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The Botneheia Formation (Middle Triassic) in Edgeøya and Barentsøya, Svalbard: lithostratigraphy, facies, phosphogenesis, paleoenvironment

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Abstract: The Middle Triassic Botneheia Formation in Edgeøya and Barentsøya, eastern Svalbard embraces an organic carbon-rich, fine-grained clastic succession (up to 100 m thick) that makes the best petroleum source unit in the region. This paper presents new lithostratigraphic subdivision and detailed description of the formation, followed by its paleoenvironmental interpretation and reconstruction of the depositional history. The Botneheia Fm is subdivided into two members occurring in stratigraphic order: (1) the lower Muen Mb (new unit), and (2) the upper Blanknuten Mb (extended description). Nine informal lithostratigraphic units are defined as well in the formation, five in the Muen Mb (units 1 to 5), and four in the Blanknuten Mb (units 6 to 9). The Botneheia Fm records a second-order transgressive-regressive cycle in the Triassic succession of Svalbard that was developed in an open shelf environment. It embraces two superimposed, third-order transgressive pulses followed by stepwise regression. The rises of sea level were associated with consequent deterioration of bottom environment, from prevailing oxic bottoms in the Muen Mb, through mostly dysoxic bottoms in the upper part of the Muen Mb and the lower part of the Blanknuten Mb, to euxinic conditions in the middle part of the Blanknuten Mb. The regressive trend terminated the Svalbard euxinia, and ended up in regional disconformity at top of the Botneheia Fm. Superimposed on the second transgressive pulse was the development and maintenance of high biological productivity in surficial waters that led to increased contribution of organic carbon in sediment and phosphogenesis.

Key words: Svalbard, Middle Triassic, Botneheia Formation, lithostratigraphy, facies, phosphogenesis, paleoenvironment.

Introduction

The Middle Triassic Botneheia Formation in Svalbard (Mørk *et al.* 1982) embraces a succession of bituminous marine shales that crops out in central and eastern Spitsbergen, Barentsøya, Edgeøya, and SW Nordaustlandet, extending into wide underwater area in the NW Barents Sea Shelf (Leith *et al.* 1992; Harland 1997; Mørk *et al*. 1999; Dallmann *et al.* 2002). In eastern Svalbard, this formation contains up to 12 wt. % organic carbon and occurs at the oil window maturity level, providing it should be a key target in reconstructing sedimentary and burial processes that led to the formation of Mesozoic oil in the region (Forsberg and Bjorøy 1983; Mørk and Bjorøy 1984; Schou *et al.* 1984; Abdullah 1999; Krajewski 2000d, e).

This paper presents detailed description and new lithostratigraphic subdivision of the Botneheia Fm in eastern Svalbard, followed by its paleoenvironmental interpretation and reconstruction of the depositional history. The classification of the Triassic succession is used here in accordance with the definitions presented in the *Lithostratigraphic Lexicon of Svalbard* (Mørk *et al*. 1999). The new Muen Member and a new hypostratotype for the Blanknuten Member have been approved by the Norwegian Committee on Stratigraphy.

Geological background

The Eastern Svalbard Platform shows nearly flat-lying Late Paleozoic and Triassic strata exposed in NE Spitsbergen (Olav V Land), SW Nordaustlandet (Gustav Adolf Land), Barentsøya, and Edgeøya, that are disturbed locally by extensive Early Cretaceous basic igneous activity, mainly in the form of sills (Harland 1997). The Triassic succession rests with a stratigraphic gap on the Permian Kapp Starostin Formation, and consists of two major sedimentary cycles classified into the Sassendalen and Kapp Toscana groups (Mørk *et al*. 1999). Best and most complete sections are known from coastal and near coast exposures in Edgeøya and Barentsøya (Fig. 1). The Sassendalen Group (Early–Middle Triassic) attains *ca* 300 m in eastern Svalbard, and consists of two formations: (1) the Vikinghøgda Fm; and (2) the Botneheia Fm. The Vikinghøgda Fm consists of dominantly dark grey shales, mudstones and siltstones, and is overlain by the Botneheia Fm embracing considerably darker, mostly black shales and mudstones, phosphatic in the upper part (Fig. 2). The overlying Kapp Toscana Group (Late Triassic–Early Jurassic) is more than 500 m thick. In Edgeøya and Barentsøya, it is represented by two lithostratigraphic units: (1) the Tschermakfjellet Fm; and (2) the De Geerdalen Fm. The Tschermakfjellet Fm embraces marine dark grey to black shales and siltstones with common clay-ironstone (sideritic) concretions, whereas the De Geerdalen Fm is a deltaic sandstone succession.

Previous work

The succession attributed to the Botneheia Fm in eastern Svalbard has already been known to Lindström (1865), Nordenskiöld (1866) and Wittenburg (1910). Falcon (1928) proposed first stratigraphic classification of the Triassic strata, and dis-

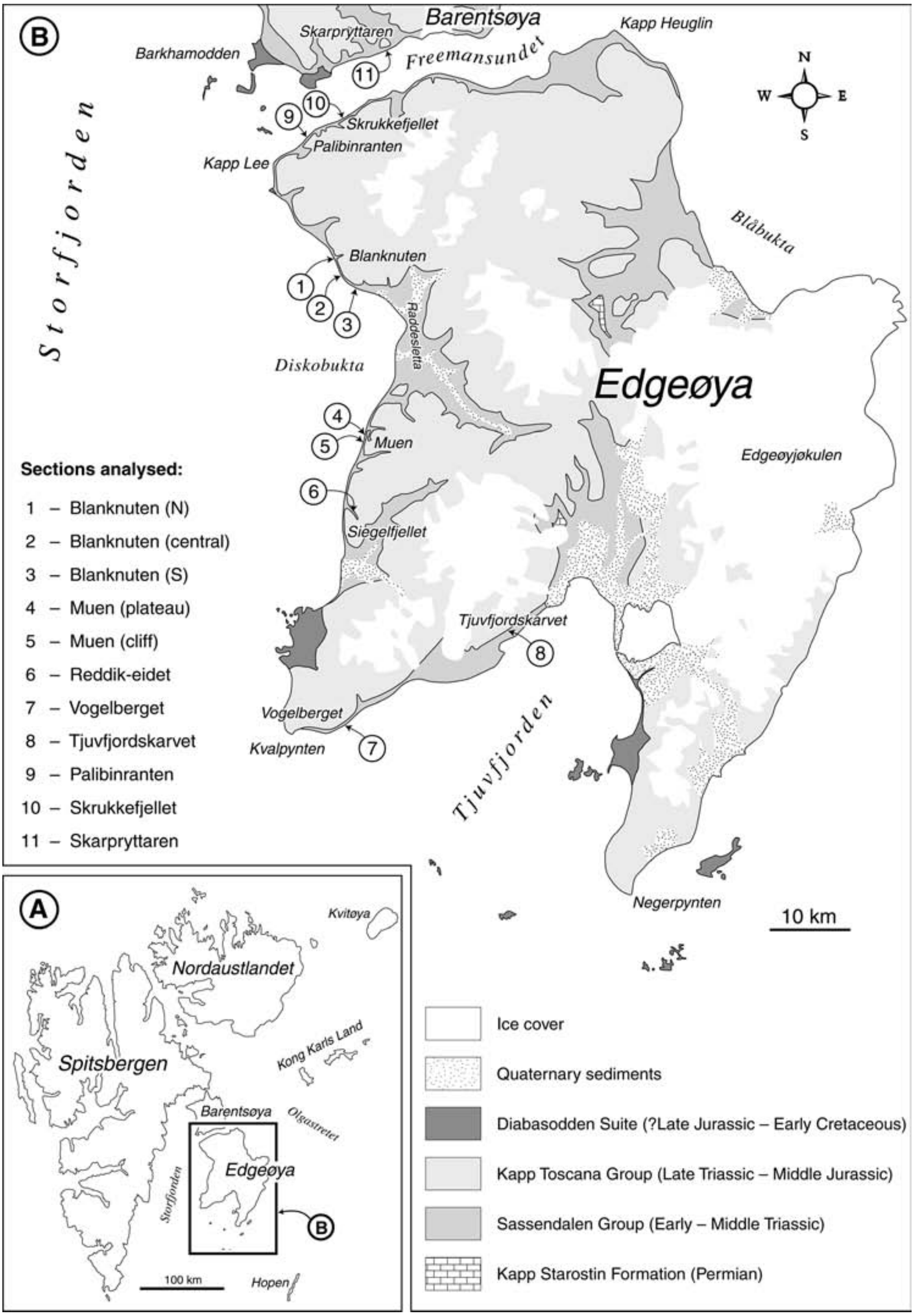


Fig. 1. **A**. Sketch map of the Svalbard archipelago. **B**. Geological map of Edgeøya and southern Barentsøya showing sections of the Botneheia Fm investigated in this paper (1–11). Geology after Dallmann *et al.* (2002), simplified.

cerned the Sassendalen Group succession (including Botneheia Fm) as the "Oil Shales group". Further details on the geology and paleontology of the Botneheia Fm were presented in the works of Klubov (1964; 1965a, b), Buchan *et al.* (1965), Flood *et al.* (1971), Tozer (1973), and Lock *et al.* (1978). The latter authors were the first to suggest direct correlation of upper part of the succession ("oil shales member") with the Botneheia Fm of Spitsbergen. Winsnes (1981) and Winsnes and Worsley (1981) presented geological map of Barentsøya and Edgeøya 1:500.000 showing distribution of the Triassic strata, repeated in recent compilation by Dallmann *et al.* (2002). Mørk *et al*. (1982) proposed new lithostratigraphic classification of the succession, which provided a base for currently accepted scheme (Mørk *et al*. 1999). Useful compilation of geological knowledge on the succession in eastern Svalbard can be found in the extensive work of Harland (1997).

Materials and methods

Detailed field observations and measurements of the Botneheia Fm were collected at seven locations in western Edgeøya and at one location in southern Barentsøya (Fig. 1). In Edgeøya, the following sections were studied: (i) Blanknuten north of Diskobukta (three sections in western slope and cliff – locations 1–3 in Fig. 1); (ii) Muen (two sections in coastal and near coast exposures – locations 4 and 5), and (iii) Siegelfjellet (section in Reddik-eidet creek – location 6) south of Diskobukta; (iv) Vogelberget and (v) Tjuvfjordskarvet in Tjuvfjorden (two sections in coastal cliffs and slopes – locations 7 and 8); and (vi) Palibinranten and (vii) Skrukkefjellet in Freemansundet (two sections in near coast exposures – locations 9 and 10). In Barentsøya, detailed section in the slope from the coast up the mountain Skarpryttaren was analyzed (location 11). Supplementary observations were collected along near coast exposures from Kapp Lee to Palibinranten (Freemansundet) and from Kapp Lee to Blanknuten (Storfjorden) in NW Edgeøya, and at eastern slopes of a mountain range between Willybreen and Hübnerbreen (Lomberget, Isormen) in NE Barentsøya.

Type sections of the two members of the Botneheia Fm have the following location: (1) the Muen Mb (new unit here defined) at Muen; and (2) the Blanknuten Mb at Blanknuten (Figs 2–4). There are two separate outcrops of the Botneheia Fm at Muen: (i) coastal cliff west of point 340 m a.s.l. that is located SW of the main summit (420 m a.s.l.), referred here to as the "Muen cliff"; and (ii) slopes and cliffs rimming a table mountain separated by steep gorge from the main summit, referred to as the "Muen plateau". Detailed section of the formation at Muen, and the stratotype for the Muen Mb, is a compilation of the two (Fig. 5A–F). It should be noted that access to the lower part of the formation at Muen cliff is difficult and requires climbing abilities. At Blanknuten (479 m a.s.l.), there is a continuous outcrop belt of the upper part of the formation along a prominent cliff in the western slope that continues over

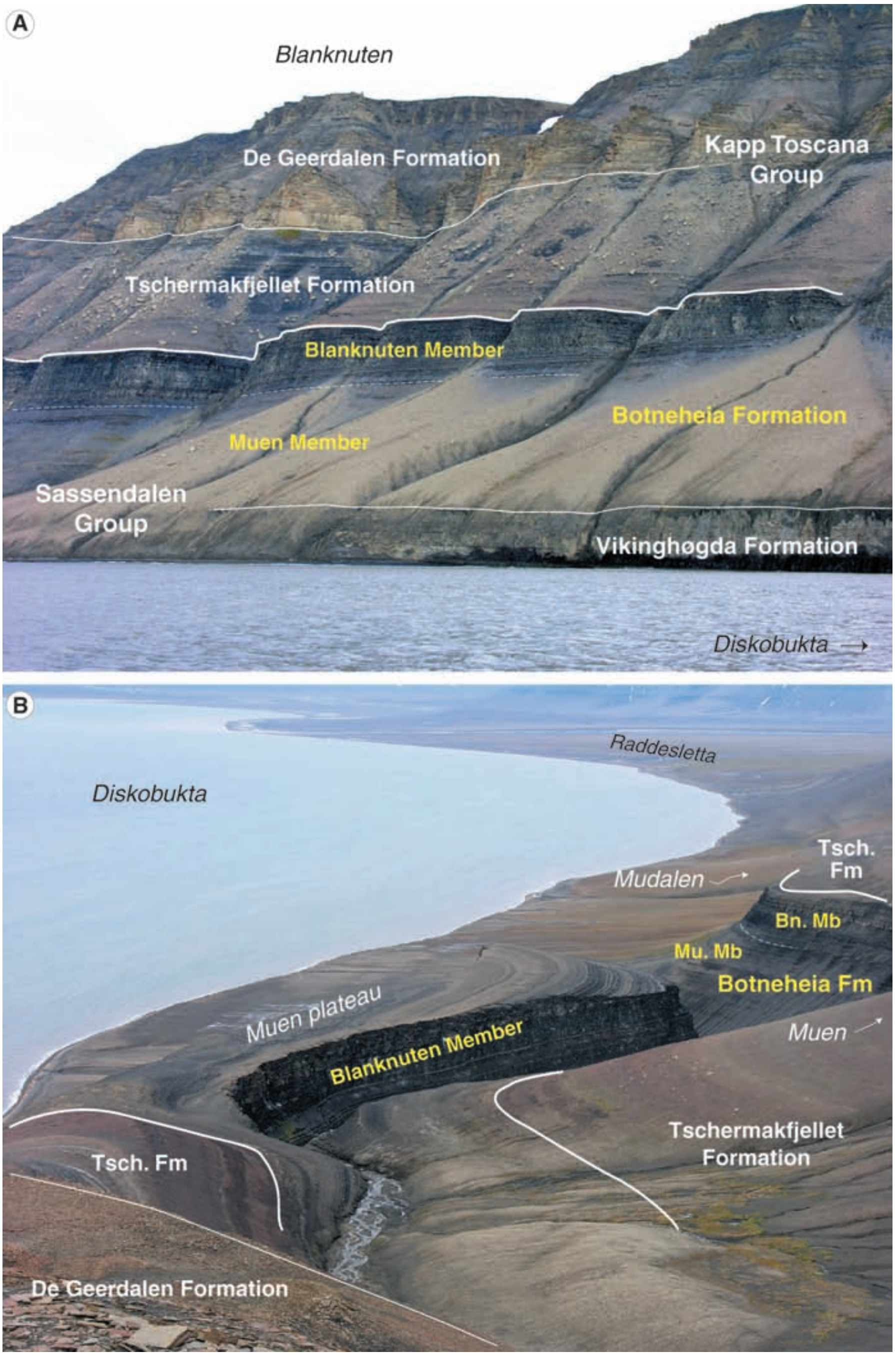


Fig. 2. Position of the Botneheia Fm in the Triassic succession of eastern Svalbard. **A**. Western slope of Blanknuten north of Diskobukta in western Edgeøya (hypostratotype for the Blanknuten Mb). **B**. Muen (plateau) south of Diskobukta in western Edgeøya (stratotype for the Muen Mb). Mu. Mb – Muen Mb; Bn. Mb – Blanknuten Mb; Tsch. Fm – Tschermakfjellet Fm.

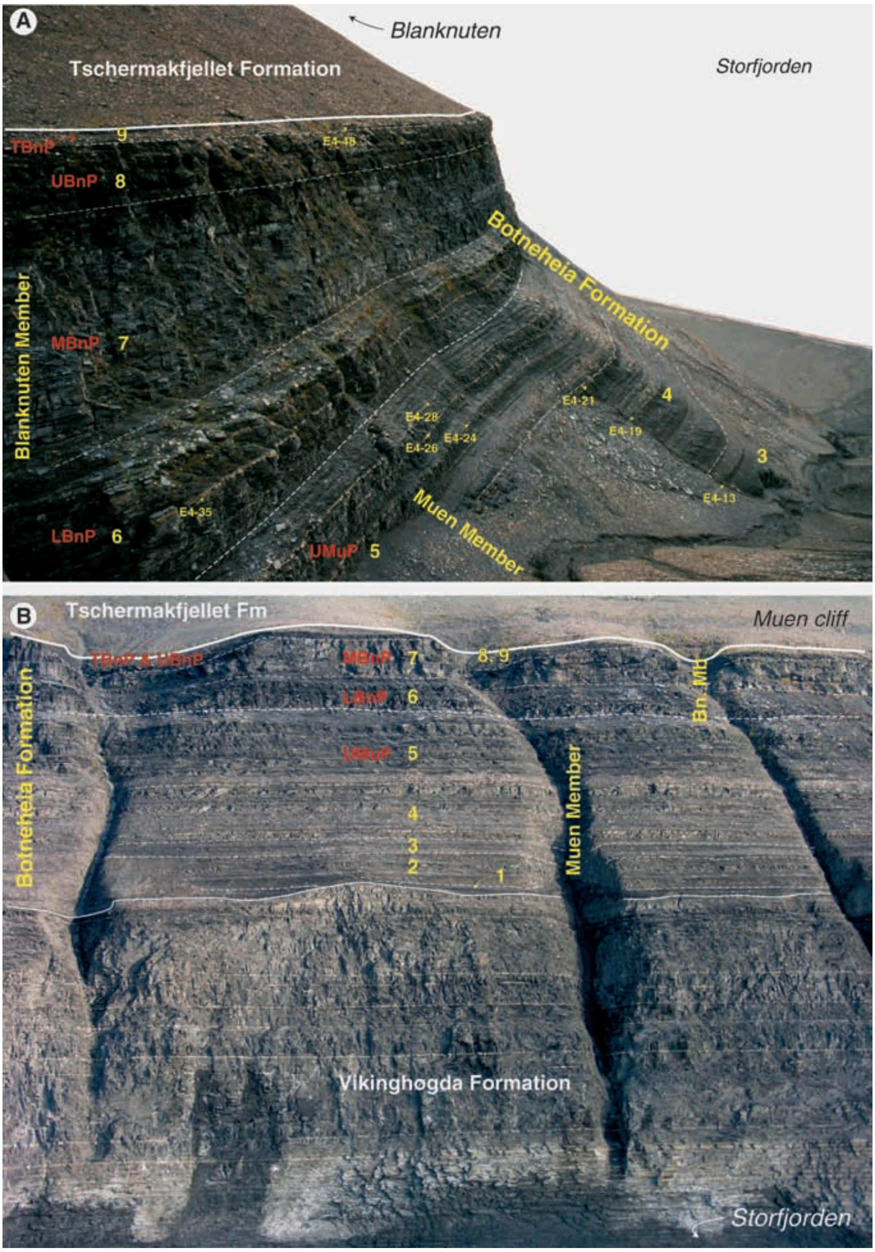


Fig. 3. Lithostratigraphic subdivision of the Botneheia Fm in eastern Svalbard. **A**. Hypostratotype section of the Blanknuten Mb in rocky gorge in northern part of western slope of Blanknuten, Edgeøya. **B**. Stratotype section of the Muen Mb at Muen cliff, Edgeøya. Indicated are informal lithostratigraphic units (1–9) and some distinct beds in the Blanknuten section. For other explanations see text.

a distance of *ca* 2.5 km. This cliff was defined as the stratotype for the Blanknuten Mb by Mørk *et al.* (1999, fig. 3-12 on p. 143: type section M-25 located in the south-

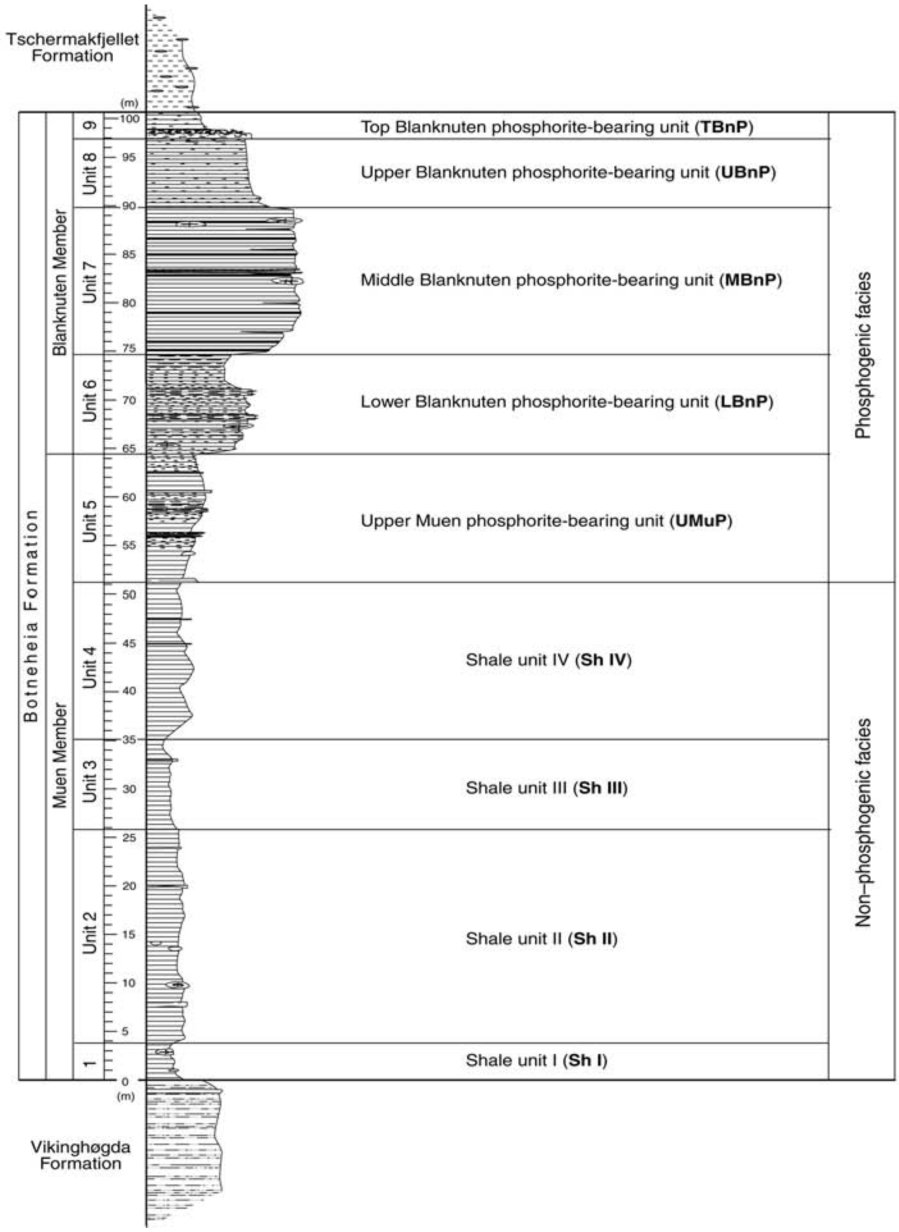


Fig. 4. General section of the Botneheia Fm in eastern Svalbard showing its new lithostratigraphic subdivision. Based on type sections of the Muen and Blanknuten mbs.

ern part of the cliff). However, the best and nearly complete section of the formation can only be observed in the northern part of the cliff, where a rocky gorge cuts into the western slope facing Storfjorden (location 1 in Fig. 1). This section (Blanknuten N) is here defined as hypostratotype for the Blanknuten Mb (Fig. 5A–F).

Over two hundred rock samples were collected along the studied sections and in reference locations. 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. 92 samples were cut with a diamond saw, and their sections were analyzed in detail. 74 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 48 bulk samples and 18 separated mineral fractions 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 – CFA) was calculated from XRD data using the equations of Gulbrandsen (1970) and Shuffert *et al.* (1990).

Lithostratigraphy

Botneheia Formation

The Botneheia Fm in eastern Svalbard is here subdivided into two members occurring in stratigraphic order: (1) the lower Muen Mb, and (2) the upper Blanknuten Mb (Fig. 4). The Muen Mb is defined for the first time, and its detailed description is presented below. The definition of the Blanknuten Mb follows that of Mørk *et al.* (1999), though with precise location of boundaries, detailed description, and lithostratigraphic subdivision reflecting its facies development typical of eastern Svalbard exposures. Nine informal lithostratigraphic units (units 1 to 9) are discerned in the formation, five in the Muen Mb (units 1 to 5), and four in the Blanknuten Mb (units 6 to 9). Discrimination of these units has been found useful for local correlations, classification of facies, and reconstruction of stages of deposition of the succession.

Muen Member (new unit)

Distribution: The member is distributed throughout the Triassic succession in eastern Svalbard, though usually it is covered by scree or poorly exposed.

Status of unit: Formal.

First use of name: Here.

Current definition: Here.

Synonyms and references: "Dark grey shale" of Lock *et al.* (1978).

Origin of name: After Muen, a mountain (420 m a.s.l.) located south of Diskobukta between Mudalen and Rakkardalen in western Edgeøya, where the member is best exposed.

Type section: (Fig. 5A–F). Stratotype: Muen, western Edgeøya (coastal cliff facing Storfjorden and slopes around the so called plateau; Figs 2, 3). The GPS coordinates for the base of the sections at Muen cliff and Muen plateau are N77°48.922' E21°20.859' and N77°49.488' E21°22.895', respectively.

Reference sections: Blanknuten, western Edgeøya (rocky gorge in the northern part of western slope; Fig. 3A); Reddik-eidet in western Edgeøya (northern slope of Siegelfjellet; Fig. 6A); Skrukkefjellet in northern Edgeøya (slope facing Freemansundet; Fig. 6B).

Thickness: 54 m at type section; 65 m at Blanknuten. At most localities thickness of the Muen Mb is difficult to measure because of its poor exposition. The member thins northeastwards in northern Edgeøya and Barentsøya.

Depositional age: Anisian. Biostratigraphic relations are poorly constrained in eastern Svalbard (Flood *et al.* 1971; Lock *et al.* 1978), providing that the depositional age can widely be elucidated by comparison with the succession exposed in Spitsbergen (Buchan *et al.* 1965; Tozer and Parker 1968; Korchinskaya 1972; Weitschat and Lehmann 1983; Weitschat and Dagys 1989). The occurrence of Early to Middle Anisian ammonoids in shale succession attributed to the Muen Mb is reported by Lock *et al.* (1978) from Edgeøya and Barentsøya. Tozer (1973) reports Middle Anisian ammonoids from Torellneset area (SW Nordaustlandet) on the basis of fossil collection made by Dr. Oscar Kulling in 1931. Klubov (1965a, b) reports Anisian ammonoids from the topmost part of the Muen Mb and the lower part of the Blanknuten Mb in Edgeøya, which suggests that the boundary between the two is located in Upper Anisian. This is consistent with the results of Weitschat and Lehmann (1983) from Spitsbergen, who place the Anisian/Ladinian boundary in the middle of the Blanknuten Mb. It should be noted however that the lower part of the Muen Mb in eastern Svalbard shows facies development that seems to be missing in Spitsbergen (see below). It might therefore appear that the succession in Edgeøya and Barentsøya provides the most complete record of Anisian sedimentation in the Svalbard basin.

Underlying unit: Vikinghøgda Formation.

Overlying unit: Blanknuten Member.

Superior unit: Botneheia Formation.

Main lithology: Shale and mudstone with recurrent carbonate cementstone beds and rare carbonate concretions. In the upper part of the member there appear phosphate nodules in the shale and a few phosphatic carbonate cementstone beds.

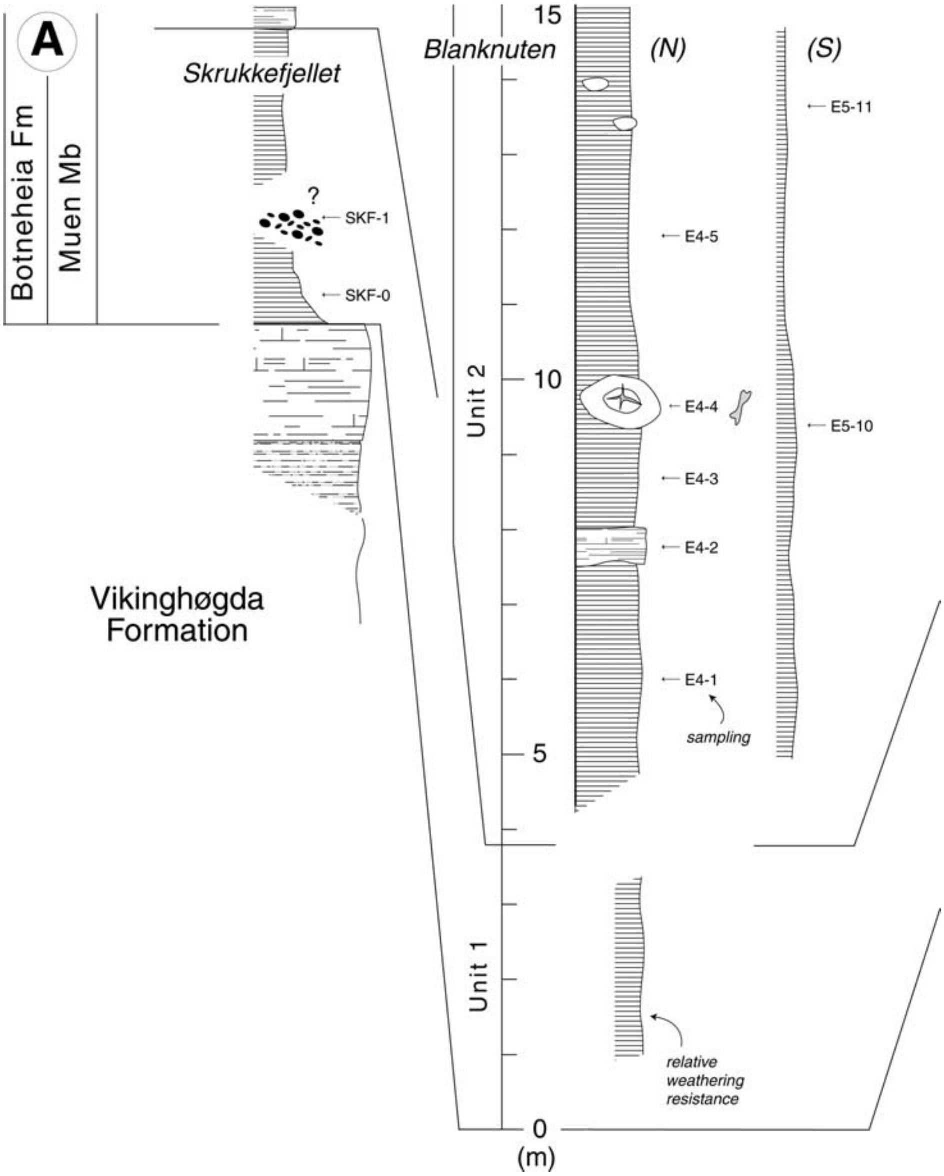
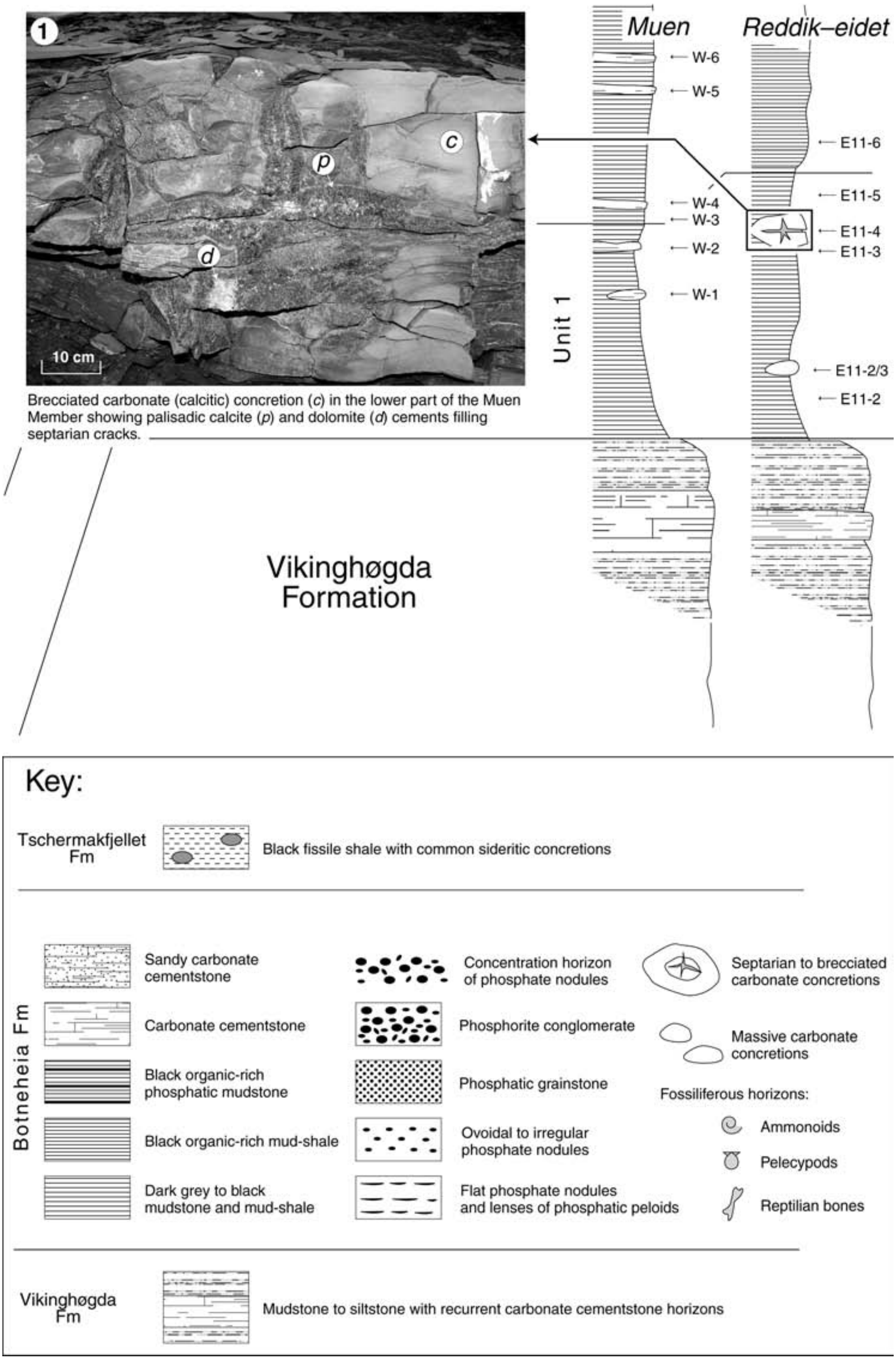
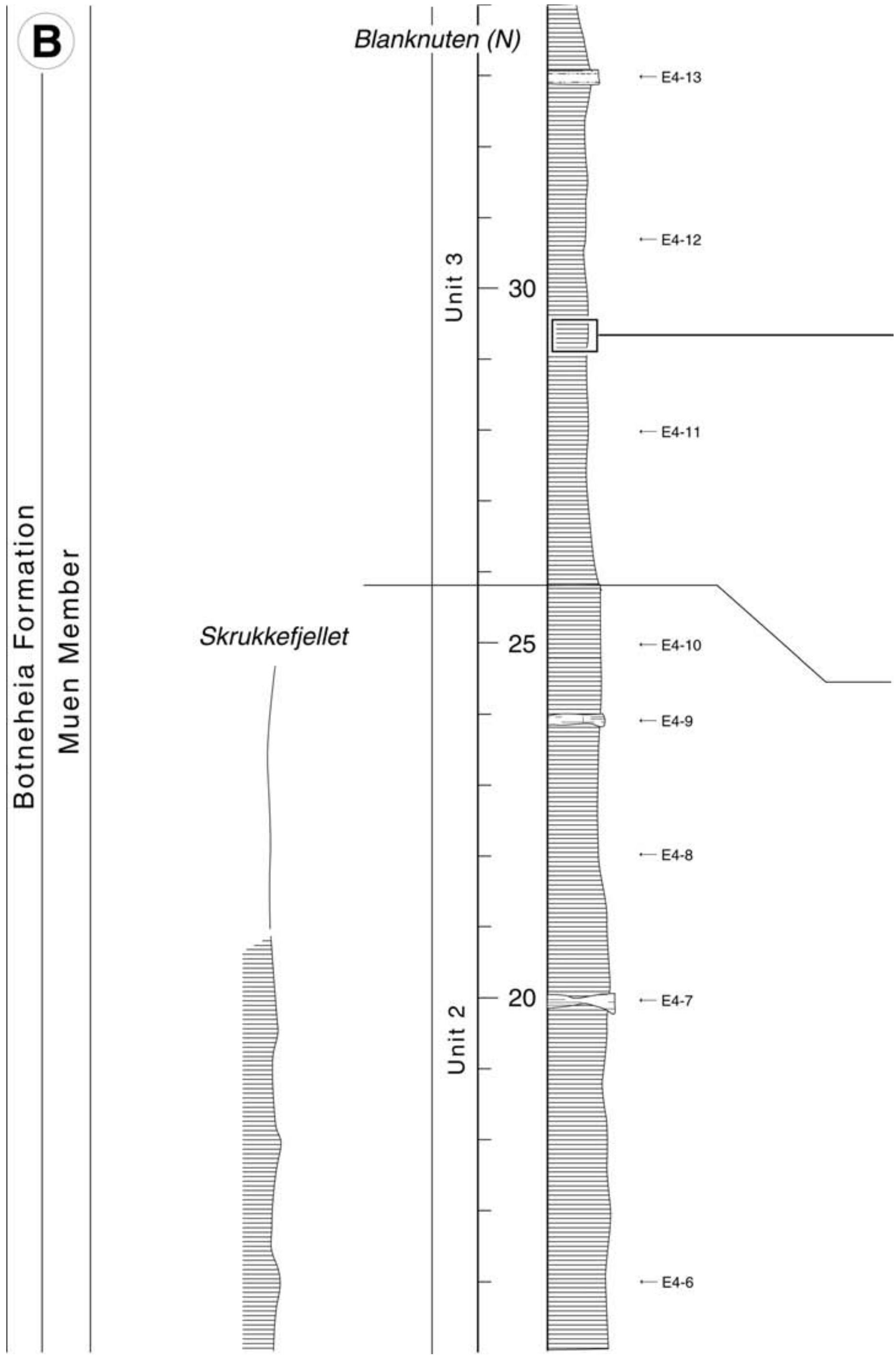


Fig. 5**A**–**F**. Sections of the Botneheia Fm in western Edgeøya and southwestern Barentsøya. Photographs included show typical lithologies of the formation. For location of the sections see Fig. 1.

Lower boundary definition: The lower boundary of the member is also the lower boundary of the Botneheia Fm. The boundary is placed at an abrupt change of lithology from resistant, dark grey mudstone and siltstone of the Vikinghøgda Fm to soft, fissile black shale of the Muen Mb (Figs 2, 3, 6). The topmost deposit in the Vikinghøgda Fm is commonly a pile of carbonate cementstone beds 0.5–2 m

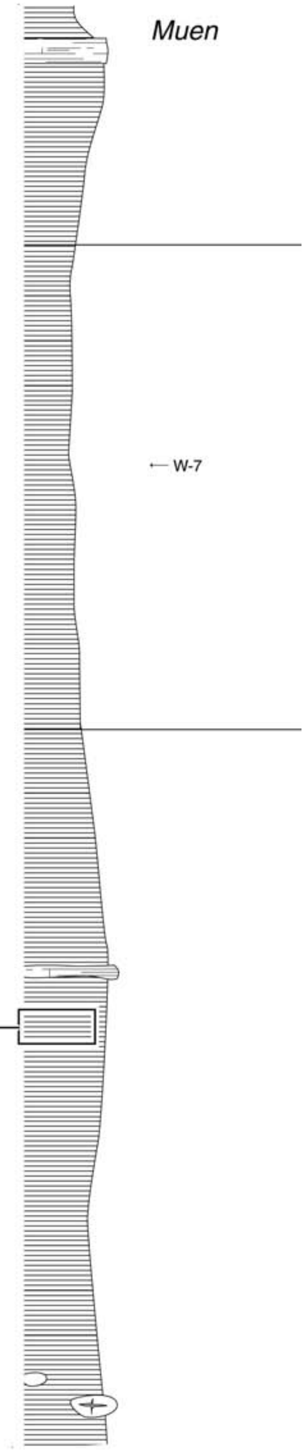


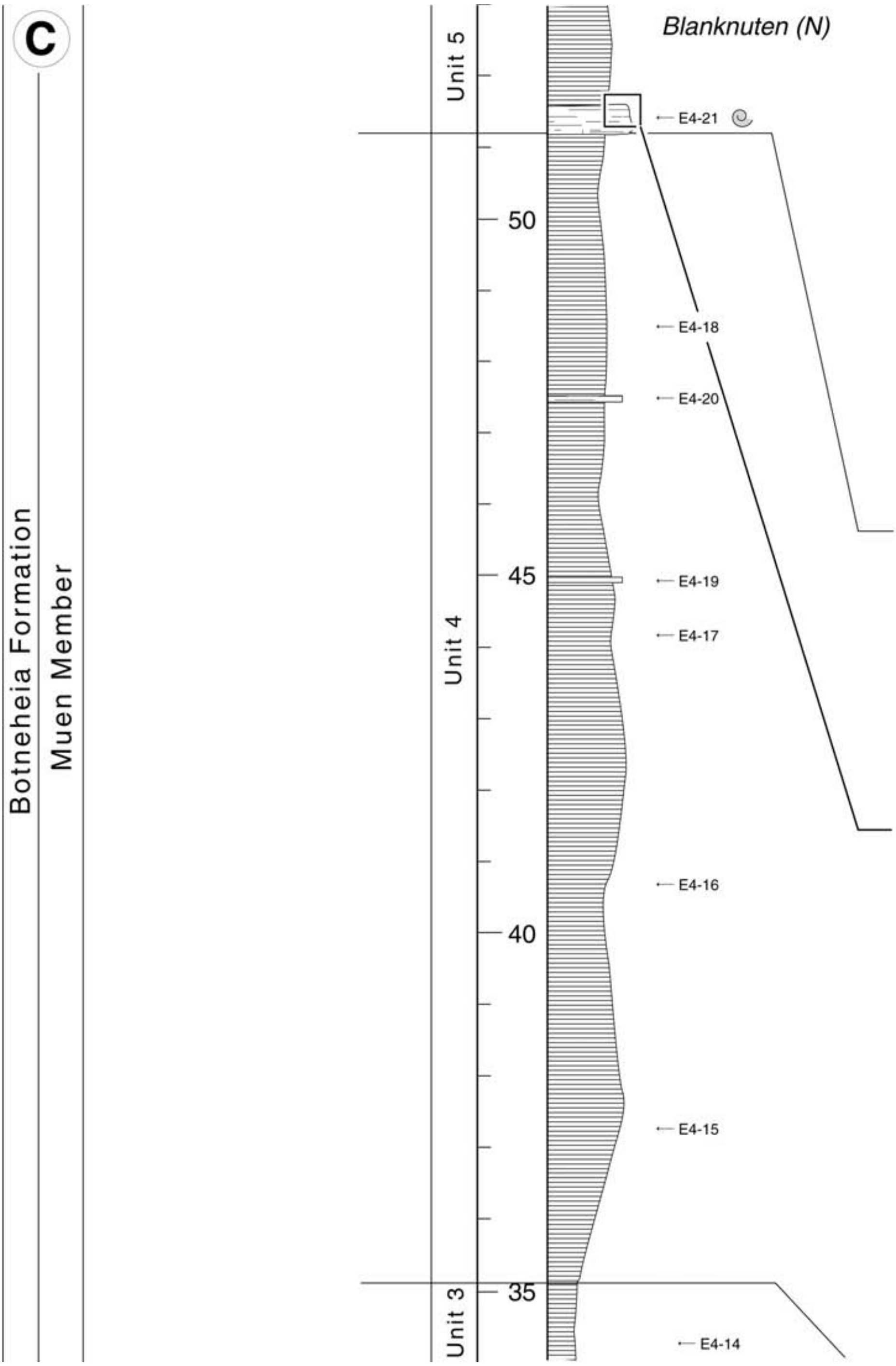
Brecciated carbonate (calcitic) concretion (*c*) in the lower part of the Muen Member showing palisadic calcite (*p*) and dolomite (*d*) cements filling septarian cracks.


B
Botneheia Formation
Muen Member
Blanknuten (N)
Skrukkefjellet
Unit 3
Unit 2
30
25
20
E4-13
E4-12
E4-11
E4-10
E4-9
E4-8
E4-7
E4-6

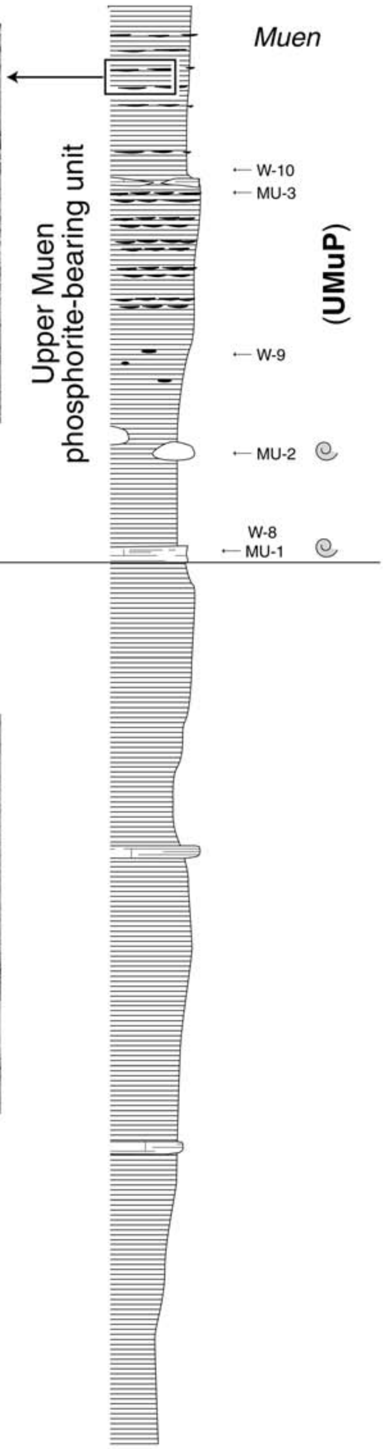
Soft, fissile black mud-shale in the middle part of the Muen Member.

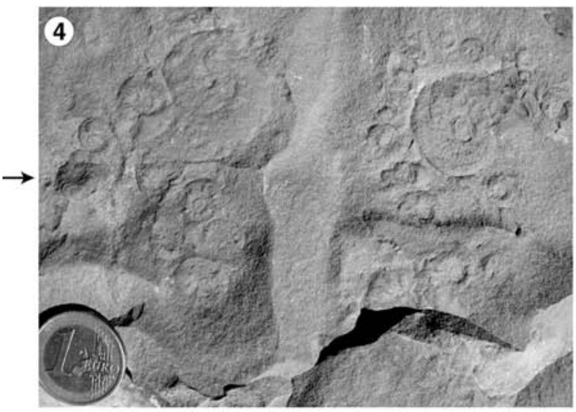
Dark grey mudstone to mud-shale with weakly developed fissility in the lower part of the Muen Member.



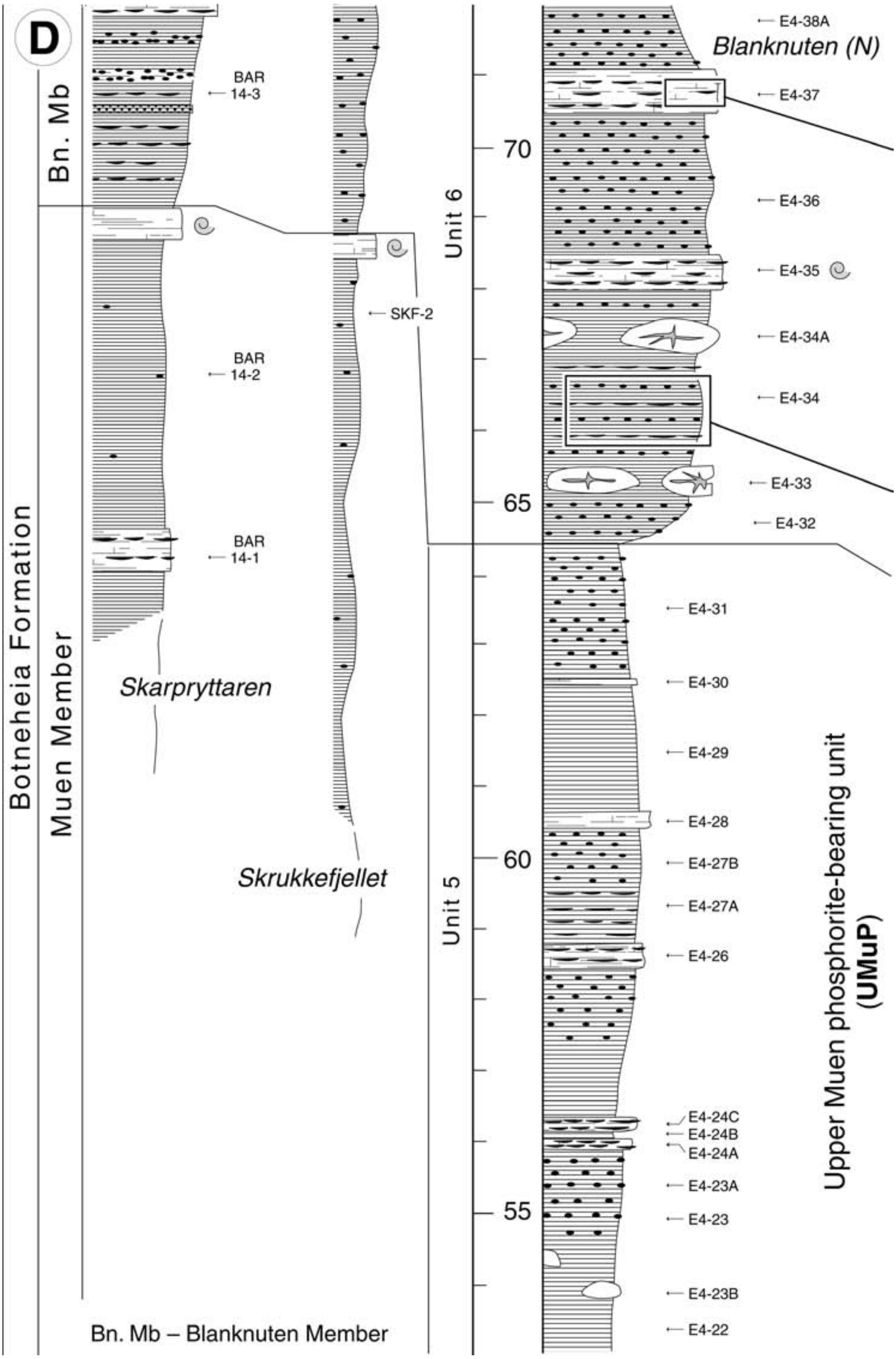

C
Botneheia Formation
Muen Member
Unit 5
Unit 4
Unit 3
Blanknuten (N)
50
45
40
35
E4-21
E4-18
E4-20
E4-19
E4-17
E4-16
E4-15
E4-14

Thin lenses of concentrated phosphatic peloids in black mud-shale in the upper part of the Muen Member.





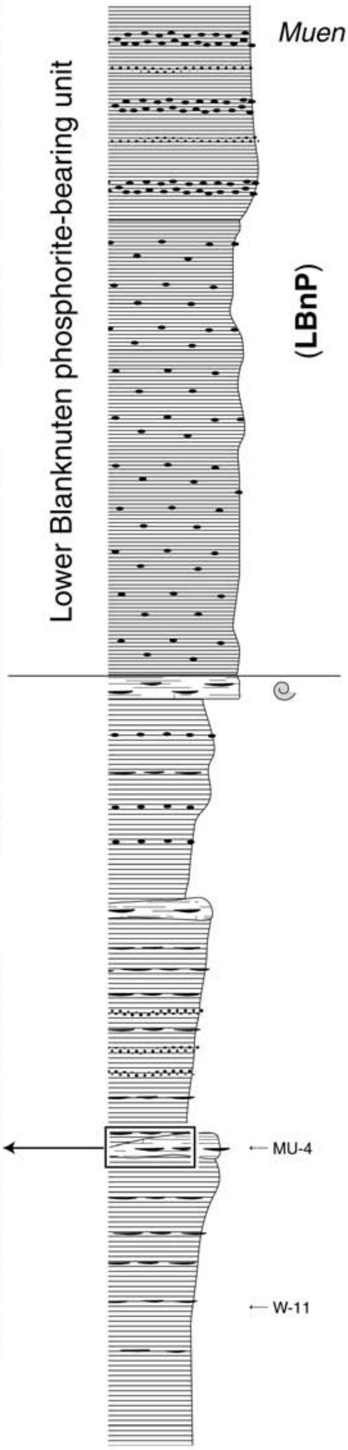
Flattened moulds of ammonoids in carbonate (dolomitic) cementstone bed in the middle part of the Muen Member.

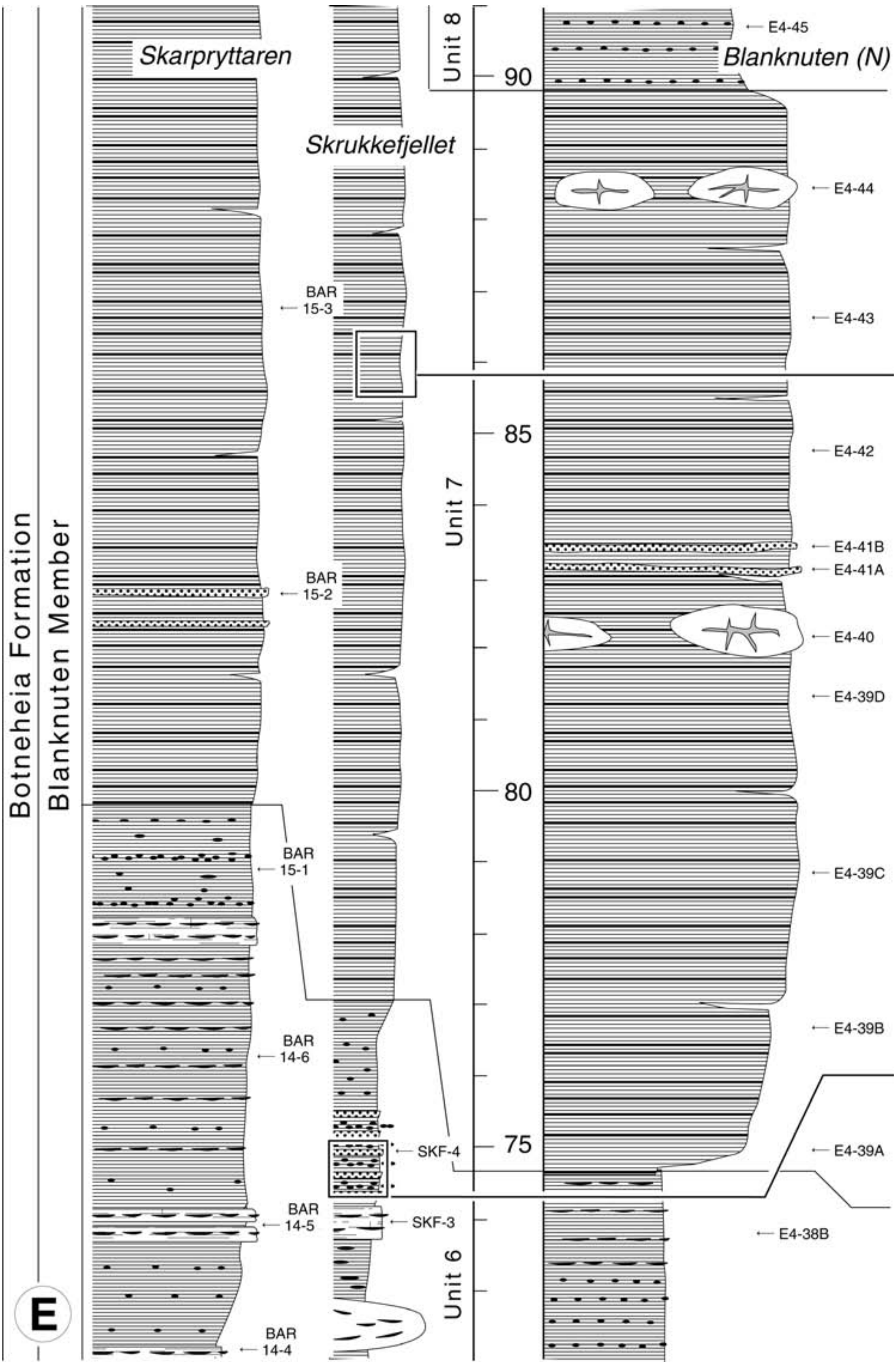

D
Botneheia Formation
Bn. Mb
Muen Member
BAR 14-3
BAR 14-2
BAR 14-1
Skarpryttaren
SKF-2
Skrukkefjellet
Unit 6
Unit 5
70
65
60
55
Blanknuten (N)
E4-38A
E4-37
E4-36
E4-35
E4-34A
E4-34
E4-33
E4-32
E4-31
E4-30
E4-29
E4-28
E4-27B
E4-27A
E4-26
E4-24C
E4-24B
E4-24A
E4-23A
E4-23
E4-23B
E4-22
Upper Muen phosphorite-bearing unit (UMuP)
Bn. Mb – Blanknuten Member

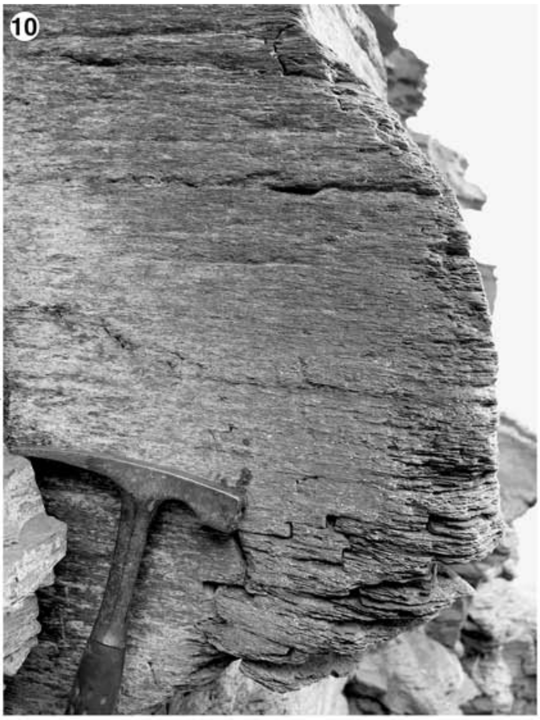
Seams and lenses of phosphatic peloids in carbonate (dolomitic) cementstone bed at base of the Blanknuten Mb cliff. Some of the lenses show low-angle cross and ripple lamination.

Flat and ovoidal phospate nodules in black organic-rich mud-shale at base of the Blanknuten Mb cliff.

Lensoidal carbonate (dolomitic) cementstone in black phosphatic mud-shale in the middle part of the formation.

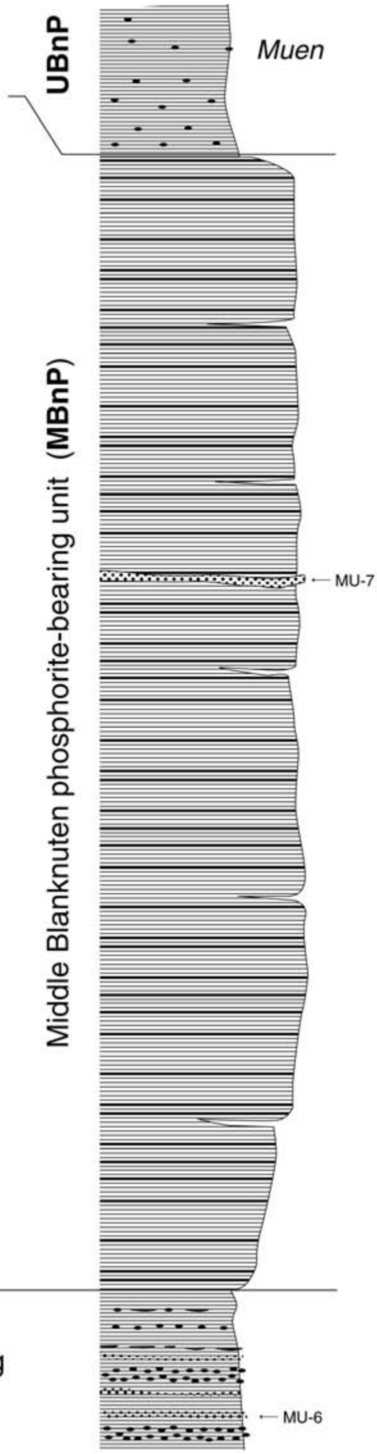



E
Botneheia Formation
Blanknuten Member
Skarpryttaren
Skrukkefjellet
Blanknuten (N)
Unit 8
Unit 7
Unit 6
90
85
80
75
BAR 15-3
BAR 15-2
BAR 15-1
BAR 14-6
BAR 14-5
BAR 14-4
SKF-4
SKF-3
E4-45
E4-44
E4-43
E4-42
E4-41B
E4-41A
E4-40
E4-39D
E4-39C
E4-39B
E4-39A
E4-38B

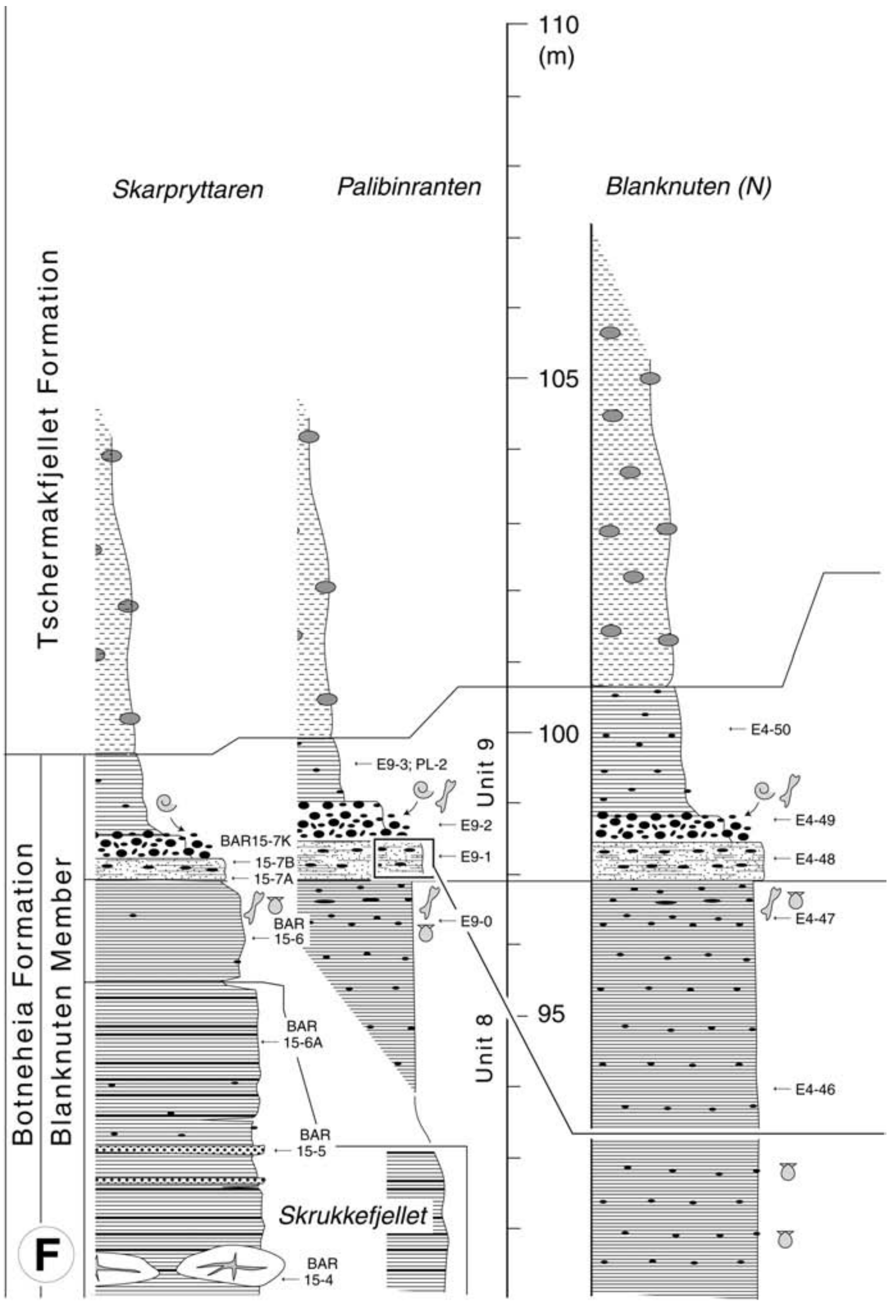


Massive organic-rich phosphatic mudstone forming the steep, middle part of the Blanknuten Mb cliff. The mudstone weathers into paper shale.

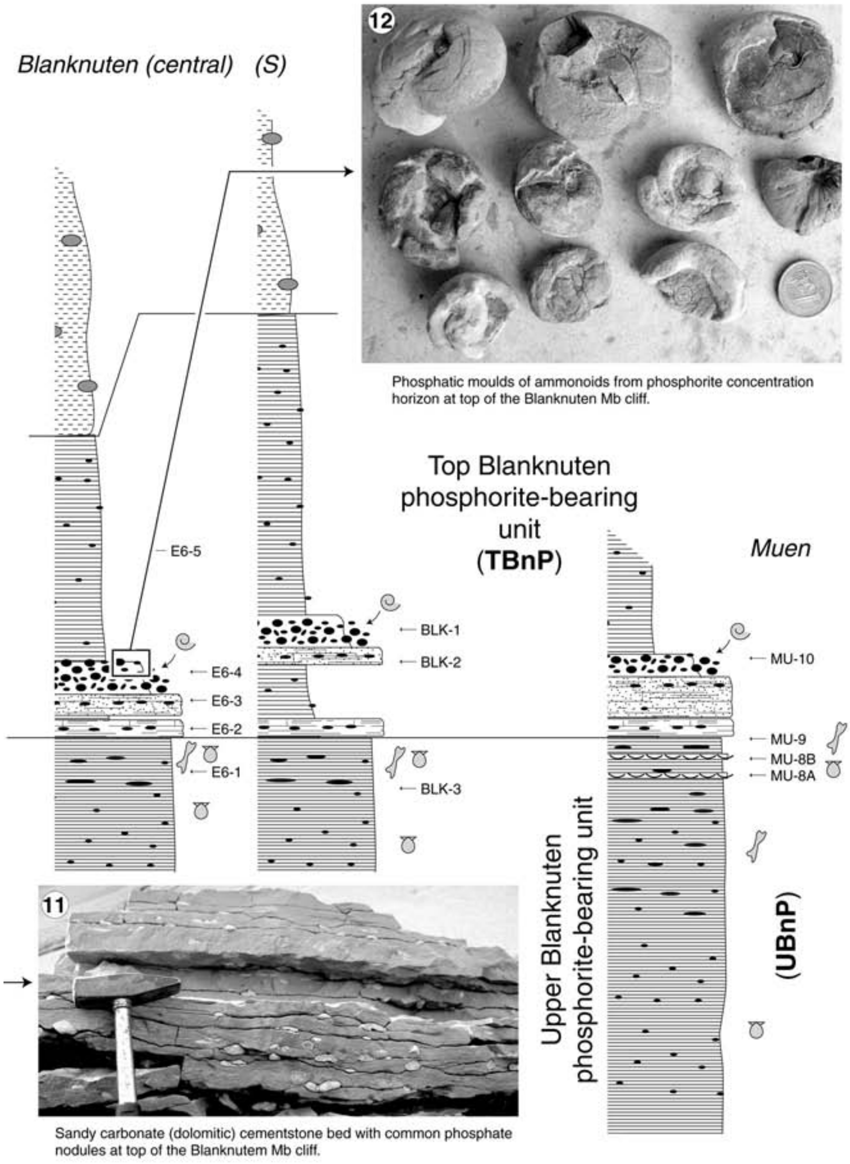
Sequence of nodular phosphorite conglomerates and phosphatic grainstone layers intercalated with thin seams of black organic-rich shale at base of the Blanknuten Mb cliff.



Lower Blanknuten phosphorite-bearing unit (**LBnP**)



thick (Fig. 5A). The boundary marks the onset of a transgressive sedimentary cycle in the Triassic sequence (Mørk *et al.* 1989), and may be represented by disconformity surface. It is roughly attributed to the Early/Middle Triassic bound-



ary (Weitschat and Lehmann 1983), though facies analysis and lithostratigraphical relations suggest its diachronous character in Svalbard (Krajewski *et al.* 2007).

Upper boundary characteristics: The upper boundary of the member occurs at top of the soft shale succession forming lower part of the Botneheia Fm (Figs 2, 3, 7). This boundary is located at an abrupt change in slope morphology at foot of the Blanknuten Mb cliff. In most outcrops it is placed at top of a distinct carbonate cementstone bed that caps soft black shale interval containing rounded to flat phosphate nodules. It is the second cementstone bed in the Muen Mb that yields abundant, flattened ammonoids (Fig. 5D). Exception is the outcrop belt at Blanknuten where this bed is missing. The boundary there is located at top of black shale interval with abundant rounded phosphate nodules, which is sharply overlain by more resistant phosphatic shale interval with two horizons of large carbonate, often septarian concretions.

Subdivision: The member is subdivided into five informal units occurring in stratigraphic order (units 1 to 5), out of which the lower four are referred to as shale units I (*Sh I*), II (*Sh II*), III (*Sh III*), and IV (*Sh IV*), and the topmost fifth is the upper Muen phosphorite-bearing unit (*UMuP*) (Figs 4, 5A–D).

Description: The Muen Mb consists of fine-grained clastic deposits enriched in organic carbon, with considerable contribution of phosphate nodules in the upper part.

The units I (3–5 m thick) and III (7–9 m) consist of soft, fissile shale, usually black in colour (Fig. 5B – Photo 3). The thicker units II (10–22 m) and IV (14–16 m) are dominated by dark grey to black mudstone and shale showing less fissility and slightly greater weathering resistance (Fig. 5B – Photo 2). The basal unit I seems to be discontinuous along coastal exposures in western Edgeøya, accommodating to indistinct depressions on top surface of the Vikinghøgda Fm (Fig. 3B). The shale succession of units I to IV shows no macroscopic phosphate fraction. The basal phosphorite concentration horizon, observed at many places in Spitsbergen, is missing in eastern exposures. Detailed examination of one doubtful occurrence at Skrukkefjellet, northern Edgeøya revealed that the basal phosphorite there is an allochthonous slope deposit with no relation to the underlying bedrock (Figs 5A, 6B). Up to eight yellow-weathering carbonate cementstone beds (0.1–0.5 m thick) make marker horizons in the shale succession of units I to IV (Fig. 5A–C). Rare, flattened ammonoid imprints can be found in these beds. Large carbonate concretions occur in the lower two units. They are often septarian or strongly brecciated, showing generations of carbonate cements filling cracks (Fig. 5A – Photo 1). Reptilian bone fragments are observed in central parts of the concretions.

The unit V (13–18 m thick) consists of black shale with common macroscopic phosphate fraction (Fig. 5C, D). The lower and upper boundaries of the unit are accentuated by yellow-weathering carbonate cementstone beds with abundant, flattened ammonoids (Fig. 5C – Photo 4). Phosphate occurs in the form of flat, rounded to irregular nodules, usually 0.5 to a few cm across, as well as seams and lenses (0.2–2.5 cm thick, 5–50 cm long) of minute phosphate peloids and grains cemented either by phosphate or carbonate. Most of the nodules are pristine in nature, though horizons of allochthonous nodules resulted from synsedimentary reworking of the sediment are noted at some levels. Phosphatic seams and lenses occur recurrently in some shale intervals, making a characteristic, easy to recognize lithology in the upper Muen phosphorite-bearing unit (Fig. 5C – Photo 5). Continuous beds or lensoidal bodies of carbonate cementstone developed in these intervals also exhibit a striking, carbonate-to-phosphate striped texture (Fig. 5D – Photo 6).

Blanknuten Member (new hypostratotype)

Distribution: The member is distributed throughout the Triassic sequence in Edgeøya and Barentsøya, exposed as a characteristic cliff-forming stratigraphic unit at top of the Sassendalen Group. This cliff is the most prominent horizon of the Triassic succession, being easily traced both in the field and on aerial photographs (Flood *et al.* 1971; Lock *et al.* 1978). Most outcrops provide excellent sections of the member, though its middle part is often difficult to access. Best section of the member is exposed in a coastal cliff of Vogelberget in Tjuvfjorden, southern Edgeøya, but the access to it is dangerous and not recommended.

Status of unit: Formal.

First use of name: Mørk *et al.* (1982).

Current definition: Mørk *et al.* (1999); here improved with a better exposed hypostratotype.

Synonyms and references: “Oil Shales group (member)” of Falcon (1928) and Lock *et al.* (1978); “papery black shales” of Flood *et al.* (1971); Blanknuten Bed of Mørk *et al.* (1982); Blanknuten Member of Mørk *et al.* (1999).

Origin of name: After Blanknuten, a mountain (479 m a.s.l.) located north of Diskobukta in western Edgeøya, where the member was first described.

Type section: (Fig. 5A–F). Stratotype: Blanknuten, western Edgeøya (rocky gorge located south of the mountain; Mørk *et al.* 1999). Hypostratotype: Blanknuten, western Edgeøya (rocky gorge in the northern part of western slope facing Storfjorden; Figs 2, 3). The GPS coordinates for the base of the hypostratotype section are N77°59.659’ E21°11.295’.

Reference sections: Muen, western Edgeøya (coastal cliff facing Storfjorden and slopes around the so-called plateau; Figs 2B, 3B); Skrukkefjellet in northern Edgeøya (slope facing Freemansundet; Fig. 6B); Palibinranten in northern Edgeøya (slope facing Freemansundet; Fig. 7A); Skarpryttaren in southern Barentsøya (slope facing Freemansundet; Fig. 7B).

Thickness: 36 m at type section; 41 m at Muen; 30–32 m at Skrukkefjellet and Skarpryttaren. The member thins northeastwards in Edgeøya and Barentsøya.

Depositional age: Late Anisian–Ladinian. Biostratigraphic relations are poorly constrained in eastern Svalbard (see above). Klubov (1965a, b) reports Anisian

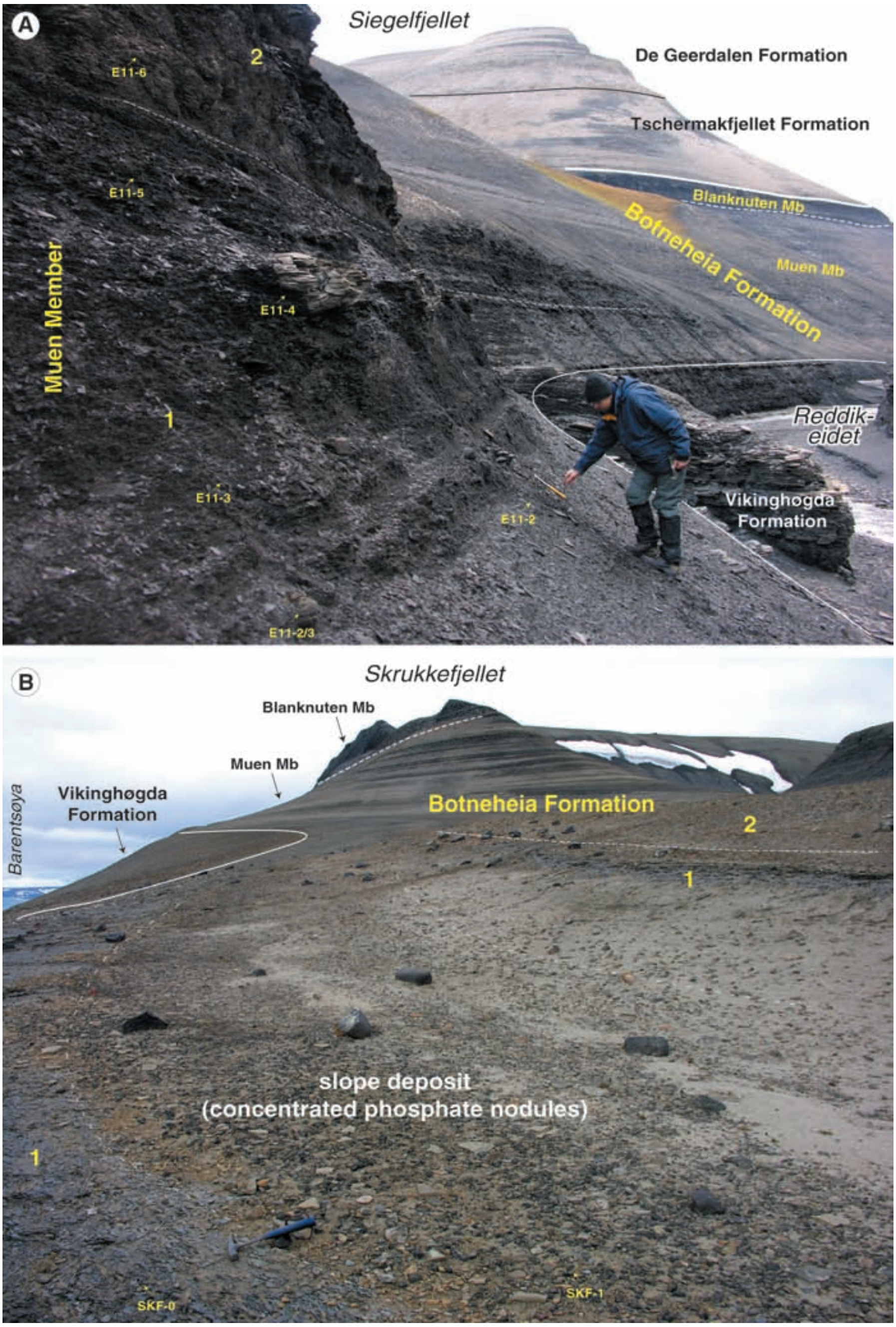


Fig. 6. Lower boundary of the Botneheia Fm and its contact with the underlying Vikinghøgda Fm in eastern Svalbard. **A**. Section at Reddik-eidet, Edgeøya (location 6) showing the lowermost shale units of the formation. **B**. Section at Skrukkefjellet, Edgeøya (location 10) showing a belt of phosphate nodules at bottom of the Botneheia Fm developed as a result of recent slope processes. 1, 2 – units 1 and 2; indicated are selected sampling locations.

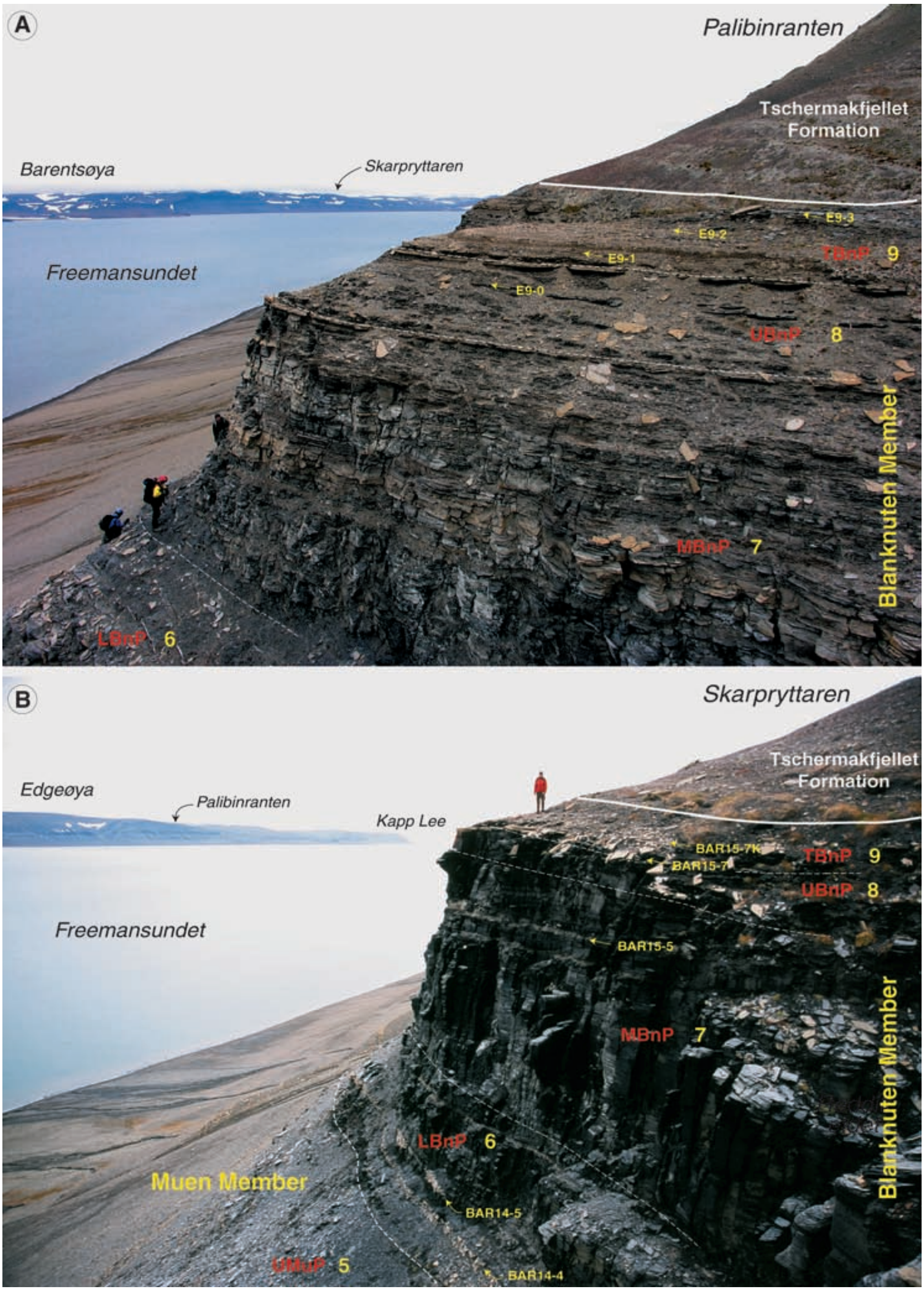


Fig. 7. Upper boundary of the Botneheia Fm and its contact with the overlying Tschermakfjellet Fm in eastern Svalbard. Sections at (**A**) Palibinranten, Edgeøya (location 9), and (**B**) Skarpryttaren, Barentsøya (location 11) showing lithostratigraphic subdivision of the Blanknuten Mb. 5–9 – units 5 to 9; indicated are selected sampling locations. For other explanations see text.

ammonoids from the lower part of the succession attributed to the Blanknuten Mb, and Ladinian forms close to its top. Flood *et al.* (1971) and Lock *et al.* (1978) report topmost Anisian forms from the member. It is probable that at least a younger part of Ladinian is missing in the member due to condensation, non-deposition and erosion at top of the Botneheia Fm (Lock *et al.* 1978).

Underlying unit: Muen Member.

Overlying unit: Tschermakfjellet Formation (Kapp Toscana Group).

Superior unit: Botneheia Formation.

Main lithology: Mudstone and shale, often phosphatic (nodules, grains, seams and lenses), with recurrent carbonate cementstone beds and horizons of carbonate concretions; subordinate phosphorite conglomerates, and beds and layers of phosphatic grainstone.

Lower boundary definition: In the hypostratotype section at the northern gorge of Blanknuten, the lower boundary of the member is defined at base of cliff-forming mudstones and shales in the upper part of the Botneheia Fm (Mørk *et al.* 1999). At this level there is an abrupt change in slope morphology at foot of the Blanknuten Mb cliff (Figs 2, 3, 7). In most other outcrops the boundary is placed at top of a distinct carbonate cementstone bed with abundant, flattened ammonoids that caps soft black shale interval with phosphate nodules of the uppermost part of the upper Muen phosphorite-bearing unit (see reference sections; Fig. 5D). Exception is the outcrop belt at Blanknuten (including type section) where this bed is missing.

Upper boundary characteristics: The Blanknuten Mb is overlain by dark grey to black shales with abundant purple-weathering sideritic concretions of the Tschermakfjellet Fm ("Purple Shales group" of Falcon 1928). This boundary occurs slightly above the top of the Blanknuten Mb cliff that forms a prominent bench on coastal slopes (Figs 2, 3, 7). It is an erosional surface that cuts discordantly soft, black phosphatic shale interval overlying phosphorite concentration horizon exposed along the bench (Fig. 5F). This interval has not been discerned so far, and the old definition placed the boundary at the underlying concentration horizon (Mørk *et al.* 1999). In some outcrops in Barentsoya, it is observed tectonic mixing of the topmost shales of the Botneheia Fm and the lowermost shales of the Tschermakfjellet Fm.

Subdivision: The Blanknuten Mb is subdivided into four informal units occurring in stratigraphic order (units 6 to 9), which are referred to as the lower (LBnP), middle (MBnP), upper (UBnP), and top (TBnP) Blanknuten phosphorite-bearing units (Figs 4, 5E, F). This subdivision follows tripartite morphology of the Blanknuten Mb cliff, which embraces the lower steep rocky slope (LBnP), the middle rocky wall (MBnP), and the upper steep rocky slope (UBnP) (Fig. 3A). The top Blanknuten phosphorite-bearing unit (TBnP) crops out along a prominent bench above the Blanknuten Mb cliff (Fig. 7).

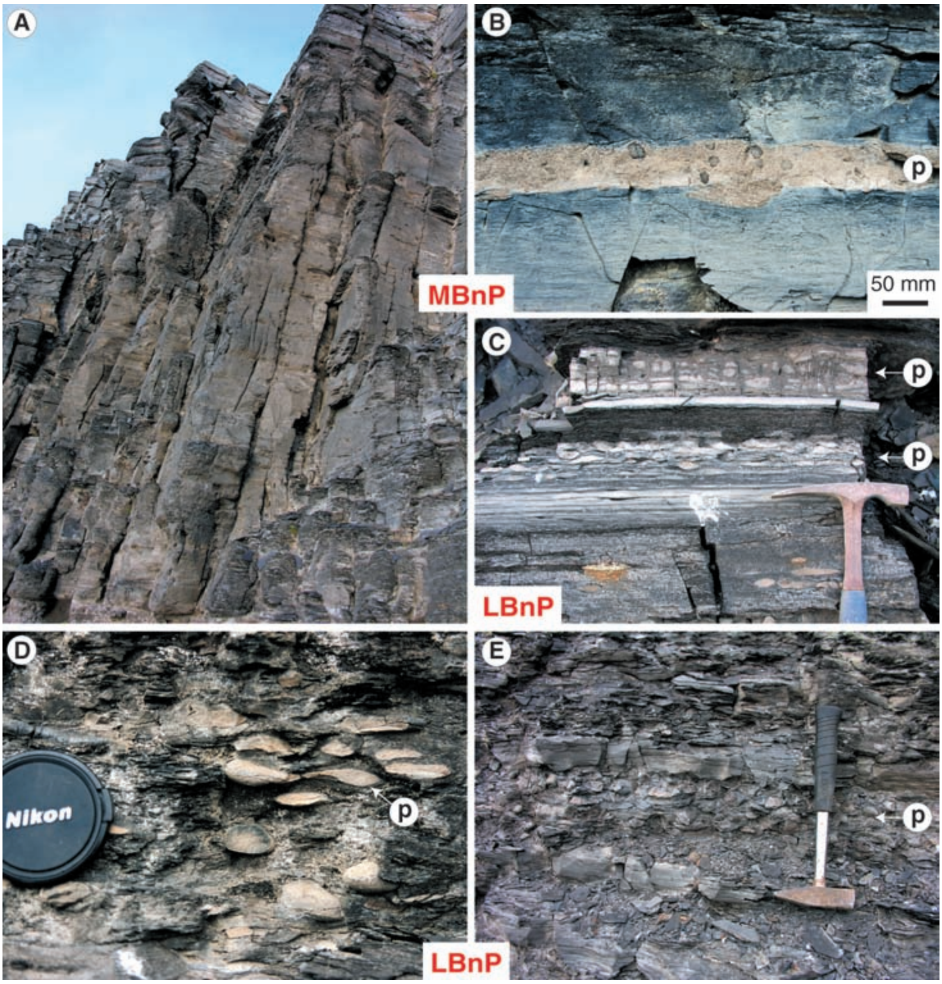


Fig. 8. Selected lithologic features of the lower (LBnP) and middle (MBnP) Blanknuten phosphorite--bearing units (6 and 7). **A**. Massive mudstone forming the steep, middle part of the Blanknuten Mb cliff lacks macroscopic phosphate fraction, but contains abundant phosphate peloids. Skrukkefjellet, Edgeøya (location 10). **B**. Bed of phosphatic grainstone with scattered phosphate nodules (p) in the middle of the massive mudstone sequence. Note the erosional bottom surface of the bed. Blanknuten, Edgeøya (location 1). **C**. Sequence of phosphatic nodular conglomerates and grainstones (p) in black shale in lower part of the Blanknuten Mb cliff. Muen, Edgeøya (location 4). **D**. Ovoidal to lenticular pristine phosphate nodules (p) in black shale in lower part of the Blanknuten Mb cliff. Blanknuten, Edgeøya (location 1). **E**. Horizon of allochthonous phosphate nodules (p) in black shale in lower part of the Blanknuten Mb cliff. Blanknuten, Edgeøya (location 2).

Description: The Blanknuten Mb consists of fine-grained clastic deposits strongly enriched in organic carbon, with considerable contribution of macroscopic phosphate fraction in its lower and upper parts.

The unit 6 (8–11 m thick) shows lithologic and textural variation, embracing black shale intervals with a spectrum of types of phosphate deposits, phosphorite conglomerates and grainstones, phosphatic cementstone beds, and horizons of large carbonate concretions (Fig. 5D, E). In black shale intervals, the phosphate nodular accumulations are dominantly pristine in nature (Fig. 8D, E). They consist of rows or homogeneously distributed nodules 0.5–7 cm in size, showing flat, elongated, cylindrical to irregular shapes (Fig. 5D – Photo 7). Allochthonous accumulations are represented by recurrent seams and lenses of phosphatic peloids and grains (0.1–2 cm thick) that commonly show low-angle cross and ripple lamination. Where embedded in carbonate cementstone, they make easy to recognize, striped rock texture (Fig. 5D – Photo 8). This phosphatic cementstone forms several distinct, yellow-weathering beds, and large lenticular and discoidal bodies in the lower Blanknuten phosphorite-bearing unit (Figs 3A, 7B). The thickest discoidal body (up to 1.5 m) was observed in the Skrukkefjellet section (Fig. 5E). Beds and layers of phosphorite conglomerate and phosphatic grainstone interfinger with layers and seams of black shale forming complex lithological sequences (Fig. 5E – Photo 9). These deposits originated as a result of sedimentary reworking, concentration and redeposition of the pristine phosphate fraction. Two horizons of large carbonate concretions occur in the lower part of the unit at Blanknuten (Fig. 5D). They are septarian or strongly brecciated as a rule, and may contain liquid bitumen in the crack systems.

The unit 7 (14–16 m thick) consists of massive, organic-rich mudstone that commonly weathers into paper shale (Fig. 5E – Photo 10). In outcrops along western Edgeøya and southern Barentsøya, this unit lacks macroscopic phosphate fraction, except a few layers and beds (1–10 cm thick) of phosphatic grainstone in its middle and upper parts (Fig. 8A–C). Small phosphate nodules and peloidal seams appear further northeast in Barentsøya (Isormen, Lomberget). The mudstone also shows changing admixture of detrital grains, becoming more silty southwards in Edgeøya and northwestwards in Barentsøya. Two horizons of large carbonate concretions (up to 2 m wide) occur in the unit. Similarly to concretions in the underlying unit, they are septarian and contain bitumen in their central, cracked parts.

The unit 8 (2–8 m thick) consists of black shale with phosphate nodules that are uniformly distributed in the succession or form more or less distinct horizons. Most of the nodules are pristine in nature. Their shapes vary widely, from ovoidal to irregular. Characteristic are complex nodules composed of branched bodies that are considerably flattened in vertical sections (Fig. 9B, C). These nodular structures might originate as a result of phosphatization of *Thalassinoides* traces (Mørk and Bromley 2008). There are several layers or indistinct beds strongly enriched in fossils, including shells and imprints of *Daonella* and reptilian and fish bone fragments (Fig. 5F). Some of these layers are represented by true shell coquinas hosting complete or nearly complete reptilian skeletons (Fig. 9D, E).

The unit 9 (2–7 m thick) consists of the lower part dominated by phosphorite concentration horizon, and the upper part represented by black shale with pristine phosphate nodules (Fig. 5F). The unit is cut discordantly by an erosional surface

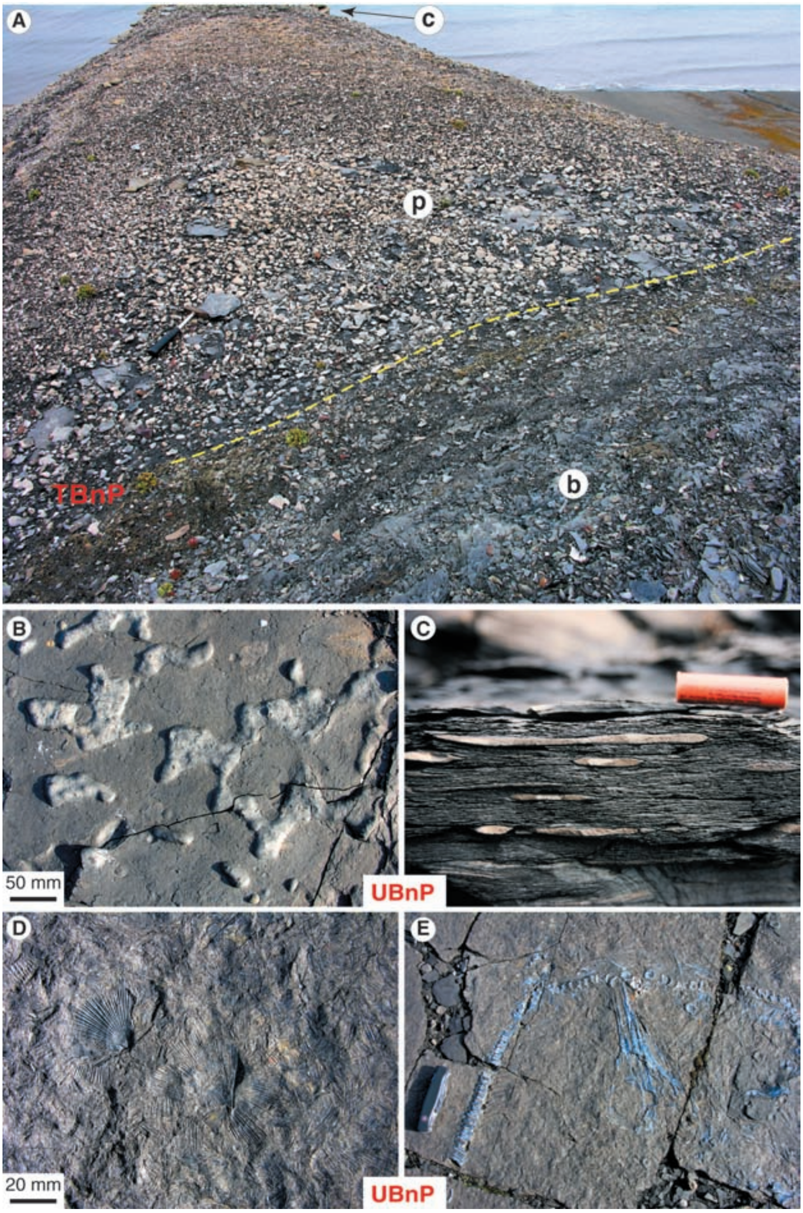


Fig. 9. Selected lithologic features of the upper (UBnP) and top (TBnP) Blanknuten phosphorite-bearing units (8 and 9). **A**. Bench at top of the Blanknuten Mb cliff showing sequence of deposits in unit 9: c – sandy carbonate cementstone with phosphate nodules; p – phosphorite concentration horizon with phosphatic ammonoids and reptilian bones; b – topmost interval of black shale with ovoidal phosphate nodules. Blanknuten, Edgeøya (location 2). **B**. Irregular, branched pristine phosphate nodules in black shale of unit 8; planar view. The nodular structures resemble phosphatized *Thalassinoides* traces (Mørk and Bromley 2008). **C**. Vertical section through the branched nodules showing their compressed structure. **D**. Coquina composed of *Daonella* shells in the upper part of unit 8; planar view. **E**. Ichthyosaur skeleton in coquina bed in the upper part of unit 8; planar view. B–E – Muen, Edgeøya (location 4).

that is overlain by shale succession of the Tschermakfjellet Fm. The lower part consists of two sandy cementstone beds that are either superimposed one over another or separated by a thin interval (up to 1.5 m thick) of black phosphatic shale. The sandy cementstone beds contain common phosphate nodules and weather yellow, making easy to trace marker horizon at the edge of the Blanknuten Mb cliff (Fig. 5F – Photo 11). Overlying is a horizon (up to 0.6 m thick) of mostly loose phosphate nodules that are concentrated due to synsedimentary winnowing and reworking. This horizon contains abundant phosphatic ammonoids and reptilian bone fragments (Fig. 5F – Photo 12). It covers a prominent bench developed at many locations at top of the Blanknuten Mb cliff (Fig. 9A). The topmost shale interval is poorly exposed, being mostly covered by debris of purple-weathering sideritic concretions downfallen from the overlying Tschermakfjellet Fm. Detailed observations in shallow pits reveal that the shale is similar to the one occurring in unit 8. Pristine phosphate nodules are predominantly ovoidal (up to 5 cm across), and uniformly distributed in the sediment. At some outcrops the content of phosphate nodules is negligible.

Facies development and petrology

The Botneheia Fm in eastern Svalbard embraces a succession of fine-grained marine clastics that is dominated by mud-shale and mudstone, with negligible contribution of silty and sandy lithologies. All the lithologies referred in former geological works to as limestones, argillaceous limestones, silty limestones, and marls are not sedimentary, but represent diagenetic deposits originated under burial, termed in this paper “carbonate cementstones” (see below). Exceptions are thin coquinoid beds and layers concentrated in the upper part of the Blanknuten Mb, which at places can be considered impure bioclastic limestones or bioclastic marlstones.

The formation shows the presence of two major sedimentary facies occurring in stratigraphic order: (1) the non-phosphogenic facies; and (2) the phosphogenic facies. These facies make parts of the succession classified here into informal units 1–4 and 5–9, respectively (Fig. 4). The boundary between them is located in the upper part of the Muen Mb, and defined by first appearance of common phosphate in shale.

The non-phosphogenic facies embraces two types of sediment: (A) soft mud-shale with well defined fissility; and (B) slightly more resistant mud-shale and mudstone with lesser fissility (Fig. 5B – Photos 2, 3). These types dominate lithostratigraphic units 1 and 3, and 2 and 4, respectively. Microscopic and XRD survey shows that both types contain no phosphatic constituents, except rare skeletal debris of fish and reptilia (Fig. 11).

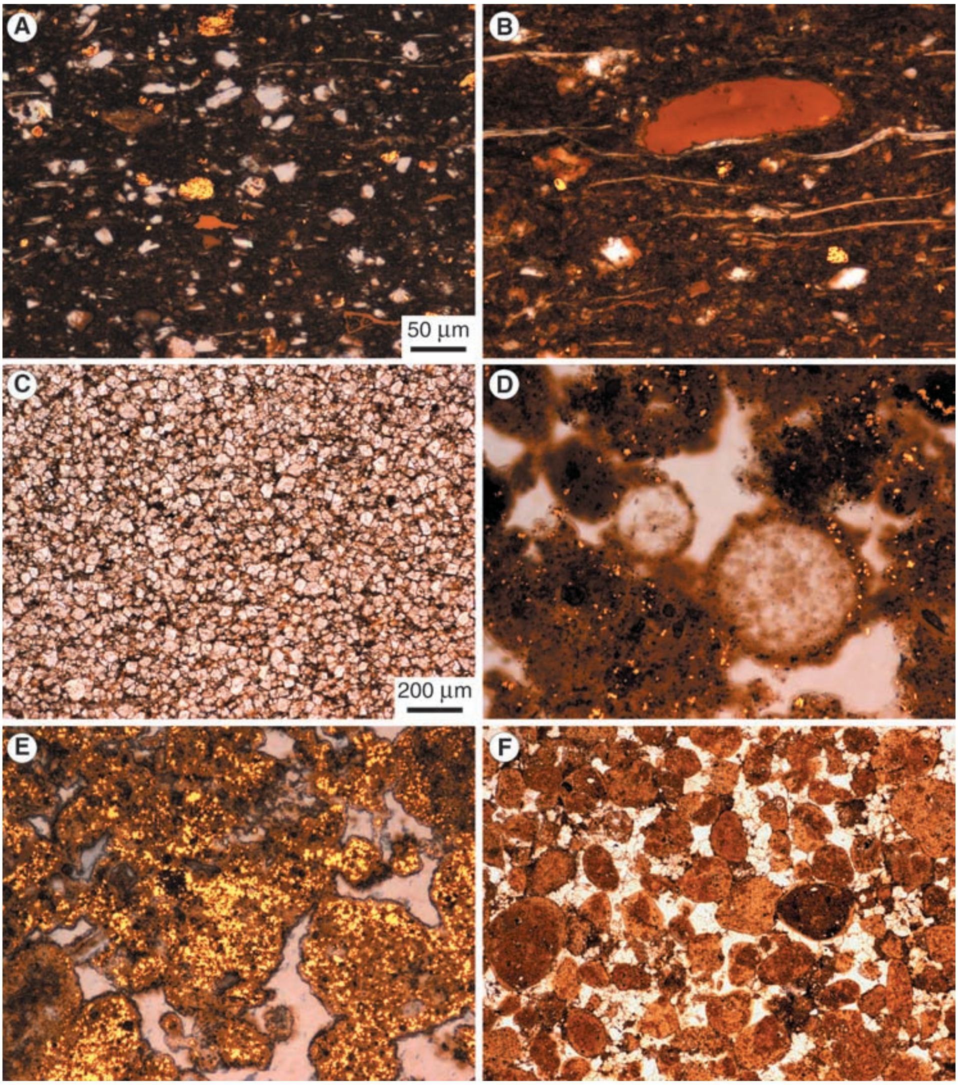


Fig. 10. Selected microscopic features of the Botneheia Fm in eastern Svalbard. **A**. Black mud-shale in lower part of the Muen Mb (unit 3) showing land-derived organic fraction and common microgranular pyrite. Blanknuten, Edgeøya (location 1). **B**. Black, massive mudstone in middle part of the Blanknuten Mb (unit 7) showing *Tasmanites*, thin-shelled pelecypods, and microgranular pyrite in organic-rich matrix. Skarpryttaren, Barentsøya (location 11). **C**. Dolomitic sparite making matrix of cementstone bed in upper part of the Muen Mb (unit 5). Blanknuten (location 1). **D**. Phosphatic ghosts after radiolaria and peloids in matrix of a phosphate nodule in lower part of the Blanknuten Mb (unit 6). Skarpryttaren (location 11). **E**. Strongly pyritized peloidal phosphatic matrix in upper part of the Blanknuten Mb (unit 8). Blanknuten (location 1). **F**. Phosphatic grainstone composed of peloids and grains cemented by blocky calcite spar in middle part of the Blanknuten Mb (unit 7). Blanknuten (location 1). Scale in A and C is for A, B, D and C, E, F, respectively. A–F – combined TLM and RLM photomicrographs, normal light.

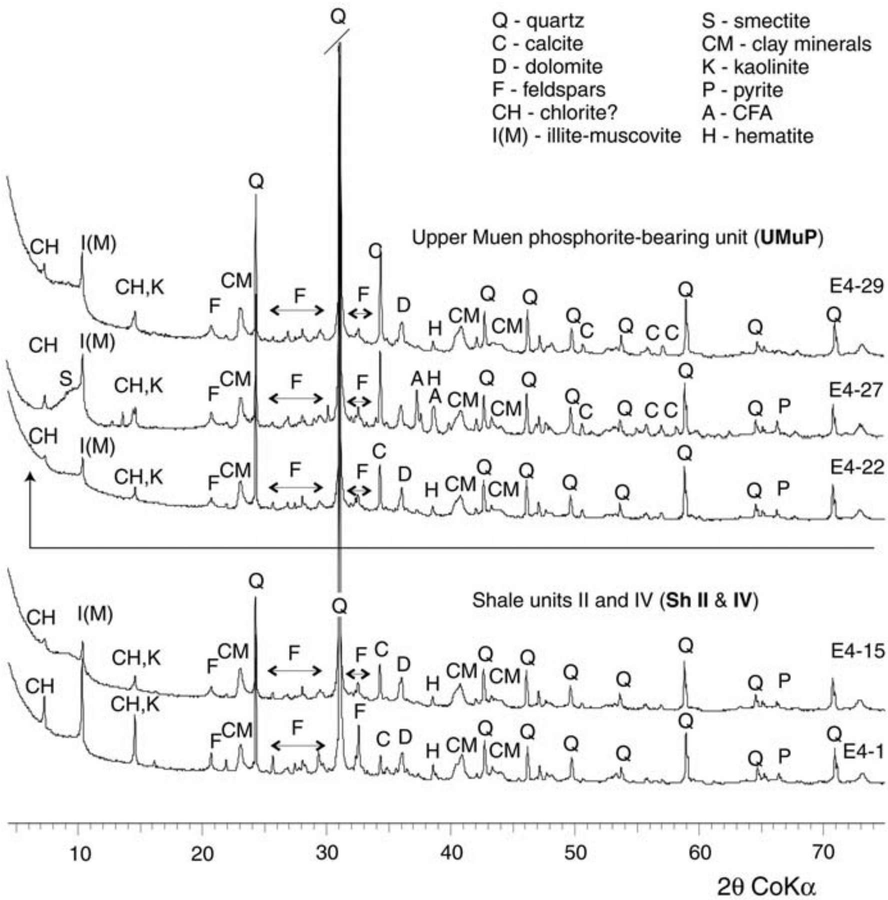


Fig. 11. Selected XRD patterns of bulk rock samples from the Muen Mb.

The type A sediment is dominated by clayey matrix (illite, smectite, chlorite, kaolinite) embedding detrital quartz grains (5–50 μm in size), plates of detrital micas (up to 100 μm long), rare detrital feldspar (10–50 μm), and accessory carbonate clasts (40–70 μm). Coarser detrital grains are seldom observed. Elongated detrital and organic components are sub-parallel to parallel oriented, though most of the shale shows no lamination. Rare examples show seam-like layers 50–100 μm thick that are enriched in silt-size quartz grains, and interspaced by muddy intervals (100–500 μm) dominated by clayey matrix with elevated content of organic carbon. Organic carbon is represented by amorphous and structured fractions (Fig. 10A). The amorphous fraction consists of minute seams, lenses and clusters, some of which contain (poly)framboidal and microgranular pyrite. The structured fraction is dominated by debris of land-derived plants. This fraction is at places severely pyritized and dominates organic pool in units 1 and 3. Pyrite crystals and framboids occur throughout the sediment, but iron (hydr)oxides are also observed.

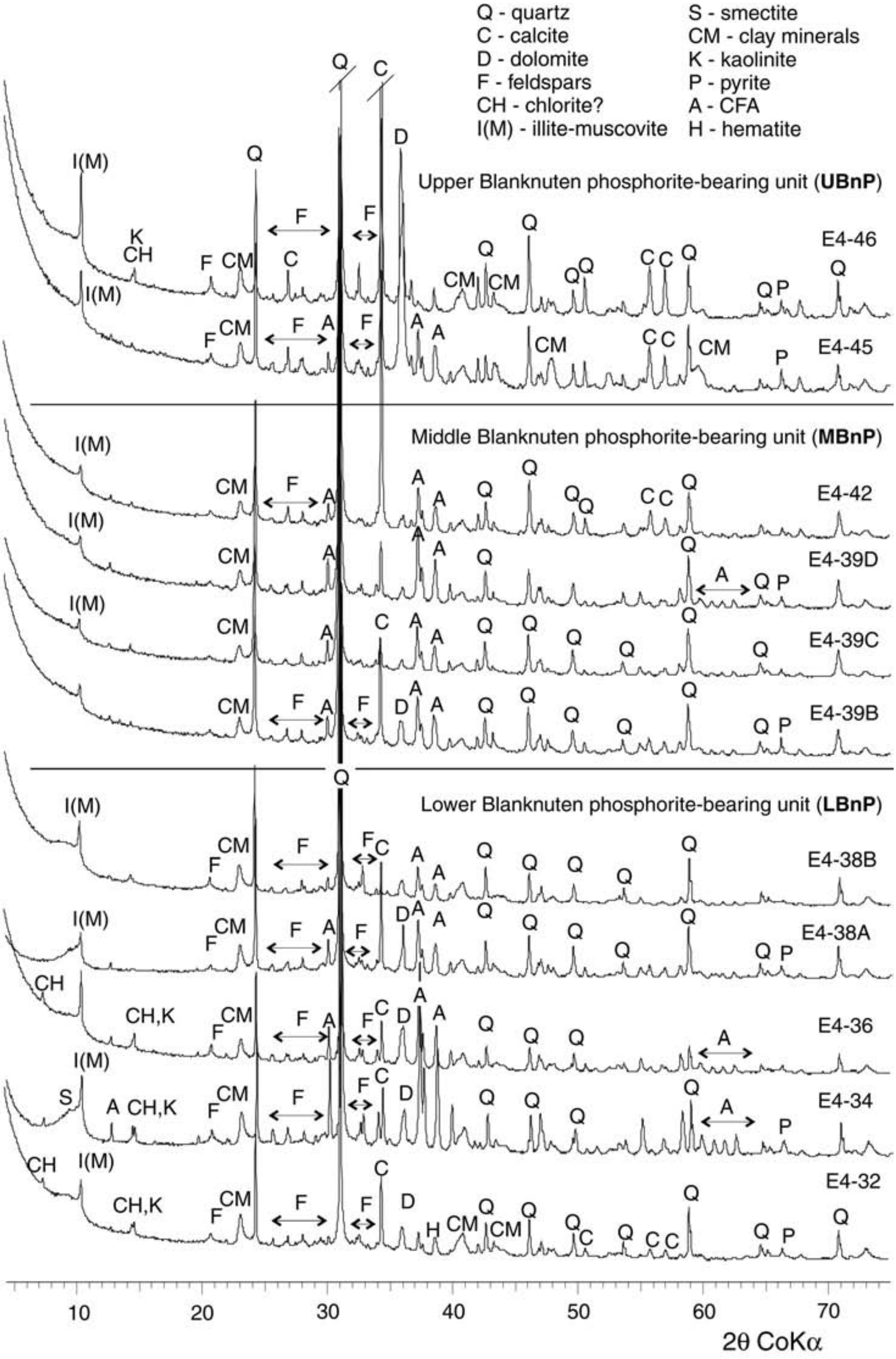


Fig. 12. Selected XRD patterns of bulk rock samples from the Blanknuten Mb.

Rare tests of arenaceous foraminifera have been noted in some thin sections. They usually contain pyrite framboids in chambers that are cemented either by calcite or dolomite. Dolomite rhombs and clusters of calcite cement are observed in the matrix. Some of these carbonate bodies encompass pyritic microgranules and framboids.

The type B sediment shows in general similar petrographic development, though it lacks or contains negligible amounts of land-derived organic fraction and detrital micas, contains more scattered carbonate cement (dolomite rhombs up to 50 μm in size), and shows the presence of seams of polyframboidal pyrite up to 500–600 μm long. Cloths of iron (hydr)oxides are observed, and the presence of hematite is confirmed by the XRD data (Fig. 11).

The phosphogenic facies embraces several sediment types, which are moderately to strongly enriched in sedimentary phosphate accumulations. Most of the sediment is strongly enriched in organic carbon occurring in the form of kerogen and syngenetic bitumen.

The petrographic development and classification of phosphate accumulations in the Botneheia Fm are addressed elsewhere (Krajewski 2000a–e). Here, only features typical of exposures in Edgeøya and Barentsøya are presented. Despite morphologic and textural variation, the phosphorite fraction shows the presence of only one phosphate mineral, which is carbonate fluorapatite (CFA) containing 1–3% CO_2 in the crystal lattice (Figs 12, 13).

In the phosphogenic facies of eastern Svalbard, the following types of sediment can be discerned: (C) mud-shale with pristine nodular phosphate; (D) mudstone with pristine peloidal phosphate; (E) mud-shale to mudstone with seams of allochthonous peloidal phosphate; (F) phosphorite conglomerates and grainstones; and (G) coquinoid beds.

The mudrock-based sediment types (C–E) show in general similar petrographic and XRD characteristics of the host rock (Figs 11, 12). They are mud-shales to mudstones with changing content of detrital grains in the fine to coarse silt fraction. The clay-rich matrix is composed of illite and chlorite, with some admixture of kaolinite and smectite. Quartz grains (5–60 μm) dominate the detrital fraction; feldspar (10–40 μm) is accessory, and the content of detrital micas (up to 100 μm long) is noted in some intervals. Several compositional trends can be discerned in the phosphogenic succession. There is observed irregular increase of the content of biogenic calcite upwards the succession, attaining maximum in coquinoid beds in unit 8 (UBnP). The calcite is represented by debris (100–800 μm) of thin-shelled, possibly planktonic pelecypods (*Daonella*). There are several intervals in the phosphogenic succession dominated by shells of juvenile pelecypod populations. Similar increase of the content of *Tasmanites* and pseudomorphs after radiolaria (the latter preserved in phosphate fraction) is observed (Fig. 10B, D). The content of iron (hydr)oxides decreases upwards, and drops to nil in the middle Blanknuten phosphorite-bearing unit (7). This unit lacks benthic biogenic remains, which elsewhere

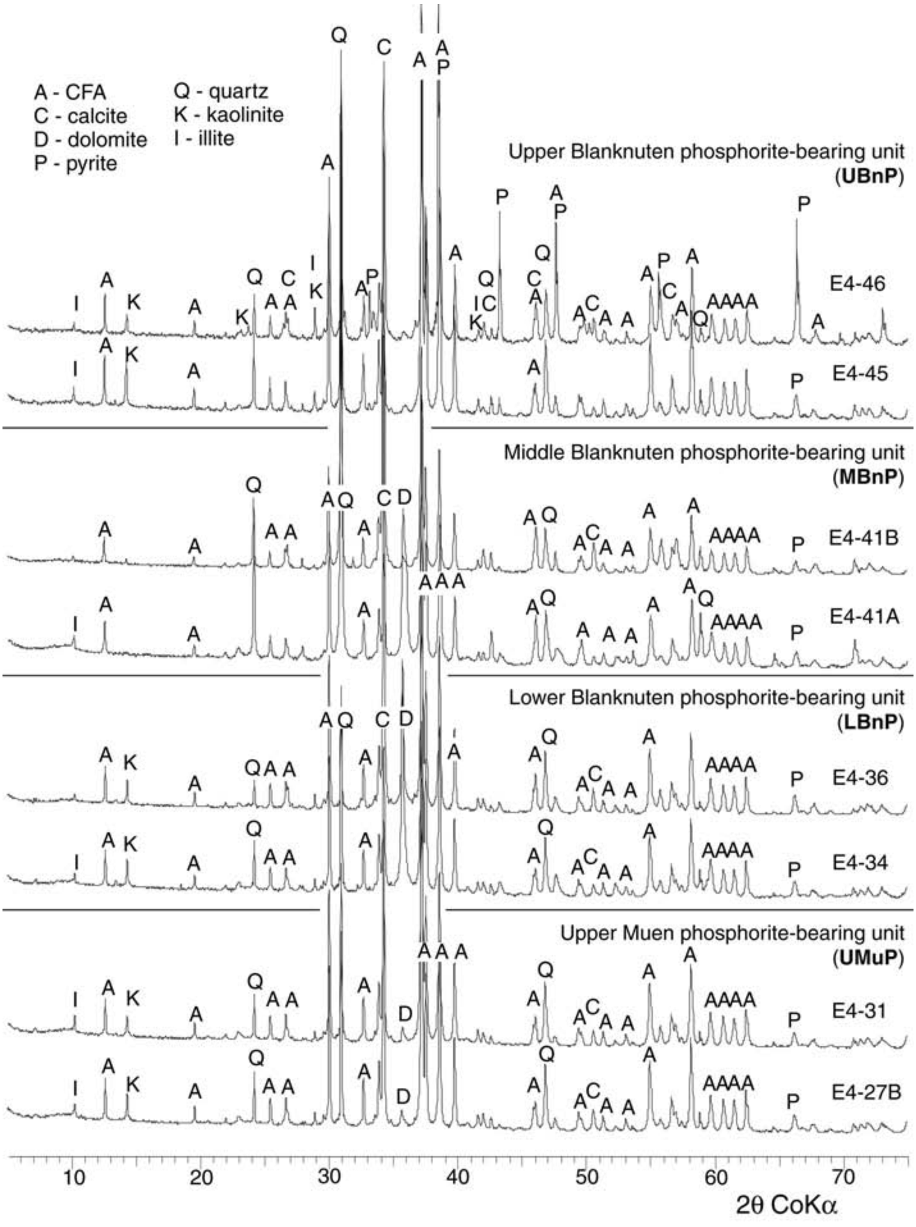


Fig. 13. Selected XRD patterns of separated phosphorite fraction from the Botneheia Fm.

in the phosphogenic facies are occasionally noted (arenaceous foraminifera tests, siliceous sponge spicules). It also contains greater amounts of detrital quartz grains and calcite cement. This cement occurs in the form of scattered crystals and clusters in the matrix as well as small infillings of the primary and secondary pores, and is responsible for the massive character and weathering resistance of rocks making the

Blanknuten Mb cliff. Pyrite is common throughout the succession, though less abundant in unit 7 due to smaller content of iron in the cliff-forming mudstone compared to the underlying and overlying black shales (units 6 and 8). Pyrite in the rock matrix is developed in the form of minute crystals (1–10 μm) and microgranular aggregates as well as framboids (2–15 μm) and (poly)framboidal seams. There are also observed scattered dolomite rhombs (10–80 μm), some encapsulating pyrite crystals and framboids in their central parts.

Organic carbon is abundantly present in the phosphogenic facies. Kerogen is dominated by amorphous fraction, though with noticeable admixture of structured components. In the rock matrix, most of the organic fractions show compressional deformations, and occur in the form of elongated seams, lenses, and irregular clusters (up to 200 μm) variably associated with mineral components, mostly clay minerals and authigenic pyrite. Uncompressed structures are observed in phosphate nodules and grains, owing to very early, punctuated phosphate cementation of the sediment. They show the presence of numerous unicellular bodies 1–30 μm in size, which represent remnants of the primary planktonic producers (algae, bacteria) as well as the decomposing communities in sediment (Krajewski 2000a). Compressed *Tasmanites* algae (50–300 μm long) provide a characteristic component of the organic fraction in mud-shale and mudstone, locally abundant in the upper part of the phosphogenic succession (Fig. 10B). In sections located close to dolerite intrusions, they are usually degraded, being replaced by diagenetic carbonate and quartz cements. Contribution of land-derived organic particles is negligible throughout the sequence, with some exceptions noted in the uppermost unit 9. Bitumen are commonly observed in thin sections. They occur in the form of scattered inclusions in clay-rich matrix, within diagenetic minerals (mostly in dolomite), and in the secondary pores resulted from dissolution and degradation of mineral and organic components.

The sediment type C occurs in units 5, 6, 8, and in the upper part of unit 9. It is dominated by mud-shale showing various degrees of fissility, that contains noticeable to abundant pristine nodular phosphate accumulations (Fig. 5D – Photo 7). The phosphate nodules show a variety of textures, out of which four are common: (i) massive; (ii) peloidal; (iii) radiolaria-dominated; and (iv) pelecypod shell-dominated. There is observed a spectrum of intermediate textures representing various mixtures of the discerned end-member types. The massive nodules are composed of a homogeneous phosphate matrix containing uncompacted organic and skeletal components, and scattered mineral grains. Compressional structures are observed at nodule margins. Peloidal nodules consist of phosphate peloids (50–500 μm), variably packed and cemented either by calcite or phosphate (Fig. 10E). The radiolaria-dominated nodules tend to concentrate at discrete horizons, mostly in the Blanknuten Mb. They show the presence of numerous phosphatic pseudomorphs and moulds of radiolaria skeletons, variably encrusted by phosphate cement (Fig. 10D). Pure radiolarian matrices are seldom observed. The most common are peloidal-radiolarian matrices. The pelecypod shell-dominated nodules are also concentrated at discrete horizons in the upper part of the phosphogenic succession. They show the presence of numerous fragments of thin-shelled pelecypods representing remnants of juvenile populations, rimmed or ultimately cemented by phosphate. The original shell calcite is usually preserved, though there are nodules showing mouldic pores after its dissolution, filled up by second generation of phosphate or by calcite cement. The original pore space in nodules that remained void after phosphate emplacement is usually filled up by calcite. There are however nodules or their parts filled by barite or dolomite cement. Some phosphate nodules, especially those occurring in unit 8, show traces of severe pyritization that pre-dates calcite cementation.

The sediment type D (mudstone with pristine peloidal phosphate) dominates the middle Blanknuten phosphorite-bearing unit (7). Pristine phosphate peloids can hardly be seen by naked eye (Fig. 5E – Photo 10), therefore in most outcrops in eastern Svalbard this unit appears to be phosphate-free (Fig. 8A). The peloids are microscopic ovoidal, elongated to irregular bodies (20–800 μm across, usually 50–250 μm) that originated as a result of pulses of scattered phosphate precipitation in the muddy sediment (Krajewski 2000a, d). They form recurrent laminae (200 μm – 1.5 mm thick) in the muddy matrix, which repeat at rather irregular intervals (2 mm – 6 cm). The laminae consist of streaks of peloids showing variations of packing, shape and the degree of compaction. Where densely packed, the inter-granular pore space is partly filled with diagenetic carbonate cement (mostly calcite microspar).

The sediment type E (mud-shale to mudstone with seams of allochthonous peloidal phosphate) is commonly represented in units 5 and 6 (UMuP, LBnP). In these units, pristine peloidal laminae are seldom observed. If present, they are partly reworked by bottom dynamic agents to form allochthonous peloidal seams. Thicker seams and lenses of allochthonous peloids show internal structures typical of current transportation. They are therefore considered to be ultimate products of winnowing of the pristine peloidal accumulations and transportation in the sedimentary environment. They consist of nearly pure peloidal sand that is cemented either by carbonate (mostly calcite spar) or phosphate. Phosphate cementation of isolated lenses of peloids has led to the formation of phosphate nodules exhibiting complex internal structures. Seams of phosphate peloids cemented by calcite weather yellowish to pale grey. Their recurrent accumulations in shale and mudstone make a characteristic, striped lithology in the lower part of the phosphogenic succession (Fig. 5C – Photo 5).

The type F sediment (phosphorite conglomerates and grainstones) forms individual beds, piles of beds, and indistinct horizons that are noted throughout the phosphogenic succession. Four sub-types can be discerned: (i) horizons of allochthonous phosphate nodules in shale; (ii) grain-supported conglomeratic beds; (iii) grainstone beds; and (iv) mud-supported conglomeratic sequences. Horizons of allochthonous nodules are observed at some levels in units 5, 6, and 8. They resulted from short-lasted, high-energy events in the sedimentary environment that led to reworking of surficial part of the phosphogenic sediment. These horizons are mud-supported and show no clear lower and upper boundaries (Fig. 8 E). Conglomeratic beds are grain-supported, and consist of phosphate nodules that experienced several episodes of winnowing and reworking. At least a part of phosphate nodules show traces of mechanical rounding. The most prominent example is the phosphorite concentration horizon near the top of the Blanknuten Mb (Figs 5F, 9A), though conglomeratic beds are also noted in unit 6 (Fig. 5E – Photo 9). The grainstone beds consist of phosphate grains (reworked peloids, fragmented nodules) that are cemented by diagenetic carbonate cement, mostly calcite spar (Fig. 10F). These beds show sedimentary structures typical of current transportation, and commonly have erosional bases. They occur as individual beds in the mudstone of unit 7 (Fig. 8B), and interfinger with conglomeratic beds to form composite sequences in unit 6 (Fig. 5E – Photo 9). In unit 7, some of these beds encompass different fractions of grains and nodules, and show graded bedding and erosional channels at bottom suggesting turbidity current origin. The mud-supported conglomeratic sequences consists of horizons of phosphate nodules that interfinger at variable proportions with grainstone seams and layers, and are embedded in the muddy matrix (Fig. 8C). They have been discerned in unit 6. Sedimentary features suggest that they originated as a result of debris flow of the phosphorite fraction on muddy slopes.

The type G sediment is represented by coquinoid beds that are concentrated in the upper part of the Blanknuten Mb (unit 8). They are up to 10 cm thick (usually 1–4 cm), and consist of accumulations of densely packed, flattened pelecypod shells and/or their moulds (Fig. 9D). These beds contain numerous reptilian and fish bones and bone fragments. At places, they show the presence of complete or nearly complete, flattened reptilian skeletons (Fig. 9E).

The Botneheia Fm in eastern Svalbard shows two types of diagenetic carbonate deposits, which overprint in various proportions on the sedimentary facies: (H) concretions; and (I) cementstone beds and bodies.

The carbonate concretions (H) make more or less distinct horizons, in the Blanknuten Mb in particular (Fig. 5A–F). Usually they are large diagenetic bodies (0.5–2 m across) showing ovoidal shapes, though horizons of smaller concretions (0.1–0.5 m) are also noted. Most of the large nodules are septarian or strongly brecciated (Fig. 5A – Photo 1). The concretionary bodies are composed of a homogeneous matrix dominated by micritic to microsparitic calcite, with scattered remnants of the original sediment (quartz grains, clay minerals) (Fig. 14). Central parts of the concretions contain uncompressed biogenic remnants (reptilian and fish bones, ammonoids), which suggests that they started to grow relatively early during diagenesis. Cracking and brecciation commenced after considerable growth of the concretions. Cracks and septa show at least two generations of cement: (i) first generation is represented by palisadic calcite that rims the septarian space; and (ii) second generation is void-filling, and represented by blocky dolomite. The crack

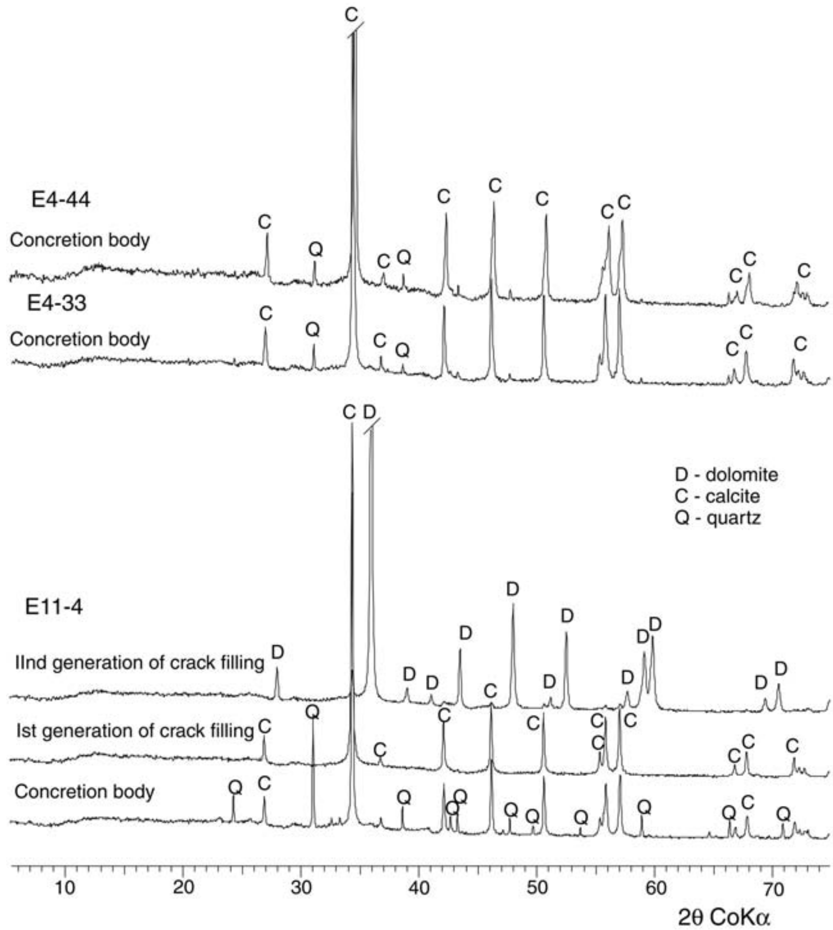


Fig. 14. Selected XRD patterns of carbonate concretions in the Botneheia Fm.

systems that still remained void after dolomite cementation commonly contain bitumen, which also make numerous inclusions in the most internal parts of dolomite infillings.

The cementstone beds and bodies (I) occur recurrently throughout the succession of the Botneheia Fm (Figs 3A, 5A–F). These deposits show matrix composed of dolomitic microspar to fine spar with mostly euhedral crystals, in which there are remnants of the original sediment (Figs 10C, 15). The extent of diagenetic emplacement of dolomite varies widely among the beds and within the beds themselves. In lensoidal and discoidal bodies there are observed lateral transitions from black shale or mudstone to compact cementstone. Detailed investigation of these occurrences suggests that the cementstones started do develop later during diagenesis, though before ultimate compaction of the sediment (Fig. 5D – Photo 6). The cementstone beds contain flattened biogenic remnants, out of which ammonoid moulds are most common (Fig. 5C – Photo 4). In phosphogenic part of the Botneheia Fm, these beds are often phosphatic, showing a characteristic carbonate-to-phosphate striped texture (Fig. 5D – Photo 8).

Paleoenvironmental interpretation

The Middle Triassic Botneheia Fm records a second-order transgressive-regressive cycle in the Svalbard basin, that was developed in an open shelf environment dominated by fine-grained clastic sedimentation (Mørk *et al.* 1982; Worsley 1986, 2008). The depositional area was likely a big embayment bordered from the west by shallow shelf and deltaic settings of western and southwestern Spitsbergen, and from the east and southeast by elevated bottoms or land area of unknown extent (Mørk *et al.* 1992; Egorov and Mørk 2000). This embayment had north connection with deep basins of the Panthalassa Ocean (Mørk *et al.* 1989; Krajewski 2000a; Embry *et al.* 2002; Cocks and Torsvik 2007).

The Botneheia Fm in eastern Svalbard embraces two superimposed, third-order transgressive pulses that were followed by stepwise regression. These pulses are interpreted to correlate with similar pulses recognized in the shallow shelf setting of the Bravaisberget Fm, which is time equivalent of the Botneheia Fm in western and southwestern Spitsbergen (Krajewski *et al.* 2007). The rises of sea level were associated with consequent deterioration of bottom environment, from prevailing oxic bottoms in the Muen Mb, through mostly dysoxic bottoms in the upper part of the Muen Mb and the lower part of the Blanknuten Mb, to euxinic conditions in the middle part of the Blanknuten Mb. The regressive trend terminated the Svalbard euxinia, and ended up in regional disconformity at top of the Botneheia Fm. Superimposed on the second transgressive pulse was the development and maintenance of high biological productivity in the shelf area that led to increased contribution of organic carbon in bottom sediments and phosphogenesis. Phosphogenesis 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). Maximum phosphogenesis occurred under dysoxic bottom conditions in the uppermost part of the Muen Mb (upper part of unit 5), and in the lower and upper parts of the Blanknuten Mb (units 6 and 8), leading to a high content of pristine phosphate in sediment. Phosphogenesis under fluctuating oxic-dysoxic conditions (lower part of unit 5) as well as under euxinic ones (unit 7) resulted in slightly suppressed content of pristine phosphate.

The lower transgressive pulse is represented by shale units I to IV of the Muen Mb, which embrace the non-phosphogenic, fine-grained clastic facies. Two episodes of enhanced supply of land-derived organic matter and detrital micas (units 1 and 3) separated by two episodes dominated by autochthonous marine production (units 2 and 4) can be discerned, suggesting fluctuations of terrigenous influences in the sedimentary environment. The scale of autochthonous production was insufficient to promote phosphogenesis, though high enough to contribute to moderate enrichment in organic carbon. Iron (hydr)oxides preserved throughout the succession, and rare remnants of benthic fauna (foraminifera, spongae) suggest prevailing oxic bottoms. However, common authigenic pyrite indicates formation of anoxic sulphidic environment below the water/sediment interface.

The lowermost part of the Botneheia Fm in Edgeøya and Barentsøya has been revealed to be phosphate-free, which elsewhere in Svalbard usually contains basal phosphorite-bearing horizon (Mørk *et al.* 1982; Krajewski 2000a, d, e; Krajewski *et al.* 2007). It is therefore possible that in eastern Svalbard there is preserved a lowermost, non-phosphogenic part of the Middle Triassic cycle, which is missing in the remainder of the area. Alternatively, there might have occurred shifts of biological productivity centres in the shelf basin that led to lateral migration of zones of bottom phosphogenesis (Karcz 2008). It is however unlikely that during the transgression phosphogenesis appeared first in the shallow shelf setting, and then shifted to deeper environments located closer to oceanic water masses. Further biostratigraphic investigations of the Botneheia and Bravaisberget fms are needed to resolve this problem.

The upper transgressive pulse commenced with the deposition of the upper Muen phosphorite-bearing unit (5). The first appearance of common phosphate in this unit marks the onset of phosphogenic conditions in eastern Svalbard. Phosphogenesis in units 5 and 6 has widely led to the formation of pristine nodules, which reflect punctuated phosphate cementation of the original, porous sediment in the nearsurface diagenetic environment (Krajewski 2000a). The second most abundant phosphate is represented by minute peloids, though they are winnowed and reworked as a rule to form allochthonous seams and layers. It was suggested that redeposited phosphorite horizons had originated as a result of storm events in the open shelf environment (Mørk and Bromley 2008). While this mechanism might explain formation of horizons of allochthonous phosphate nodules in the shale succession, it can hardly fit formation of millimetre-thick layers and seams that repeat at centimetre intervals. The most plausible explanation of their formation is the action of bottom currents over the muddy, phosphogenic bottom. In northern Edgeøya and in Barentsøya, units 5 and 6 contain sequences of redeposited phosphorite conglomerates and grainstones that represent downslope mass transport deposits from shallower parts of the basin located northeastwards. The events of mass transport to deeper parts of the basin could have been triggered by storms. Microscopic and XRD survey suggests that the muddy depositional environment was characterized by oxygen deficit resulted from enhanced oxygen consumption by the decaying organic matter. Formation of phosphate peloids, which reflect scattered, rapid phosphate cementation at numerous nucleation sites very close to the water/sediment interface (Krajewski 2000b), was associated with stabilization of redoxcline at this interface during periods between storm events. The presence of common microgranular and framboidal pyrite slightly postdating the major phase of phosphate emplacement supports this view.

The middle Blanknuten phosphorite-bearing unit (7) represents maximum drowning of the eastern Svalbard shelf. This unit shows sedimentary and petrologic features indicative of deposition under euxinic bottom conditions. Lateral facies variations suggest that the unit was deposited in a broad depression in the shelf area, which most probably was filled by a stagnant, euxinic water of considerable thickness. High biological productivity in surficial waters overlying the euxinic pillow led to maximum deposition of autochthonous organic matter that induced phosphogenesis in bottom sediment facies. Petrographic analysis shows that biological productivity contributed to blooms of unicellular algae (including *Tasmanites*) and bacteria, radiolaria, and thin-shelled pelecypods, the latter most probably showed planktonic habit, being attached to large algal colonies floating in surficial waters. Phosphogenesis contributed to the deposition of recurrent seams and layers of pristine phosphate peloids, owing to mineralization of organic phosphorus and pulses of supersaturation with respect to calcium phosphate just below the water/sediment interface (Krajewski *et al.* 1994). Phosphatic grainstone beds observed in unit 7 document events of gravitational transport of reworked phosphorite fraction from local elevations down the euxinic depression.

The overall nature of phosphate accumulations in the Botneheia Fm in eastern Svalbard and the characteristics of biological remains in the succession suggest that development of high biological productivity and phosphogenesis resulted from an input of upwelled waters from oceanic sources (see also discussion in Krajewski 2000a; Parrish *et al.* 2001; Embry *et al.* 2002). The development and maintenance of bottom euxinia was a consequence of both the enhanced oxygen consumption caused by mineralization of organic matter and the sluggish circulation related to sea-level rise and local paleogeography (Mørk *et al.* 1982; Worsley 1986, 2008; Krajewski 2000b, d).

Tentative correlation of the upper transgressive pulse across the Svalbard basin suggests that rapid rise of sea-level associated with the input of upwelled waters and the formation of bottom euxinia in eastern Svalbard had profound effects on environmental changes in Spitsbergen. The most important effects were: (i) the formation of organic-rich shales of the uppermost part of the Passhatten Mb (Bravaisberget Fm) along western Spitsbergen (Krajewski 2000e; Krajewski *et al.* 2007); (ii) rapid cessation of deltaic system of the Karentoppen Mb (Bravaisberget Fm) in southern and southwestern Spitsbergen (Karcz 2008); and (iii) progradation of shallow shelf, sandy phosphogenic facies of the Somovbreen Mb (Bravaisberget Fm) southwestwards in Sørkapp Land, *i.e.* towards the so-called western land area (Krajewski 2000a).

Shallowing of sedimentary environment observed in the upper Blanknuten phosphorite-bearing unit (8) diminished the euxinic water pillow due to recurrent

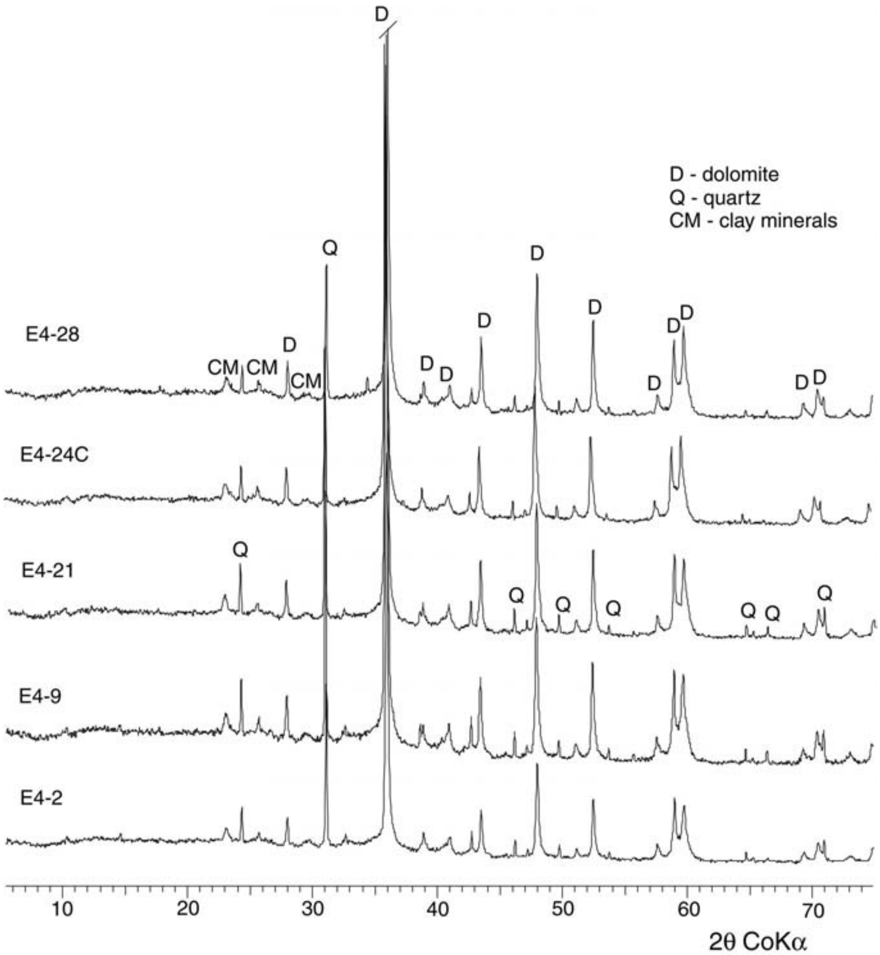


Fig. 15. Selected XRD patterns of carbonate cementstone beds in the Botneheia Fm.

stirring and ventilation caused by dynamic environmental agents. These events introduced much oxygen into the euxinic waters, and also contributed to injections of hydrogen sulphide into the surficial productivity zone. The coquinoid and bone beds occurring in the unit represent mass mortality events caused by toxic pulses of hydrogen sulphide. Stepwise ventilation of the euxinic environment has led to reappearance and then domination of dysoxic bottoms upwards the succession, and the interdependent domination of nodular phosphate accumulations over peloidal ones. The regressive trend terminated in the sandy cementstone bed and the overlying phosphorite concentration horizon occurring at base of the top Blanknuten phosphorite-bearing unit (9). The latter horizon reflects a period of enhanced reworking and non-deposition in eastern Svalbard that extends to central Spitsbergen, and is likely to correlate with the development of shallow marine to brackish succession (Van Keulenfjorden Mb of the Bravaisberget Fm) in western and southwestern Spitsbergen.

The youngest sediment present in the Botneheia Fm in eastern Svalbard suggests renewed muddy sedimentation with phosphogenesis, though this episode is incompletely preserved due to subsequent erosion that made a sequence boundary towards the overlying Tschermakfjellet Fm (Kapp Toscana Gp).

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