derived organic detritus to the sediment facies of the Somovbreen Mb.

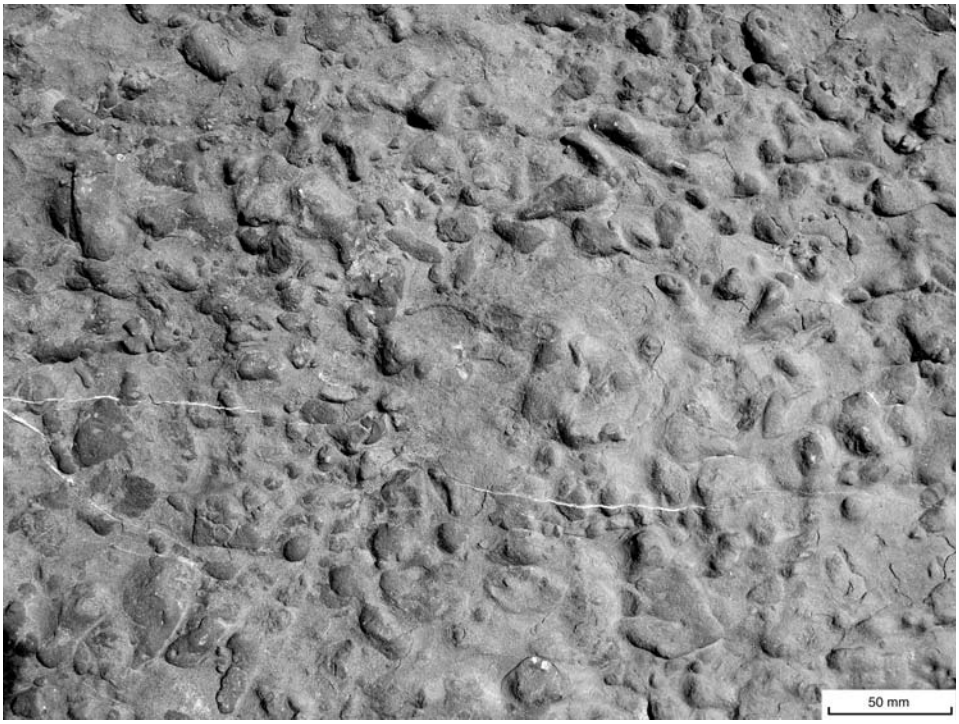



Fig. 16. Phosphorite (I). Pristine nodular horizon developed in muddy siltstone of the lower part of the Passhatten Mb (unit 3). Photo of bedding surface.

Ubiquitous calcitic cementation of siltstones and sandstones of the Passhatten and Somovbreen mbs post-dated early precipitation of pyrite, and also at least partial compaction of the sediment. The latter is indicated by flattened calcite-cemented fossils that escaped phosphate authigenesis (Fig. 10), as well as by calcite-cemented injection structures in phosphatic fossils (see below). It has been suggested on the basis of carbon isotopic study that the calcite cement originated in deeper parts of the early diagenetic sulphate reduction zone (Krajewski 2000c). This view is supported here, though it should be noted that detailed microscopic investigation points to later episodes of burial recrystallization of the cements.

**Phosphorite**. — Phosphorite is the dominant authigenic deposit in the Bravaisberget Fm. It owes its origin to sedimentary transformations of organically-bound phosphorus deposited in excess in the form of fresh, marine organic matter (Krajewski *et al.* 1994). The phosphorite at Bravaisberget embraces a variety of deposits showing mostly nodular and peloidal development, which are represented by various mixtures of two end members: (1) the pristine phosphates (accumulations developed and preserved *in situ* without subsequent reworking or redeposition); and (2) the allochthonous phosphates (accumulations that resulted from synsedimentary reworking of pristine phosphates, with or without lateral transport involved) (Krajewski 2000a, in press). The third major development type discerned in the Middle Triassic of Svalbard, i.e. the condensed phosphate, is poorly represented at Bravaisberget. It is confined to a few thin, discontinuous phosphatic crusts in the lower and upper parts of the Passhatten Mb. Despite textural variation, all the phosphorite deposits are composed of one phosphate mineral, which is ultra- to microcrystalline carbonate fluorapatite (francolite) containing 1–3% carbon dioxide in the apatite lattice (Fig. 15).

At Bravaisberget, the phosphorite occurs throughout the Passhatten Mb and in the lower part of the Somovbreen Mb, where it concentrates in five phosphorite-bearing sequences (Fig. 7). The Van Keulenfjorden Mb lacks phosphorite deposits, except for a thin, discontinuous lag at base of the member.

Accumulations of phosphate nodules are conspicuous in the sequence. The nodules are authigenic mineral bodies 0.5–10 cm in size showing flat, oval, irregular to composite shapes, which originated as a result of punctuated cementation of sediment with apatite. Oval to irregular nodules typically occur in sandstone and siltstone beds, while flat nodules are preferentially found in silt- to mud-shale. Some nodules are phosphatized faecal pellets and phosphatic infillings of fossils, mostly ammonoids. Mørk and Bromley (in press) report early phosphatization of *Thalassinoides* traces, a feature well developed in the Passhatten Mb at Festningen located north of the study area. At Bravaisberget (and at other sections of the Bravaisberget Fm in western Spitsbergen), nodular phosphate tends to concentrate in coarser-grained beds, especially in those showing traces of prolonged exposition at sea bottom. Pristine nodular horizons are seldom preserved. Rare examples suggest formation of nodules below the zone of active bioturbation, though close to the water/sediment interface. Thin horizons of pristine nodules also occur at some levels in the shale sequence, reflecting discrete omission surfaces in fine-grained sediment (Fig. 16). Common are allochthonous deposits that embrace winnowed, reworked, and redeposited horizons. The winnowed and reworked horizons show nodules that were displaced from their original growth position, but remain at place of their formation. The redeposited horizons show signs of lateral transport of nodules caused by current action and/or by gravity mass flow (Fig. 17A). A similar mechanism is suggested by Mørk and Bromley (in press) for concentration of phosphate nodules due to heavy storms. There are also composite nodular beds showing several stages of nodule growth and their winnowing and reworking (Fig. 17B). Ubiquitous reworking has led to formation of phosphorite conglomerates with densely packed nodules and phosphoclasts. These conglomerates are common in the basal (unit 1) and middle (unit 5) phosphorite-bearing sequences in the Passhatten Mb.

The upper part of the Passhatten Mb at Bravaisberget (unit 7) shows beds and indistinct seams and lenses composed of phosphatic grainstone (Fig. 18A, B). The grainstone consists of phosphatic peloids and coated grains of the fine to coarse sand fraction, that are concentrated as a result of intense winnowing and reworking. Some of the peloids show composite internal structure, reflecting stages of

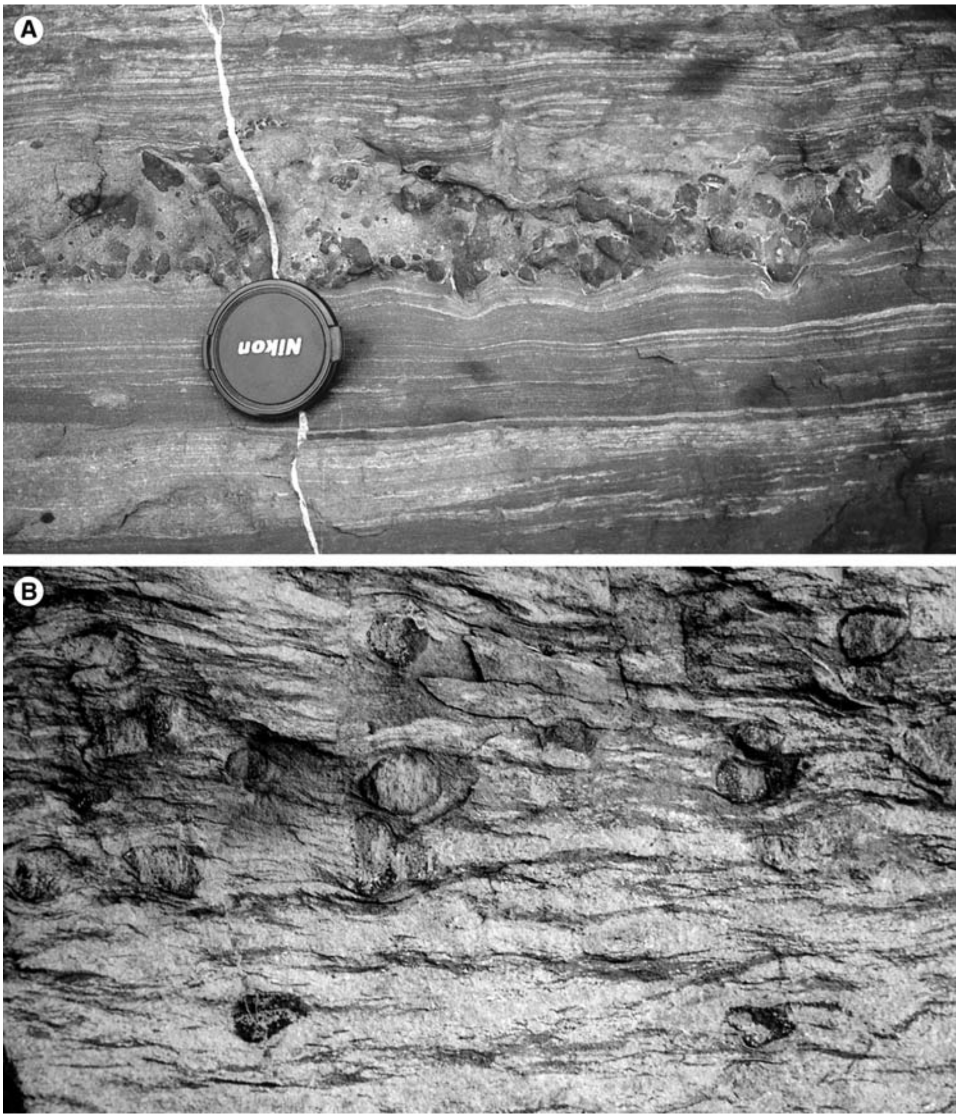
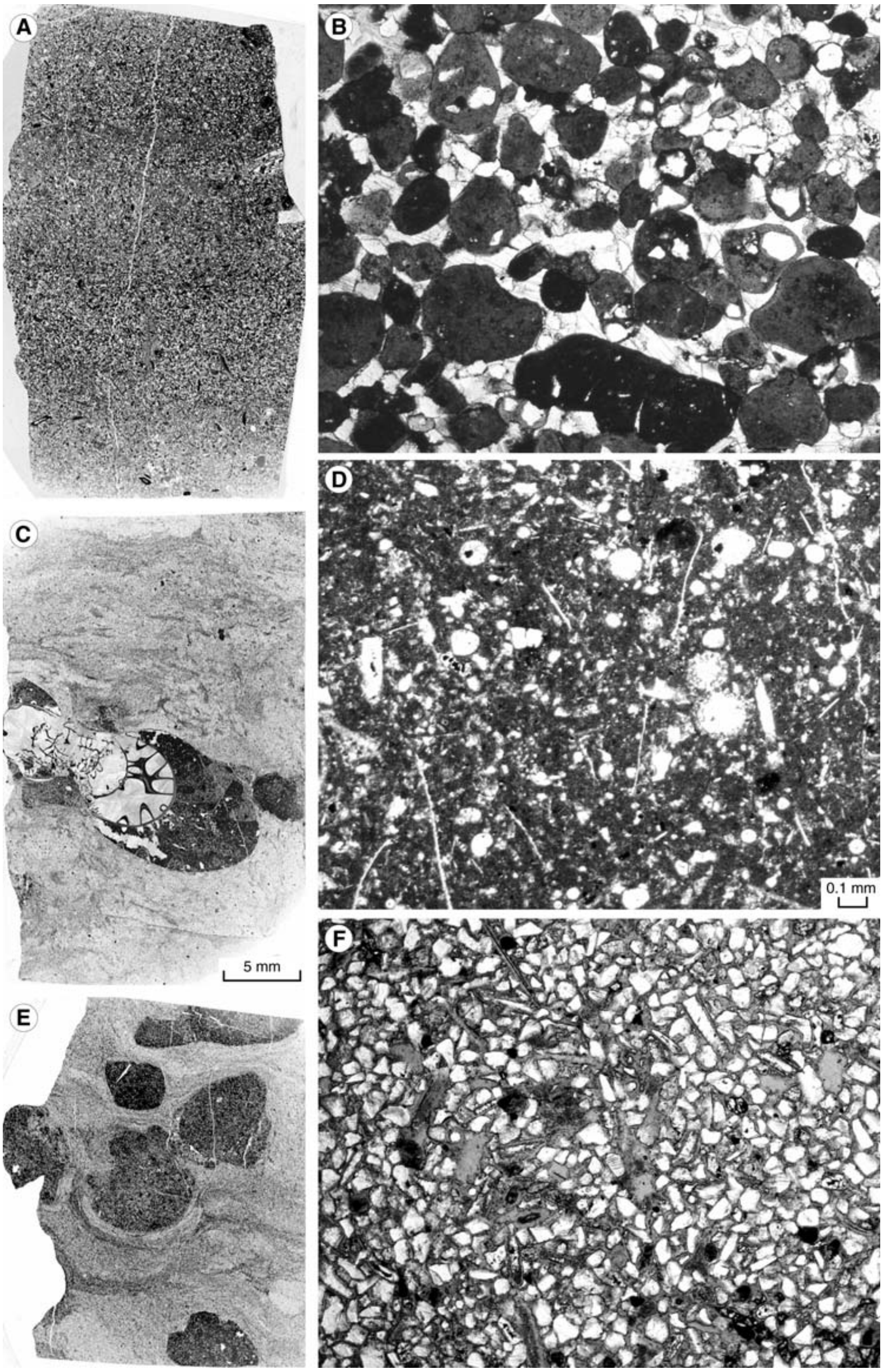



Fig. 17. Phosphorite (II). **A**. Redeposited phosphorite horizon in black, laminated shale of the lower part of the Passhatten Mb (unit 4). Note the load deformations of shale lamination below the phosphorite horizon. **B**. Generations of pristine and allochthonous phosphate nodules occur in hummocky-laminated, muddy sandstone in the lower part of the Somovbreen Mb (unit 9). The nodules are 2 to 4 cm along the horizontal axis. Field photos of weathered surfaces.

phosphate precipitation interrupted by winnowing episodes. Similar grains, resembling phosphatized ooids, were interpreted to represent bank deposits at Festningen (Mørk *et al.* 1982).

Because of very early cementation by phosphate, the matrices of phosphate nodules provide information on the original composition and texture of the sedi-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ment, which outside the nodules were mainly obliterated due to compaction and mineral transformation. Microscopic examination of nodular matrices along the Passhatten Mb at Bravaisberget indicates that the original, organic carbon-rich sediment was enriched in radiolarian tests and, at coarser-grained intervals, also in spicules of siliceous sponges (see also Krajewski 2000a). These biogenic remains occur in the form of phosphatic moulds and imprints in the nodules, and are hardly preserved in the host sediment, suggesting advanced dissolution of biogenic silica during post-depositional history of the sequence. Detailed study of diagenetic processes in the Bravaisberget Fm (Krajewski 2000c) documents early formation of scattered quartz cement that followed dissolution of biogenic silica. The two processes preceded ubiquitous cementation of the sequence with calcite, which suggests that they operated in the early diagenetic sulphate reduction zone.

**Sandstone of the Van Keulenfjorden Mb**. — The sequence of the Van Keulenfjorden Mb at Bravaisberget embraces two sedimentary units (units 11 and 12) that have already been recognized by Pčelina (1983) and Mørk *et al.* (1999). The latter authors present detailed section of the sequence at Bravaisodden, which is defined as the stratotype for the member in Svalbard (section M-23; see also Figs 2, 4B). Our study shows that the sequence consists of very fine- to fine-grained sandstone and siltstone beds showing massive, laminated, planar- and cross-bedded internal structure. The rocks are submature to mature quartzarenites, with accessory content of detrital feldspar and clay minerals, mostly illite (Fig. 12). They are strongly altered by diagenetic processes, including pyritization, dolomitization, and silicification. The member at Bravaisodden shows excellent exposures of the subvertical trace fossil *Polykladichnus,* interpreted by Mørk and Bromley (in press) to represent shallow, high-energy environments.

The base of the Van Keulenfjorden Mb shows thin lag horizon composed of reworked and rounded sandy phosphate nodules (Fig. 19). The nodules form grain-supported layer that is partly infiltrated by sediment of the overlying sandy sequence. They have pyritized external zones, in which micrgranular pyrite replaces the original phosphate cement and fills rudimentary pore space. The pyritization zone of the lag horizon extends upward into the basal sandstone beds

← Fig. 18. Phosphorite (III). **A**. Compact phosphatic grainstone in the upper part of the Passhatten Mb (unit 7). **B**. The grainstone is dominated by phosphatic peloids and coated grains, and is cemented by calcitic spar. **C**. Nodular phosphorite in sandy siltstone bed in the middle part of the Passhatten Mb (unit 5) showing section of phosphatic ammonoid. Note the injection sediment structure in the central, calcite-cemented part of the fossil. **D**. Compact phosphatic infilling of external chamber of the ammonoid showing common moulds of radiolarian tests and siliceous sponge spicules. **E**. Reworked nodular phosphorite horizon in bioturbated sandstone in the middle part of the Passhatten Mb (unit 5). **F**. Nodular matrix is a sandy sediment dominated by quartz grains cemented by phosphate (ultracrystalline carbonate fluorapatite). Note the admixture of phosphate-replaced fragments of thin-shelled pelecypods and phosphatic moulds of siliceous sponge spicules. A, C, E – photographs of thin sections; B, D, F – TLM photomicrographs, normal light. The scale in C and D is for A, C, E and B, D, F, respectively.

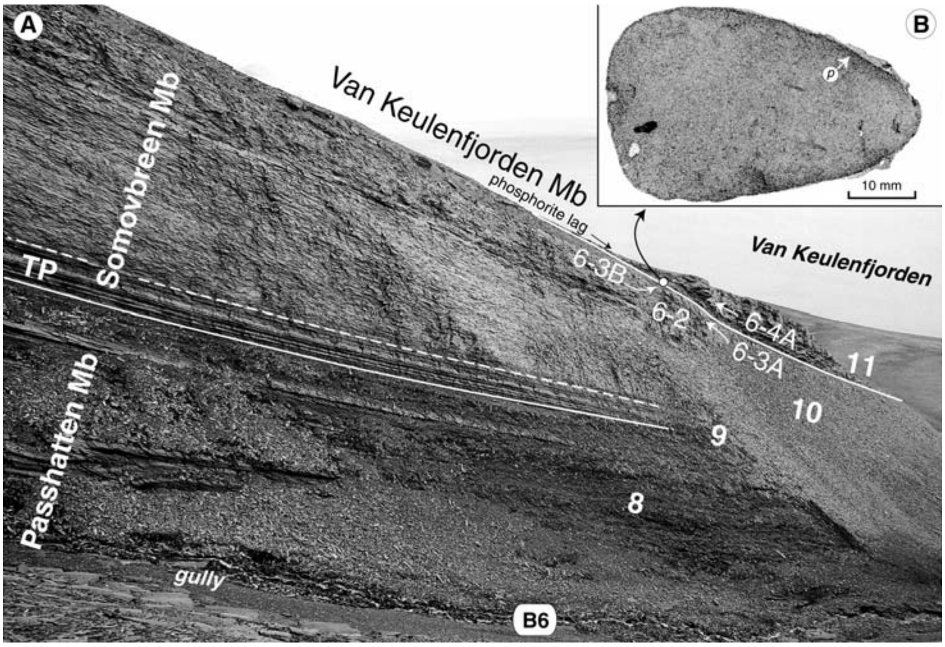


Fig. 19. Sandstone of the Van Keulenfjorden Mb (I). **A**. Upper part of the Bravaisberget Fm (units *8*, *9*, *10*, and *11*) exposed at eastern side of rocky gully at SE flank of Bravaisberget (section *B6*). The sequence of Van Keulenfjorden Mb rests upon a discontinuity surface, which is covered by nodular phosphorite lag. Numbers and arrows show position of samples analyzed in this paper. *TP* is the top phosphorite-bearing sequence (unit *9*). **B**. Thin section photograph of phosphate nodule from the lag at base of the Van Keulenfjorden Mb. The nodule is rounded as a result of reworking in sedimentary environment, and shows pyritized external zone (*p*) resulted from subsurface pyritization in the early diagenetic sulphate reduction zone.

of unit 11. This interval can be recognized in the field by a dominant reddish weathering colour. Microgranular pyrite is common throughout the Van Keulenfjorden Mb, where it occurs in the form of microscopic aggregates showing features of diagenetic recrystallization (Fig. 20A). Microprobe analyses show that the pyrite in the member has strikingly similar chemical composition to sedimentary pyrite occurring in the underlying Somovbreen and Passhatten mbs. This composition is close to pure pyrite, with negligible contribution of Co, Ni, Cu, Cd, and Zn in some analyzed microcrystals. It is typical of sedimentary pyrite formed as a result of bacterial sulphate reduction in early diagenetic environment (Krajewski and Luks 2003). It is therefore likely that common pyritization of the Van Keulenfjorden Mb reflects prolonged maintenance of originally porous and permeable clastic sediment in the sulphate reduction zone. This is supported by a general lack of calcite cement in the member, which in the underlying sandy bodies filled up the pore space at early stages of diagenesis.

Dolomite is the only carbonate cement in the Van Keulenfjorden Mb (Fig. 12). It occurs in the form of minute rhombs (30–100 μm in size) that are randomly dis-

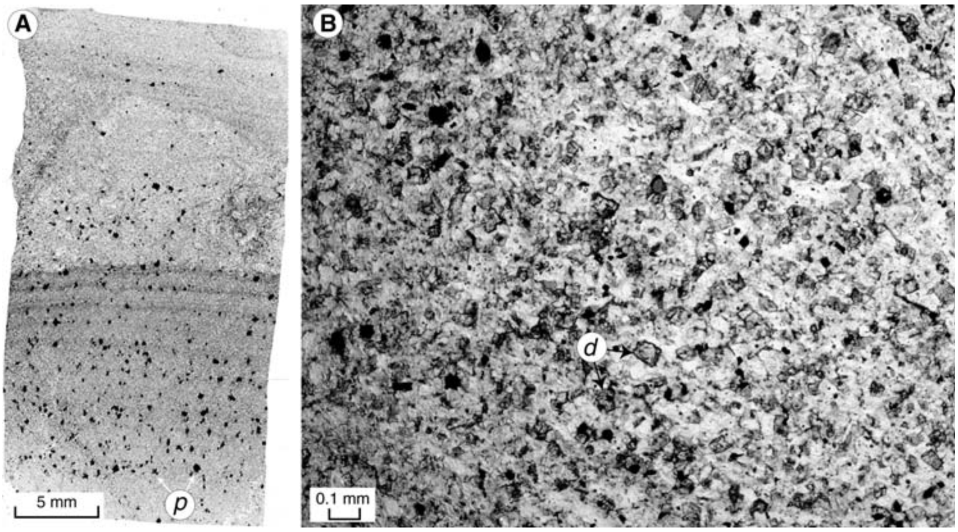


Fig. 20. Sandstone of the Van Keulenfjorden Mb (II). **A**. Laminated silty sandstone in the lower part of the member showing common pyrite aggregates (*p*) scattered through the rock matrix. Thin section photograph. **B**. Sandstone of the upper part of the member showing severe dolomitization and silicification. The rock shows interlocking mosaic of quartz crystals in which discrimination of the original sediment grains is difficult, as well as common, randomly distributed dolomite rhombs (*d*). TLM photomicrograph, normal light.

tributed throughout the rock matrix (Fig. 20B). These crystals show zoned internal structure and chemical composition similar to dolomite crystals scattered in sandstones and siltstones of the Passhatten and Somovbreen members. Mean composition of the dolomite is $Ca_{1.02}Mg_{0.88}Fe_{0.10}(CO_3)_2$, though with wide variations in the content of iron and magnesium. Similar dolomite and ankerite cements abundantly occur in coarser-grained intervals and beds of the Botneheia Formation, making recurrent cementstone horizons. Preliminary study of these cements (K. P. K.) suggests their development at later stages of diagenesis under increased burial of the sequence.

Silicification is common in the Van Keulenfjorden Mb. It is manifested by silica overgrowths of the original detrital grains and silica clusters in the inter-particle pore space, with consequent matrix recrystallization to form quartz-dominated dolomitic rock. Recrystallization of quartz cement was associated with recrystallization of pyrite aggregates, and resulted in interlocking boundaries between the two mineral phases.

## Discussion

The Bravaisberget Fm at Bravaisberget provides insight into a general shallow shelf development of the Middle Triassic depositional system in Svalbard. The sequence embraces the thickest known development of the organic-rich facies in western Spitsbergen.

The base of the Bravaisberget Fm contains phosphorite conglomerates that mark the onset of Middle Triassic transgression and immediate establishment of high biological productivity conditions in the shelf area. These conditions lasted throughout the deposition of the Passhatten Member (up to unit 9). The member shows recurrent development of sequences dominated by black shale (units 2, 4, 6 and 8) and the composite sequences enriched in phosphorite (units 1, 3, 5 and 7). This facies pattern reflects interplay between low-energy, organic-prone environments and higher-energy environments that concentrated coarser clastics and phosphorite. It could be explained by differentiated morphology of the shelf, in which extended areas with organic-rich, fine-grained sedimentation housed elevated clastic sediment bodies (bars) that focused phosphogenesis due to suppressed depositional rates and enhanced mineralization of organic matter. Spatial and temporal migration of clastic bars in the organic-rich shelf area accounts for the observed vertical changes in the dominant lithology and the associated sedimentary features in the Passhatten Mb. Sequences dominated by black shale reflect deposition on muddy bottoms, with a general low oxygen content and intermittent action of bottom currents. Composite sequences of phosphatic siltstones and sandstones that interfinger with black shale reflect deposition on sides of the clastic bars, where recurrent progradation of coarser-grained beds on the muddy bottom occurred along with downslope redeposition of phosphorite. The bar top sequences consist of thick beds of siltstone and sandstone showing common traces of winnowing and reworking as well as ubiquitous bioturbation of sediment. Accumulations of allochthonous phosphate nodules and peloids form recurrent horizons and conglomeratic beds in the bar top sequences. Units 3 and 5 show the well-developed bar top sequences in their middle parts, that are under- and overlain by the bar side sequences passing gradually into the dominant muddy bottoms (Fig. 7). Mørk and Bromley (in press) regard strongly bioturbated siltstone beds as having formed due to sporadic stirring up of the sediment by storms in a dominantly anoxic environment. While this storm mechanism may have dominated in the more offshore environments further east on Svalbard, the bar mechanism suggested here seems to have played the major role in the shallow shelf areas along western Spitsbergen.

The basal phosphorite-bearing sequence (unit 1) can be recognized along the western Spitsbergen outcrop belt, from Isfjorden in the north to Hornsund in the south. These deposits immediately followed the basal Anisian transgression, indicating that they probably represent an isochronous horizon. The lower, middle, and upper phosphorite-bearing sequences recognized at Bravaisberget (units 3, 5 and 7) can be traced over a distance of several kilometres along the outcrops in western Nathorst Land and in northern Wedel Jarlsberg Land and northern Torell Land (see also Różycki 1959). This outcrop belt is supposed to be roughly parallel to the margin of the Middle Triassic depositional shelf in Svalbard (Mørk *et al*. 1982, Krajewski 2000a). The observed extent of these sequences should likely correspond to axial dimensions of clastic bars in the shallow shelf area. In inner Hornsund, located 80 km to the south from Bravaisberget, there are two phosphorite-bearing sequences in the Passhatten Mb, which are interpreted to represent the bar sequences (Krajewski 2000e). These sequences cannot be directly correlated. They represent discontinuous sediment bodies that originated as a result of complex migration of phosphogenic bars in the organic-rich shelf depositional area.

The succession of the Passhatten Mb at Bravaisberget shows a general two-stage evolution, with the upper part (units 6–8) dominated by black, fine-grained deposits suggesting a general deeper-water development, compared to the lower part (units 1–5), which concentrates clastic bar sequences indicative of a shallower development. This suggests a transgressive pulse in the upper part of the Passhatten Mb, which overlapped on the variegated shelf depositional environments discussed above. The two parts of the Passhatten Mb have been ascribed to the 3rd or 4th – order sequences discerned in the Triassic succession in Svalbard (sequences 4 and 5), and supposed to reflect regional transgressive pulses in the Boreal Ocean (Van Veen *et al.* 1992; Mørk *et al.* 1993; Mørk 1994; Egorov and Mørk 2000; Embry and Mørk in press).

The onset of deposition of sandy facies of the Somovbreen Mb at Bravaisberget terminated organic-rich environments of the Passhatten Mb. This facies change is abrupt, resulted from a rapid shallowing trend and progradation of clastic sediment bodies from the west and southwest (Krajewski 2000a). The main sandy sequence of the Somovbreen Mb thins southeastwards along the outcrop belt in northern Wedel Jarlsberg Land and northern Torell Land. At Passhatten, located 15 km SSE of Bravaisberget, the sandy facies of the Somovbreen Member wedges out (Różycki 1959). It reappears and thickens up further south in Torell Land, attaining nearly 40 m in inner Hornsund (Birkenmajer 1977; Krajewski 2000e). To the north, the sandy sequence of the Somovbreen Mb can be traced on both sides of Van Mijenfjorden. However, it thins northwards in Nordenskiöld Land, being replaced at Festningen by bank deposits with phosphatic ooids (Mørk *et al.* 1982).

The top phosphorite-bearing sequence (unit 9) at Bravaisberget is interpreted to have developed in front of prograding sandy bodies of the Somovbreen Mb under conditions of suppressed depositional rates and common interactions of dynamic agents with the shelving bottom. The phosphorite-bearing sequence occurring in a similar facies position in inner Hornsund contains recurrent condensed beds with phosphatic crusts, suggesting pronounced non-deposition episodes just before progradation of sandy bodies of the Somovbreen Mb (Krajewski 2000a). Increasing-upward sedimentation rates in the Somovbreen Mb at Bravaisberget, resulted from enhanced supply of terrigenous clastic material, terminated the phosphogenic environments. However, these environments lasted with changing intensity of phosphogenesis throughout the depositional history of the Somovbreen Mb at shallow shelf areas that showed recurrent non-depositional interludes and/or suppressed sedimentation rates (Krajewski in press).

The top of the Somovbreen sequence at Bravaisberget records a non-depositional event with intermittent erosion, during which local reworking and concentration of sandy phosphate nodules produced thin phosphorite lag horizon. This event was associated with abrupt change of the environment that introduced brackish depositional system of the Van Keulenfjorden Mb to western Spitsbergen. Similar reworking and non-deposition marks the top of the Blanknuten Mb in central and eastern Svalbard (Buchan *et al.* 1965; Mørk *et al*. 1999), though it is not clear whether these two events were coeval.

The Van Keulenfjorden Mb was deposited during the closure of the Middle Triassic shelf basin in Svalbard, and is known to occur in western and southern Spitsbergen due to filled accommodation space (Pčelina 1983; Mørk *et al*. 1999; Krajewski 2000e). At Bravaisberget, it is represented by intensively reworked sediment deposited in a general high-energy regime dominated by fine-grained clastics. The sediment remained uncemented during early diagenesis, and acted as a trap of pyrite due most probably to sulphate reduction at methane oxidation front in shallow subsurface. The lack of early calcite cementation provided space for silicification and dolomitization processes during later stages of diagenesis.

The bipartite nature of the Van Keulenfjorden Mb at Bravaisberget (units 11 and 12) can also be observed southwards in Spitsbergen. The two coarsening-upward sequences, which are dominantly sandy in Nathorst Land, Wedel Jarlsberg Land and Torell Land, become progressively muddier in their lower parts in Sørkapp Land. There is no precise biostratigraphic dating of the member. It is however likely that it corresponds to a non-deposition (or emersion) period at top of the Botneheia Fm in central and eastern Svalbard.

## Conclusions

New observations and measurements of the type section of the Bravaisberget Fm at Bravaisberget in western Nathorst Land, Spitsbergen allow to present detailed lithostratigraphical subdivision of the formation, and aid to reconstruct its depositional history. The section is representative of shallow shelf development of the Middle Triassic depositional system in Svalbard.

The subdivision of the Bravaisberget Fm at type section (209 m thick) into the Passhatten, Somovbreen, and Van Keulenfjorden mbs is sustained after Mørk *et al.* (1999), though with new position of the boundary between the Passhatten and Somovbreen mbs. The Passhatten Mb is here defined to embrace the black shale-dominated sequence that forms the lower and middle parts of the formation (160 m thick). The Somovbreen Mb (20 m thick) is confined to the overlying, calcite-cemented sequence of marine sandstones. The Van Keulenfjorden Mb (29 m thick) forms the topmost part of the formation composed of siliceous and dolomitic sandstones.

The Bravaisberget Fm records two consequent transgressive pulses that introduced high biological productivity conditions to the shelf basin. These pulses deposited organic-rich sediments of the Passhatten Mb. The succession shows pronounced repetition of sediment types resulting from interplay between organic-prone, fine-grained environments and clastic bar environments that focused phosphogenesis. The base of the Passhatten Mb is accentuated by transgressive phosphorite conglomerates. The lower part of the member (units 1 to 5) contains well-developed bar top sequences with abundant nodular phosphorite, which are under- and overlain by the bar side sequences grading into silt- to mud-shale. The upper part of the member (units 6 to 8) is dominated by mud-shale, showing the bar top to side sequence with recurrent phosphatic grainstones in its middle part. Maximum stagnation and deep-water conditions occurred during deposition of the topmost shale sequence (unit 8). Rapid shallowing trend terminated organic-rich environments of the Passhatten Mb, and was associated with enhanced phosphogenesis at base of the Somovbreen Mb (unit 9). Bioturbated sandstones of the Somovbreen Mb (unit 10) record progradation of shallow-marine clastic environments. The Van Keulenfjorden Mb embraces fine-grained sandstones (units 11 and 12) that were deposited in brackish environments reflecting infilling and closure of the Middle Triassic basin in Svalbard.

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