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DEPOSITIONAL HISTORY OF THE YOUNGEST STRATA OF THE SASSENDALEN GROUP (BRAVAISBERGET FORMATION, MIDDLE TRIASSIC–CARNIAN) IN SOUTHERN SPITSBERGEN, SVALBARD

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Abstract: The Bravaisberget Formation of southern Spitsbergen (the youngest formation of the Sassendalen Group; Middle Triassic–Carnian) comprises a succession of organic-rich and sandy phosphogenic deposits that developed in a marginal part of the Svalbard basin, in response to a high biological productivity event in the Barents Shelf. The basin margin was bounded on the southwest by the elevated structure of the Sørkapp-Hornsund High. North of the high, the subsiding shelf bottom stretched from southern to western Spitsbergen. The organic-rich, fine-grained sedimentation that gave rise to the formation of the Passhatten Member extended southward after the Anisian transgression; it reached the topmost part of the Sørkapp-Hornsund High during the maximum flooding of the basin in the early Ladinian. The sudden appearance of deltaic deposits of the Karentoppen Member directly after the maximum flooding was a consequence of short-lived tectonic activity of the Sørkapp-Hornsund High and the adjacent land area. Reworking and redistribution of the deltaic sediments during the Ladinian brought about the formation of shallow-marine clastic facies of the Somovbreen Member. Decreasing depositional rates close to the Middle-Late Triassic boundary led to a regional hiatus and the formation of a condensed phosphorite horizon at the top of the Somovbreen Member. The sedimentation of the Bravaisberget Formation ended in the early Carnian. The youngest siliciclastic and spiculitic sediments of the Van Keulenfjorden Member were deposited in southern and western Spitsbergen in shallow- to marginal-marine environments.

Key words: Svalbard, Spitsbergen, Triassic, Sassendalen Group, Bravaisberget Formation, lithostratigraphy, facies, ammonoids.

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INTRODUCTION

The Triassic succession of Svalbard (Fig. 1; Harland, 1997; Mørk *et al.*, 1999) comprises marine facies in its lower part (Sassendalen Group) and paralic facies in its upper part (Kapp Toscana Group). It records the geological evolution of the NW Barents Shelf that was constrained by eustatic sea-level fluctuations and oceanic influences, regional tectonics, and progradation of deltaic systems from local and distant source areas (Riis *et al.*, 2008; Worsley, 2008; Basov *et al.*, 2009; Gløstard-Clark *et al.*, 2010). The youngest strata of the Sassendalen Group (Botneheia and Bravaisberget formations) are enriched to a major extent in marine organic carbon and are considered to be important petroleum source rocks in the region (Mørk and Bjorøy, 1984; Bjorøy *et al.*, 2006, 2010; Karcz, 2010, 2014; Krajewski, 2013). They contain sandstone bodies in southern and western Spitsbergen (Worsley and Mørk, 1978; Krajewski, 2000c; Krajewski *et al.*, 2007; Haugan, 2012), and are overlain by thick sandstone units of the Kapp Toscana Group throughout Svalbard (Bælum *et al.*, 2012; Mørk, 2013), which have the potential to be reservoir rocks for hydrocarbons in the Barents Sea. The assessment of this northern source-reservoir system for petroleum exploration (Grogan *et al.*, 1999) depends on an understanding of the depositional, stratigraphic, and structural controls of the distribution of the organic-rich and sandy facies (Høy and Lundschien, 2011; Anell *et al.*, 2013, 2014a, b).

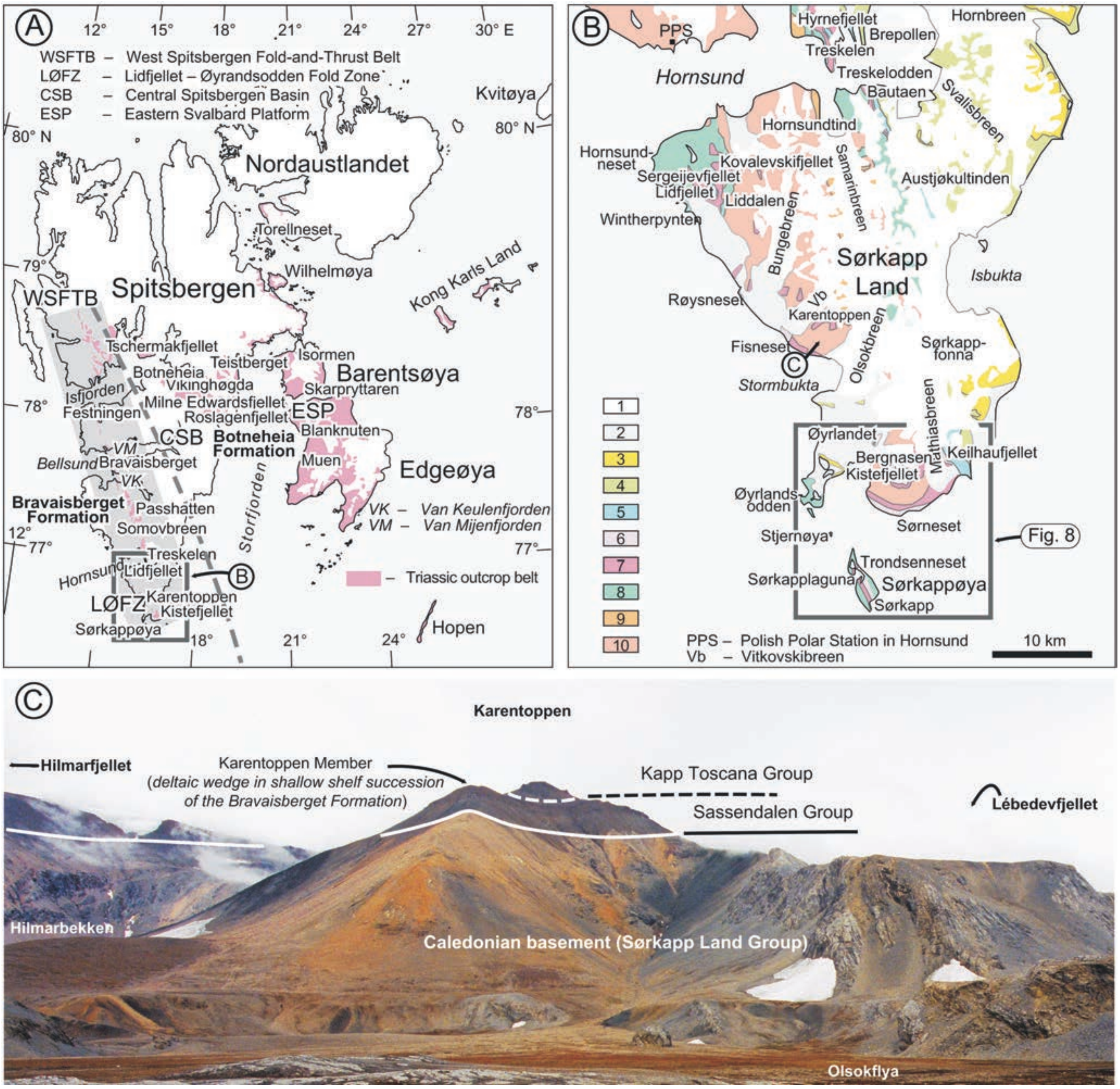


Fig. 1. The Bravaisberget Formation (Middle Triasic–Carnian) in Spitsbergen, Svalbard. **A.** Map of Svalbard showing outcrops of the Triassic succession in the West Spitsbergen Fold-and-Thrust Belt (WSFTB), including the Lidfjellet-Øyrlandsodden Fold Zone (LØFZ), and in the Eastern Svalbard Platform (ESP), including central Spitsbergen. These two developments are separated by the Palaeogene Central Spitsbergen (foreland) Basin (CSB). The suggested boundary between the areas of occurrence of the Botneheia and Bravaisberget formations (the youngest formations in the Sassendalen Group) is marked by a dashed line. The Triassic outcrop belt after Dallmann *et al.* (2002), modified. **B.** Geological map of Sørkapp Land. The area enlarged in Fig. 8 is marked by a rectangle. Geology after Winsnes *et al.* (1993), Dallmann *et al.* (1993b, 2002), Krajewski and Stempień-Sałek (2003), and unpublished materials of the present authors, simplified. 1 – ice and snow cover; 2 – Quaternary sediments; 3 – Van Mijenfjorden Group (Palaeogene); 4 – Helvetiafjellet and Carolinefjellet formations (Early Cretaceous); 5 – Janusfjellet Subgroup (Late Jurassic–Early Cretaceous); 6 – Kapp Toscana Group (Late Triassic–Middle Jurassic); 7 – Sassendalen Group (Early Triassic–Carnian); 8 – Billefjorden, Gipsdalen and Tempelfjorden groups (Carboniferous–Permian); 9 – Adriabukta Formation (Devonian); 10 – Caledonian basement. **C.** Central part of the Sørkapp-Hornsund High shows the Triassic succession of the Sassendalen and Kapp Toscana groups resting directly on the Caledonian substratum; here at Karentoppen between Vitkovskibreen and Olsokbreen. The Bravaisberget Formation shows the presence of deltaic deposits (Karentoppen Member) in the shallow-marine succession, which reflect event of supply of clastic material from a land area located southwest of the present coast of southern Spitsbergen. This is the stratotype for the Karentoppen Member (Mørk *et al.*, 1999). Photograph taken from Fisneset.

This paper presents the facies distribution, lithostratigraphy, and biostratigraphic data of the Bravaisberget Formation of southern Spitsbergen (Middle Triassic–Carnian), with particular reference to the spatial and temporal relationships between the organic-rich and sandy deposits. It demonstrates that the sandy facies of the Somovbreen Member developed over the organic-rich facies of the Passhatten Member as a result of shallow-marine reworking and redistribution of deltaic sediments (Karentoppen Member), delivered to the basin margin from a local source area. The deltaic input was a result of an event of tectonic activity that occurred directly after maximum flooding of the basin in the early Ladinian. The sandy succession of the Somovbreen and Van Keulenfjorden members straddles the Middle-Late Triassic boundary and extends into the Carnian, recording complex history of termination of fully marine environments in Svalbard. On the basis of these observations and the revision of published data, the authors discuss the local and regional controls of deposition of the Bravaisberget Formation. A new correlation is proposed between the Bravaisberget Formation of southern and western Spitsbergen and the Botneheia Formation of central and eastern Spitsbergen and eastern Svalbard.

GEOLOGICAL SETTING

The Triassic Sassendalen Group in Svalbard (Harland, 1997; Vigran *et al.*, 2014) shows pronounced differences in lithological development between the West Spitsbergen Fold-and-Thrust Belt (including the Lidfjellet-Øyrlandsodden Fold Zone) and the Eastern Svalbard Platform (including central Spitsbergen). These two tectonic settings are separated by the Central Spitsbergen (foreland) Basin, filled by Palaeogene deposits that accumulated during the time of the West Spitsbergen orogeny (Fig. 1). They represent different depositional areas of the Triassic basin in the NW Barents Shelf, with shallow-marine sandy facies concentrated in the fold belt and open-marine shaly facies dominating the platform (Mørk *et al.*, 1982; Steel and Worsley, 1984; Pčelina, 1998). The lithological contrast between these depositional systems was enhanced by differential burial and tectonic deformation of the Triassic succession that led to extensive cementation and the mechanical and chemical compaction of the fold-belt strata (Krajewski, 2000b; Krajewski and Woźny, 2009; Mørk, 2013).

Even though there are no exposed transitions between the two developments of the Triassic succession and the relatively fossil-rich platform strata are far better recognized than the fossil-poor strata in the fold belt, a consensus has been reached to present a common stratigraphic scheme for the Sassendalen Group (Mørk *et al.*, 1999). It distinguishes (in ascending order) the Vikinghøgda and Botneheia formations on the platform, and the Vardebukta, Tvillingodden, and Bravaisberget formations in the fold belt (Fig. 2). The Vikinghøgda Formation is considered to be an age equivalent of both the Vardebukta and Tvillingodden formations (roughly Early Triassic), and the Botneheia Formation is facies equivalent of the Bravaisberget Formation (roughly Middle Triassic).

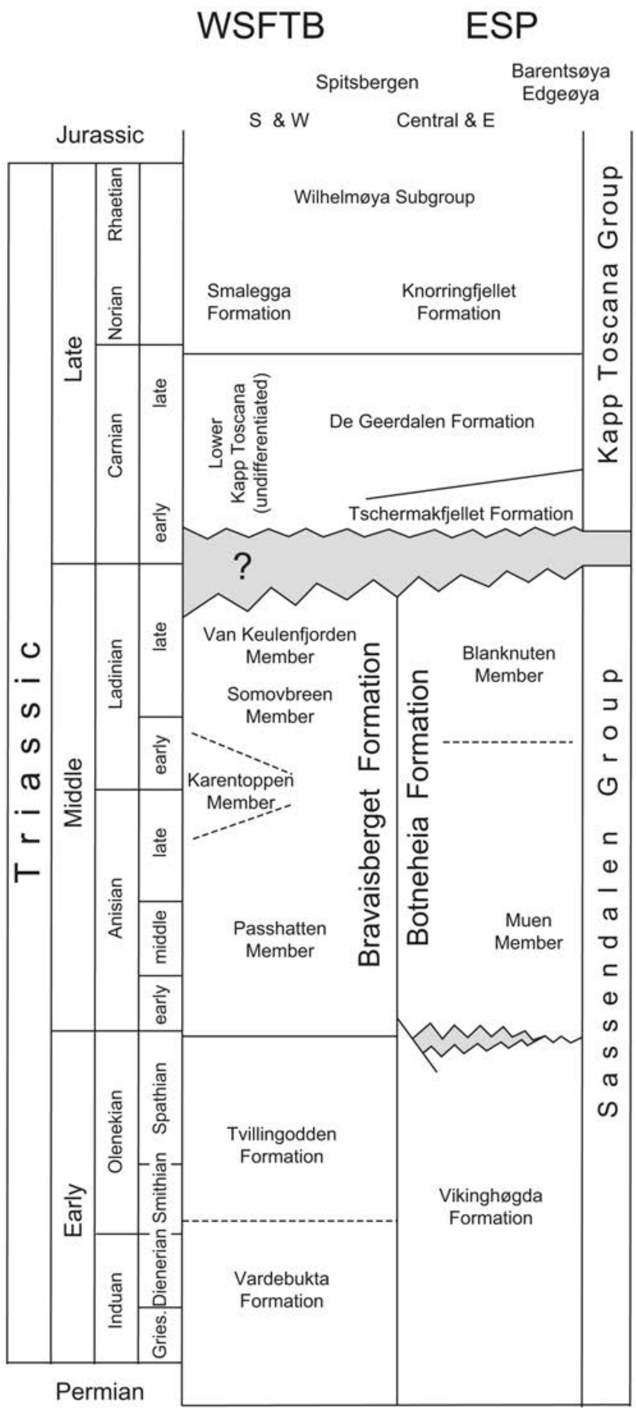


Fig. 2. The Triassic lithostratigraphic scheme of Svalbard after Nakrem and Mørk (1991), Mørk *et al.* (1999), Hounslow *et al.* (2007, 2008), and Hounslow and Nawrocki (2008), simplified. WSFTB – West Spitsbergen Fold-and-Thrust Belt (including the Lidfjellet-Øyrlandsodden Fold Zone); ESP – Eastern Svalbard Platform (including central Spitsbergen). For further explanation, see text.

The Botneheia Formation has been the subject of several studies; and its stratigraphy is best known in central Spitsbergen (Korchinskaya, 1972a; Korčinskaja, 1972b, 1982, 2000; Weitschat and Lehman, 1983; Weitschat and Dagys, 1989; Dagys and Weitschat, 1993; Pčelina, 1996; Hounslow *et al.*, 2006b, 2007, 2008; Xu *et al.*, 2009). The formation spans a period from early Anisian to late Ladinian, though the dating of its basal and top parts is ambiguous. The lower part of the formation (recognized as the Muen Member in eastern Svalbard; Krajewski, 2008) is of early to middle Anisian age in central Spitsbergen (Hounslow *et al*., 2008). It comprises a black shale facies representing a distal prodelta environment. The overlying Blanknuten Member is of late Anisian through Ladinian age (Hounslow *et al.*, 2008; Xu *et al.*, 2009). It is represented by a phosphatic black shale and mudstone succession deposited in an open shelf environment (Krajewski, 2013).

The Bravaisberget Formation has been subdivided into four members (the Passhatten, Somovbreen, Karentoppen, and Van Keulenfjorden members) that show facies complexity and differences in distribution in southern and western Spitsbergen (Pčelina, 1967, 1985; Mørk *et al.*, 1982; Krajewski, 2000c; Krajewski *et al.*, 2007). The shale-dominated Passhatten Member makes up the lower and middle parts of the formation in western Spitsbergen (Bellsund, Isfjorden). It is thought to represent organic-rich deposition in a mostly shallow-shelf environment (Karcz, 2010). It thins southward and becomes a subordinate unit of the formation on the Sørkapp-Hornsund High, a Palaeozoic uplifted structure, exposed along western Sørkapp Land (Harland, 1997). The overlying Somovbreen Member comprises a sandy to silty, marine succession encompassing and covering wedges of deltaic deposits. This member is best developed in southern Spitsbergen, thinning north of Bellsund and replaced by a succession of phosphatic ("oolitic") grainstones in the Isfjorden area (Festningen). The deltaic deposits are distinguished as the Karentoppen Member (Mørk *et al.*, 1999; Haugan, 2012). They are confined to the southern and western parts of Sørkapp Land (Fig. 1C). Both the Passhatten and Somovbreen members are phosphatic as a rule, containing mostly nodular phosphate accumulations (Krajewski, 2000a). The topmost Van Keulenfjorden Member comprises siliceous and dolomitic sandstones and shales as well as spiculitic deposits that are recognized throughout southern and western Spitsbergen (Pčelina, 1983; Mørk *et al.*, 1999; Krajewski *et al.*, 2007; Krajewski and Woźny, 2009).

Rare discoveries of ammonoids, bivalves, and conodonts in the Passhatten and Somovbreen members appear to indicate a Middle Triassic age for the Bravaisberget Formation (Buchan *et al.*, 1965; Pčelina, 1967, 1983, 1985, 1996; Korchinskaya, 1972a; Korčinskaja, 1972b; Birkenmajer, 1977; Trammer, 1978; Clark and Hatleberg, 1983; Nakrem *et al.*, 2008). Parts of the formation were assigned either an Anisian or Ladinian age, though the geological location of the fossils collected is commonly uncertain, and the validity of the palaeontological determinations is difficult to assess. In the stratigraphic scheme of Mørk *et al.* (1999) and in the subsequent papers by Hounslow *et al.* (2007, 2008) and Hounslow and Nawrocki (2008), the Passhatten Member is correlated with the lower part of the Botneheia Formation and the succession of the Somovbreen and Van Keulenfjorden members are proposed as being roughly coeval with the Blanknuten Member (Fig. 2). The discontinuous Karentoppen Member is placed between the Passhatten and Somovbreen members. However, biostratigraphic documentation of this correlation is lacking; and the facies relationships in southern and western Spitsbergen indicate diachronous boundaries between the members of the Bravaisberget Formation (Krajewski, 2000a, c, Krajewski *et al.*, 2007; Haugan, 2012).

The transition between the Sassendalen and Kapp Toscana groups in the main outcrop belt in Svalbard (Spitsbergen, Barentsøya and Edgeøya) has been interpreted as referable to the Ladinian-Carnian boundary (Dagys and Weitschat, 1993; Pčelina, 1998; Korčinskaja, 2000; Konstantinov, 2008). However, recent magneto-biostratigraphic investigations in central Spitsbergen suggest an important hiatus between the groups (Hounslow *et al.*, 2006a, b, 2007, 2008; Hounslow and Nawrocki, 2008). According to these authors, the hiatus is likely to occur over the whole of Svalbard, broadening south-westward in Spitsbergen (Fig. 2). This indicates that the termination of marine environments of the Sassendalen Group was not simply related to progradation of the prodelta/delta facies of the Kapp Toscana Group, but included a period of erosion and/or non-deposition.

The Triassic part of the Kapp Toscana Group in the platform development consists of the lower Tschermakfjellet Formation (early Carnian prodelta shale) and the upper De Geerdalen Formation (Carnian deltaic sandstone) that are overlain by the shallow-marine shale/sandstone succession of the Wilhelmøya Subgroup (Steel and Worsley, 1984; Mørk *et al.*, 1999; Hounslow *et al.*, 2007). The Wilhelmøya Subgroup in central and eastern Spitsbergen, on Wilhelmøya, and in some locations in eastern Svalbard (Knorringfjellet, Flatsalen, Svenskøya, and Kongskøya formations) straddles the Triassic-Jurassic boundary and extends into the Middle Jurassic (Bäckström and Nagy, 1985; Nagy *et al.*, 2011). This division becomes less distinct in the fold belt, where in many places only an undifferentiated succession of the lower part of the Kapp Toscana Group (shale with sandstone) has been recognized (Harland, 1997). However, in several places, the basal part of the succession is shale-dominated, and therefore classified as the Tschermakfjellet Formation (Birkenmajer, 1977; Steel and Worsley, 1984; Vigran *et al.*, 2014). The overlying sandstone-dominated unit, which in some sections is classified as the De Geerdalen Formation (Dallmann *et al.*, 1993b; Vigran *et al.*, 2014), tends to replace the shaly succession in the fold belt between Bellsund and Isfjorden (Mørk and Worsley, 2006). The Wilhelmøya Subgroup is represented by a condensed Smalegga Formation (Mørk *et al.*, 1999). It can be identified in most sections in southern and western Spitsbergen, forming a thin quartzitic sandstone unit at the top of the Kapp Toscana Group (Krajewski, 1992a, b).

MATERIALS AND METHODS

This paper reports the results of geological and palaeontological investigations of the Bravaisberget Formation in Sørkapp Land, supported by comparative studies in the Hornsund and Bellsund areas (Fig. 1A). The fieldwork concentrated on the Triassic outcrop belt, exposed along the western and southern coasts of Sørkapp Land and on the neighbouring islands (Fig. 1B). The succession in the southernmost Sørkapp Land, which gave stratigraphically important ammonoid findings, is reported here in detail. This includes detailed logs of two sections, located at Bergnasen (KS section) and Keilhaufjellet (KL section) on both sides of Mathiasbreen. The petrography of the sediment types discerned and the fossils was studied in thin sections, using transmitted- and reflected-light microscopy. The microscopic survey was supported by mineral identification, using x-ray diffraction analysis of disordered powder samples. Selected thin sections were analysed using scanning electron microscopy (back-scattered electron images and microprobe analysis) in order to reveal the composition and distribution of heavy minerals in the clastic sediments. Details of the analytical procedure and the instruments used can be found in Krajewski and Woźny (2009) and Krajewski (2013). Palaeontological investigation of the fossils was done using a binocular microscope under ×5–50 magnifications. The fossil collection of *Stolleyites planus* from the KS and KL sections (samples KL-1C.1, KL-1C.2, KL-1E, KS-17, and KS-20) is housed at the Institute of Geological Sciences, Polish Academy of Sciences in Warszawa.

RESULTS

Lithostratigraphy of the Bravaisberget Formation in southern Spitsbergen

The lithostratigraphy and facies development of the Sassendalen Group in southern Spitsbergen is given in Figure 3A–D. The Early Triassic Vardebukta and Tvillingodden formations are well developed north of Sørkapp Land, but thin toward the Sørkapp-Hornsund High, where the transgressive conglomeratic succession of the Kistefjellet Member represents the Vardebukta Formation. On the southern margin of the high (Sørkappøya), only an undifferentiated succession of shales and laminated siltstones/sandstones can be assigned to these formations.

Similar thickness reduction can be observed in the Bravaisberget Formation, which thins from more than 200 m in the Bellsund area (Bravaisberget) to about 100 m in the Hornsund area (Treskelen), and to less than 70 m in the central part of the Sørkapp-Hornsund High (Fisneset). This is associated with a significant reduction in the thickness of the shale-dominated Passhatten Member, which is progressively replaced southward by the thickening sandstone-/siltstone-dominated Somovbreen Member.

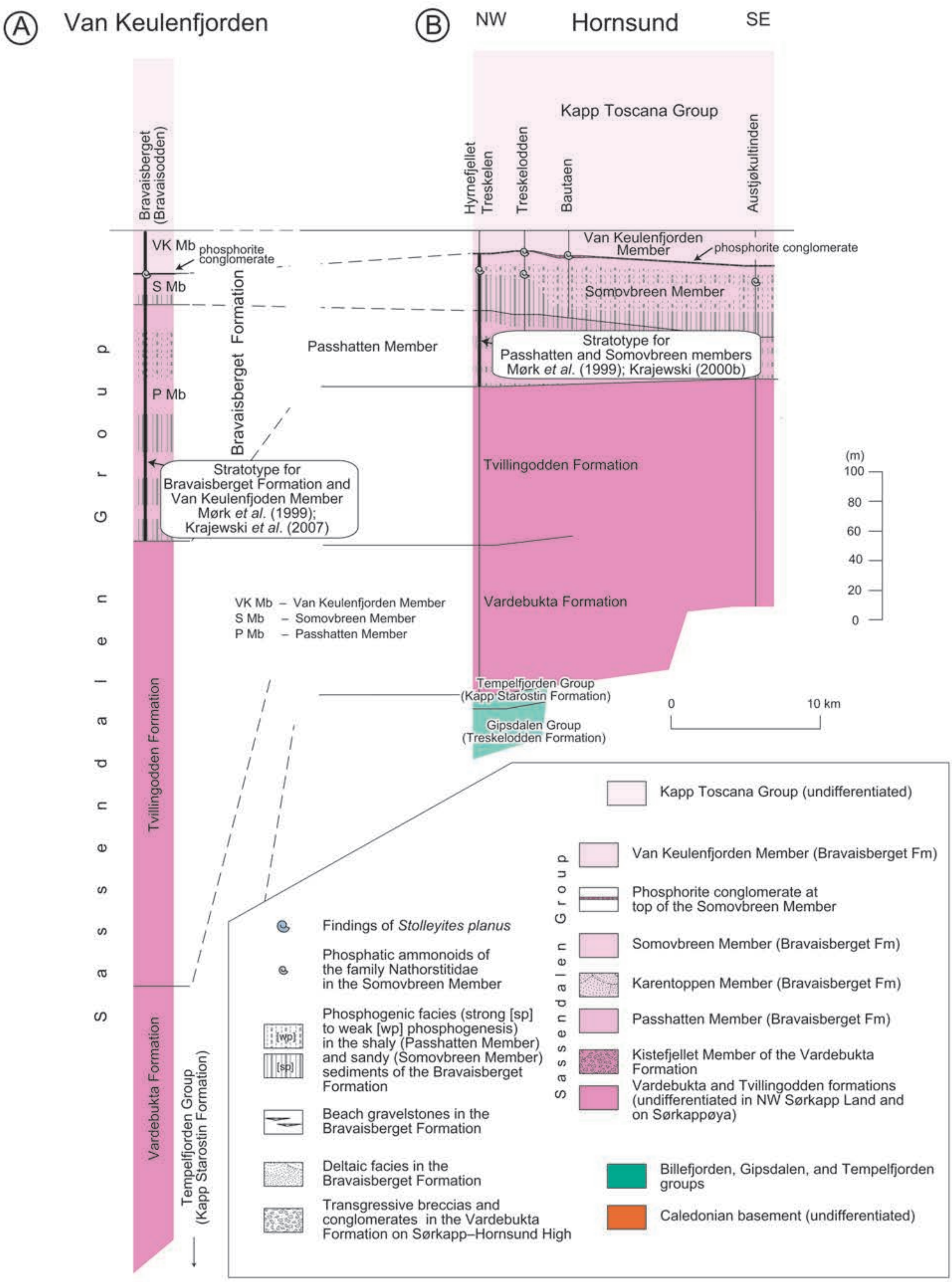
Sørkapp Land is the only area where all four members of the Bravaisberget Formation can be discerned. The marine Passhatten and Somovbreen members and the marginal marine Van Keulenfjorden Member occur in stratigraphic order. They are recognized throughout the outcrop belt in Sørkapp Land, except for the Passhatten Member that is missing in the central part of the Sørkapp-Hornsund High (Røysneset–Fisneset), and on Sørkappøya and Stjernøya. The Karentoppen Member, which comprises medium- to coarse-grained deltaic facies in the lower part of (or below) the Somovbreen Member, makes up a stratiform horizon on Sørkappøya and Stjernøya, and lensoidal bodies at Lidfjellet–Liddalen, Røysneset, and Karentoppen. It is absent in southernmost Sørkapp Land. The main deltaic facies complex recognized at Karentoppen and Lébedevfjellet (Fig. 1C) wedges out southward (north of St. Nikolausfjellet) and northward (south of Vitkovskibreen). The Karentoppen Member reappears below the Somovbreen Member on Sørkappøya and Stjernøya. It should be noted, however, that the succession exposed there is nearly vertical in the western limb of a complex synclinal structure belonging to the Lidfjellet-Øyrlandsodden Fold Zone. This structure has a continuation toward Tokrossøya and Øyrlandsodden (Permian Tokrossøya Formation), but it is separated from the St. Nikolausfjellet-Kistefjellet area by down-faulted Palaeogene strata at Øyrlandet. The deltaic wedges of the Karentoppen Member, observed along the western coast of Sørkapp Land, have a complex pattern, although they disappear north-eastward over a distance of a few kilometres (Fig. 3). This can be best demonstrated in the Lidfjellet tectonic structure (Krajewski and Stempień-Sałek, 2003), where the Karentoppen Member thins from about 30 m in the autochthonous cover (Liddalen) to less than 5 m in the overthrust unit (Lidfjellet) over a displacement distance of about 2 km, and becomes absent at Kovalevskifjellet over the next 2 km to the northeast.

The Van Keulenfjorden Member shows continuous development in southern and western Spitsbergen. It is thickest on Sørkappøya and at Kistefjellet-Bergnasen in southernmost Sørkapp Land, thinning slightly in the remainder of southern and western Spitsbergen. In the Bellsund and Hornsund areas, the member is represented by two successive coarsening-upward units (Krajewski, 2000c, Krajewski *et al.*, 2007). This subdivision becomes less distinct southwestward, where a more complex succession of alternating silty and sandy lithologies appears along the western and southern coasts of Sørkapp Land.

Facies of the Bravaisberget Formation in southern Spitsbergen

The Passhatten Member (Fig. 4) comprises a succession of dark grey to black mud- to silt-shales with siltstone/sandstone intercalations; the latter are bioturbated as a rule, with *Taenidium* and *Rhizocorallium* the dominant trace fossils. *Thalassinoides* is observed in the shale, forming flattened burrow systems filled with phosphatic sediment (see also Mørk and Bromley, 2008). The shale contains common quartz grains in the fine- to coarse-silt fractions, and flakes of detrital mica. Other detrital components, including feldspar and heavy mineral grains, are accessory. Clay minerals are dominated by illite. The succession is organic-rich, though usually it shows advanced levels of thermal alteration (Krajewski, 2000c). Both amorphous and structured organic matter occur in the shale. The organic matter is associated with authigenic, framboidal and microgranular pyrite. Microfossils observed in thin sections include siliceous sponge spicules, rare arenaceous foraminifera and radiolaria moulds, and the debris of unidentified bivalve and brachiopod shells. Their content irregularly decreases toward the Sørkapp-Hornsund High, along with a general increase of the amount of clastic grains.

The silty and sandy sediments of the Somovbreen Member (Fig. 5) are composed of quartz grains cemented by calcitic sparite. The sandy sediments are very fine- to fine-grai-



A Van Keulenfjorden
B NW Hornsund SE
Bravaisberget (Bravaisodden)
VK Mb
phosphorite conglomerate
S Mb
P Mb
Bravaisberget Formation
Passhatten Member
Stratotype for Bravaisberget Formation and Van Keulenfjoden Member Mørk et al. (1999); Krajewski et al. (2007)
Sassendalen Group
Tvillingodden Formation
Vardebukta Formation
Tempelfjorden Group (Kapp Starostin Formation)
VK Mb – Van Keulenfjorden Member
S Mb – Somovbreen Member
P Mb – Passhatten Member
Kapp Toscana Group
Hyrnefjellet Treskelen
Treskelodden
Bautaen
Austjøkultinden
Van Keulenfjorden Member
phosphorite conglomerate
Somovbreen Member
Stratotype for Passhatten and Somovbreen members Mørk et al. (1999); Krajewski (2000b)
Tvillingodden Formation
Vardebukta Formation
Tempelfjorden Group (Kapp Starostin Formation)
Gipsdalen Group (Treskelodden Formation)
(m)
100
80
60
40
20
0
0
10 km
Kapp Toscana Group (undifferentiated)
Sassendalen Group
Van Keulenfjorden Member (Bravaisberget Fm)
Phosphorite conglomerate at top of the Somovbreen Member
Somovbreen Member (Bravaisberget Fm)
Karentoppen Member (Bravaisberget Fm)
Passhatten Member (Bravaisberget Fm)
Kistefjellet Member of the Vardebukta Formation
Vardebukta and Tvillingodden formations (undifferentiated in NW Sørkapp Land and on Sørkappøya)
Billefjorden, Gipsdalen, and Tempelfjorden groups
Caledonian basement (undifferentiated)
Findings of Stolleyites planus
Phosphatic ammonoids of the family Nathorstitidae in the Somovbreen Member
Phosphogenic facies (strong [sp] to weak [wp] phosphogenesis) in the shaly (Passhatten Member) and sandy (Somovbreen Member) sediments of the Bravaisberget Formation
[wp]
[sp]
Beach gravelstones in the Bravaisberget Formation
Deltaic facies in the Bravaisberget Formation
Transgressive breccias and conglomerates in the Vardebukta Formation on Sørkapp–Hornsund High

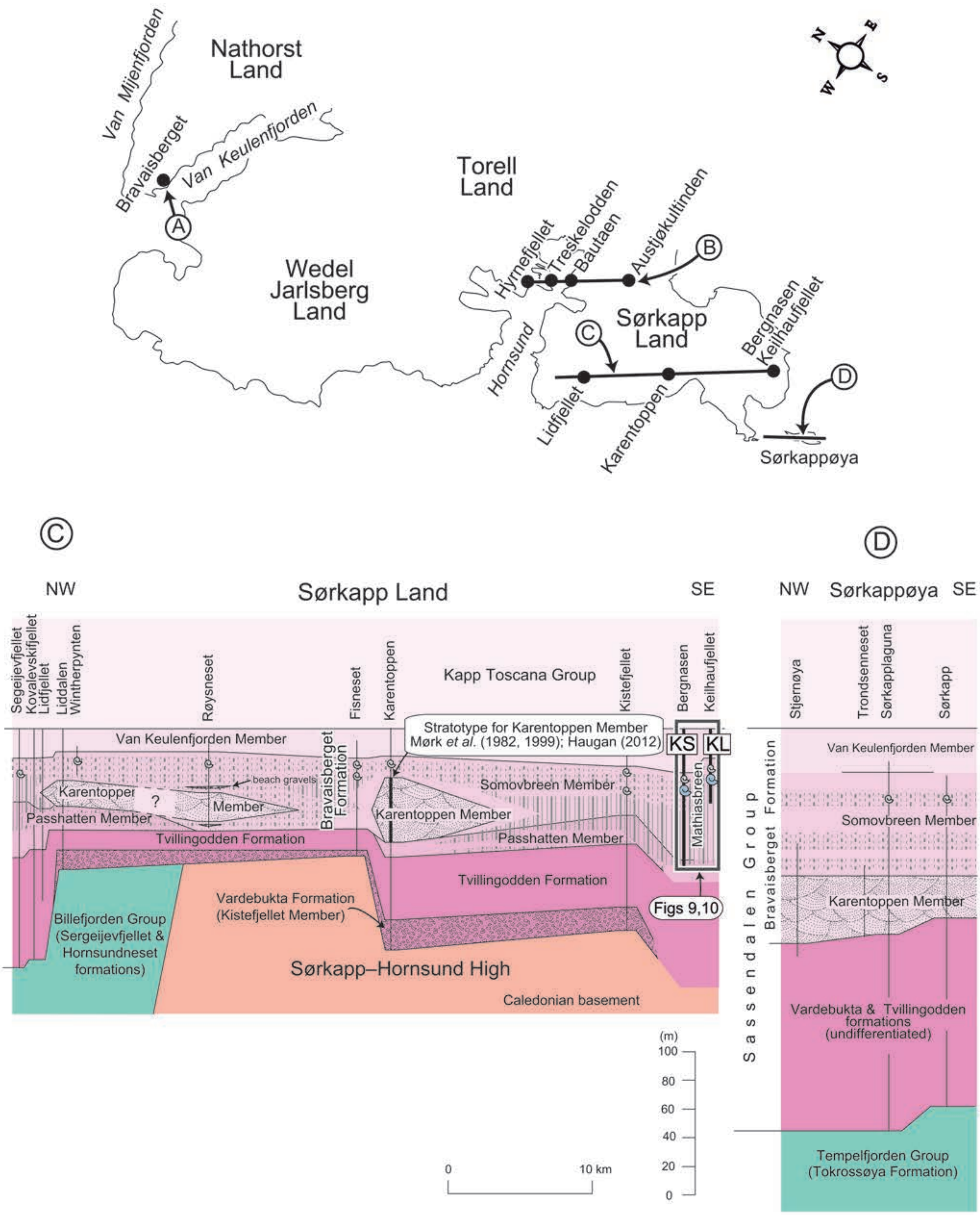


Fig. 3. Lithostratigraphy and facies of the Sassendalen Group in southern Spitsbergen. **A.** Van Keulenfjorden (Bravaisberget). **B.** Inner Hornsund and NE Sørkapp Land. **C.** Western coast of Sørkapp Land. **D.** Sørkappøya and Stjernøya. For further explanation, see text.

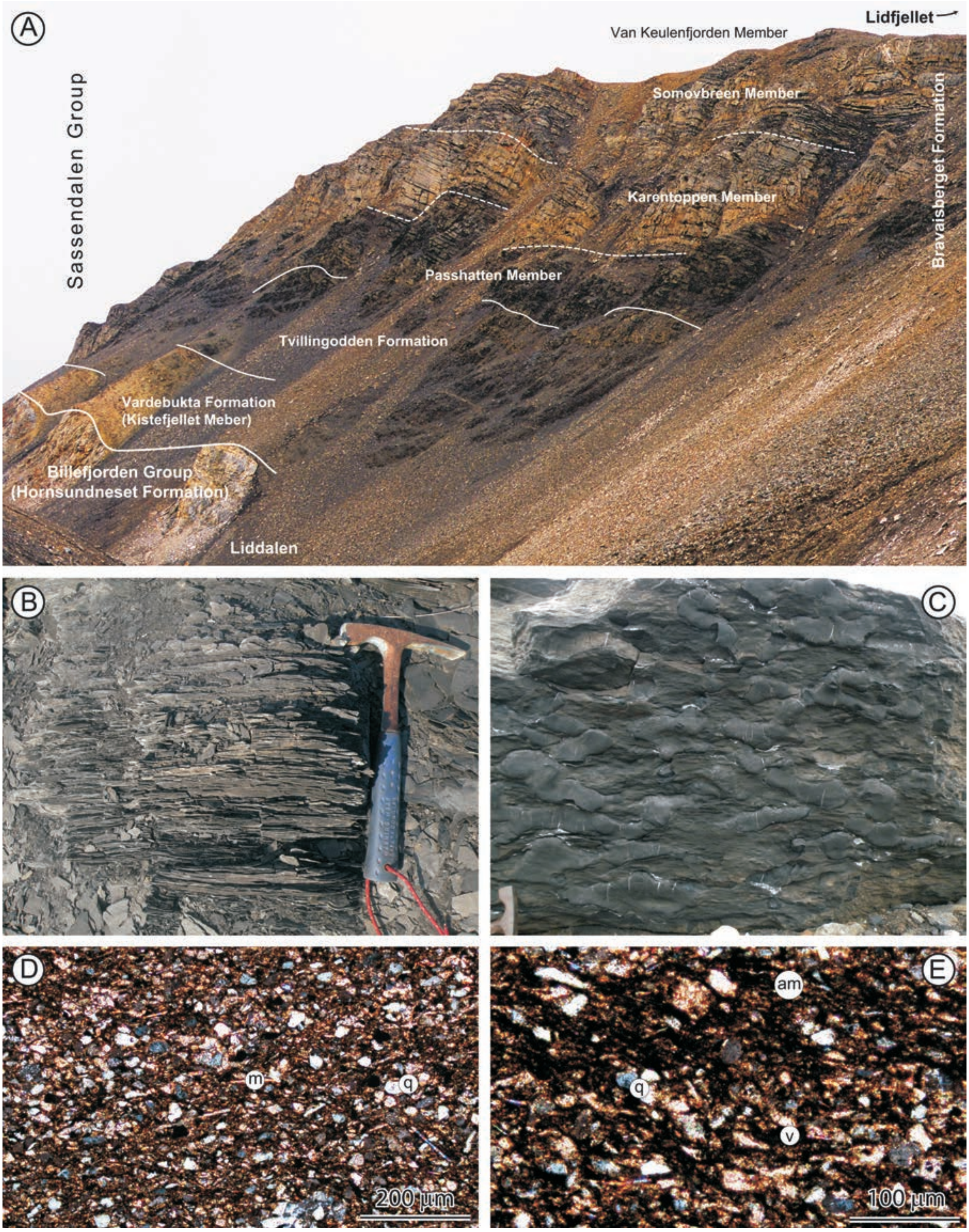


Fig. 4. Facies development of the Passhatten Member in southern Spitsbergen. **A.** Succession of the Sassendalen Group in Liddalen, NW Sørkapp Land. The succession belongs to the autochthonous part of the Lidfjellet tectonic structure (Lidfjellet-Øyrlandsodden Fold Zone), and records Triassic depositional history at northern margin of the Sørkapp-Hornsund High. The transgressive conglomerates and sandstones of the Kistefjellet Member (Vardebukta Formation) rest discordantly on quartzitic sandstones of the Carboniferous Hornsundneset Formation. They are overlain by laminated siltstones and shales of the Tvillingodden Formation. The Bravaisberget Formation is represented by the Passhatten, Karentoppen, Somovbreen, and Van Keulenfjorden members. The Passhatten Member comprises a cliff-forming black shale succession, reflecting organic-rich deposition at margin of the high before the input of coarse deltaic clastics of the Karentoppen Member. **B.** Non-laminated, fissile black shale of the Passhatten Member. Section perpendicular to bedding. Lidfjellet, NW slope. **C.** Flattened, phosphate-filled burrow system *Thalassinoides* in black shale of the Passhatten Member. Plane parallel to bedding. Lidfjellet, NW slope. **D.** Photomicrograph of black shale shown in (B). The shale contains quartz grains of the fine- to coarse-silt fractions (*q*) and detrital mica flakes (*m*) in a clay-rich matrix. **E.** Organic matter in the black shale is represented by seams of amorphous fraction (*am*) and vitrinite particles (*v*), preserved at an advanced stage of thermal alteration. Quartz grains (*q*) occur in the matrix. Lidfjellet, NW slope. (D, E) – transmitted-light microscopy, crossed nicols.

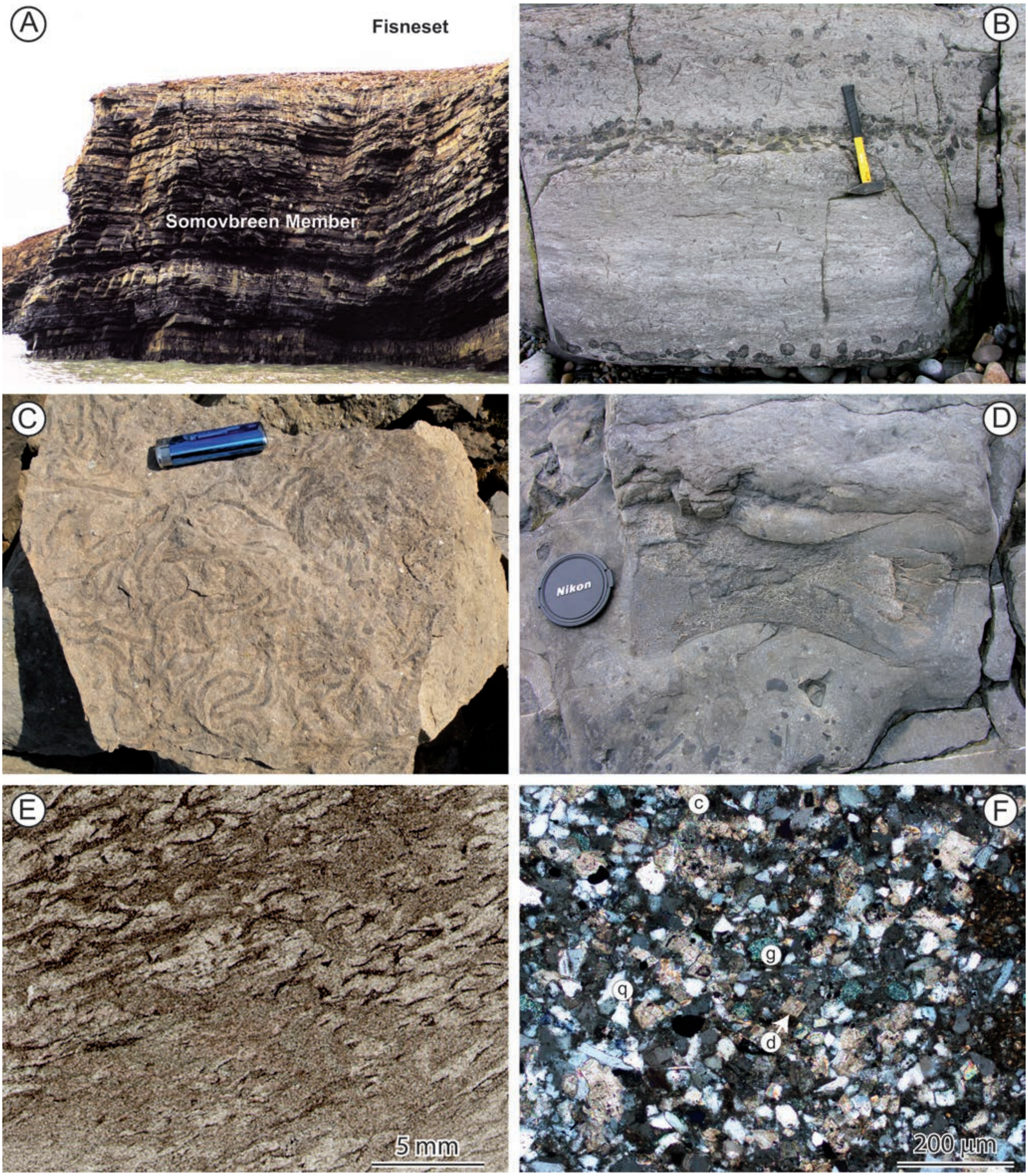


Fig. 5. Facies development of the Somovbreen Member in southern Spitsbergen. **A.** Succession of marine sandstones with siltstone/shale intercalations of the Somovbreen Member at Fisneset was deposited in front of deltaic sediments of the Karentoppen Member. The sandstone packages contain varying amounts of pristine and allochthonous phosphate nodules. **B.** Reworked horizons of allochthonous phosphate nodules and clasts in highly bioturbated sandstone of the Somovbreen Member at Røysneset. The sandstone contains common trace fossil *Skolithos*. **C.** *Taenidium* on a surface parallel to bedding in fine-grained sandstone of the Somovbreen Member at Keilhaufjellet. **D.** Reptilian bone in phosphatic sandstone of the Somovbreen Member at Røysneset. **E.** Finely bioturbated nature of sandstone of the Somovbreen Member at Kistefjellet. Thin section photograph. Section perpendicular to bedding. **F.** Photomicrograph of very fine-grained sandstone of the Somovbreen Member at Wintherpynten. The sediment consists of quartz (*q*) and glauconite (*g*) grains cemented by calcitic sparite (*c*). Diagenetic dolomite rhombs (*d*) occur as subordinate cement. Transmitted-light microscopy, crossed nicols.

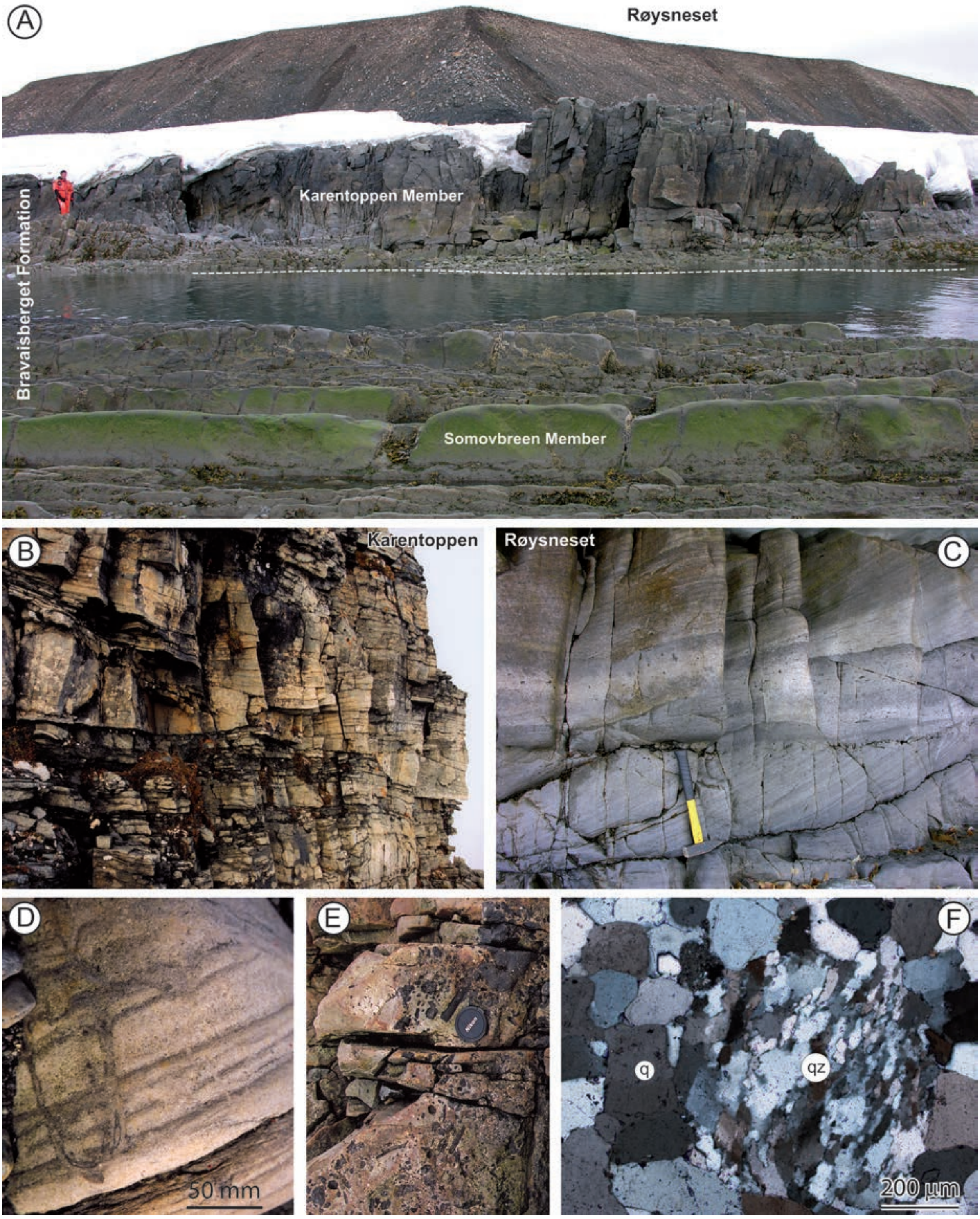


Fig. 6. Facies development of the Karentoppen Member in southern Spitsbergen. **A.** Medium- to coarse-grained sandstones filling delta distributary channel (Karentoppen Member) in the lower part of shallow marine sandstone succession of the Somovbreen Member at Røysneset. The Somovbreen Member contains in places lenses of beach gravelstone, composed of pebbles of different rocks of the Caledonian basement intermixed with allochthonous phosphate nodules and clasts. Note that the succession seen on the photo can be assessed during low tide of the sea. **B.** Part of a 30 m high cliff of the Karentoppen Member at Karentoppen showing medium- to coarse-grained sandstone lenses with tabular cross-bedding. Location of this cliff is shown in Fig. 1C. **C.** Medium- to coarse-grained sandstone lenses of the Karentoppen Member at Røysneset. The lenses show erosional boundaries, tabular cross-bedding with tangential foresets, and scattered land-plant detritus. Section perpendicular to bedding. **D.** Large *Diplocraterion*-like burrow that cuts lamina set of coarse-grained sandstone filling distributary channel at Sørkapplaguna on Sørkappøya. Section perpendicular to bedding. **E.** Land-plant detritus (black) in coarse-grained sandstone of the Karentoppen Member at Sørkapplaguna on Sørkappøya. Bedding plane. **F.** Photomicrograph of medium- to coarse-grained sandstone of the Karentoppen Member at Røysneset. The sandstone contains quartz (*q*) and quartzite (*qz*) grains, with subordinate admixture of other lithic grains. Transmitted-light microscopy, crossed nicols.

ned. They contain glauconite grains and subordinate feldspar grains and also show an elevated content of detrital zircon and rutile at recurrent levels in the succession. Coarser-grained sediments containing lithic grains appear in close proximity to the deltaic deposits of the Karentoppen Member. The sandstones and siltstones are finely bioturbated. *Taenidium* is the dominant trace fossil. However, the contribution of vertical burrows (*Polykladichnus* and *Skolithos*) irregularly increases upward within the succession. The clastic sediments show common evidence of mechanical reworking and winnowing. Biogenic components include phosphatic ammonoids, siliceous sponge spicules, debris of bivalve and brachiopod shells, and reptilian bones and coprolites. Rare fragments of petrified tree trunks have been observed north of the Sørkapp–Hornsund High.

The sandstones of the Karentoppen Member (Fig. 6) are composed of well-rounded quartz and quartzite grains of the medium- to coarse-sand fraction (in places, also the fine-gravel fraction), with a subordinate admixture of other lithic grains. In the distributary channel fills, they are arranged in packages up to a few meters thick that show large-scale tabular cross-bedding and erosional boundaries accentuated by occurrences of gravel. These packages show the presence of U-shaped burrows resembling *Diplocraterion* and scattered plant detritus. The plant detritus is concentrated at some bedding planes to form carbonaceous layers and seams. These seams become common in the Sørkappøya outcrop belt, where individual wood fragments may attain 10 cm in length. It should be noted, however, that the woody debris represents the washed and transported fraction, and that no palaeosol horizons have been noted in the deltaic succession. In the delta-front facies, the sandstones form thick, massive beds, separated by thin layers of muddy sediment or by erosional boundaries. The beds are mechanically and bioturbationally homogenized, though some exhibit wave- and current-induced sedimentary structures. *Skolithos* appears in this facies. In the Karentoppen-Lébedevfjellet section, two events of delta advancement can be discerned. They are separated by a thin, marine sandstone unit with phosphate nodules and *Thalassinoides* that reflects flooding event of the delta environment (Haugan, 2012). One thick succession of the deltaic deposits on Sørkappøya suggests that the flooding was a local phenomenon, most probably related to changes in delta configuration in SW Sørkapp Land. Close to the margins of the Karentoppen Member at Røysneset, there occur beach gravelstones composed of pebbles of different rock types of the Caledonian substratum (the Sørkapp-Hornsund High succession), intermixed with allochthonous phosphate nodules and clasts.

The Passhatten and Somovbreen members contain common phosphate deposits, including nodular, conglomeratic, peloidal and crust-type accumulations as well as phosphatic fossils, burrows and phosphatized bones (Figs 4, 5). On the Sørkapp-Hornsund High, the content of phosphate in the Passhatten Member exhibits a rather irregular pattern, reflecting phosphogenesis in shallow-marine shaly facies. It attains a maximum in the lower part of the Somovbreen Member in locations where the deltaic Karentoppen Member is missing. The upper part of the Somovbreen Member shows a noticeable decrease in the content of phosphate, though most of the phosphate fraction is represented by phosphatic ammonoids and products of their mechanical disintegration. In south-western Sørkapp Land, they are concentrated in recurrent horizons up to 0.5 m thick, which are separated by thicker sandstone packages without phosphate. In north-eastern Sørkapp Land and in inner Hornsund, the top of the Somovbreen Member is accentuated by a thin (up to 0.4 m thick), condensed phosphorite-bearing horizon or a remanié deposit, containing reworked and rounded phosphate nodules and phosphatic ammonoids.

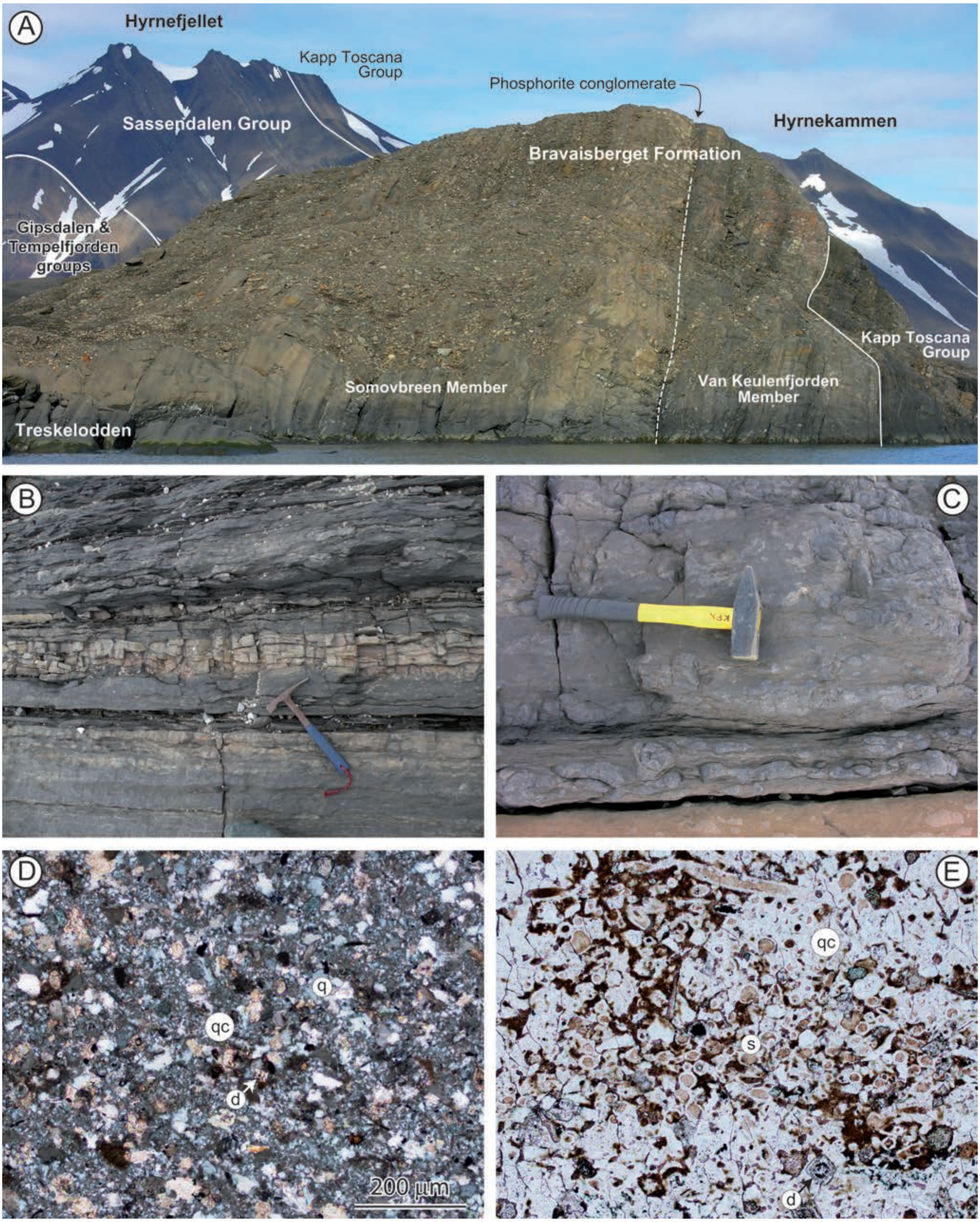
The Van Keulenfjorden Member (Fig. 7) comprises a clastic succession of quartz sandstones, siltstones, and silty shales that usually are silica-cemented and show a subordinate admixture of dolomite cement. This contrasts with calcite-cemented sandstones and siltstones of the underlying Somovbreen Member. In south-western Sørkapp Land, these sediments contain an important admixture of detrital mica and feldspar. The succession shows sedimentary features indicative of marginal- to shallow-marine environment, including structures and laminations typical of fine-grained beach deposits. *Polykladichnus* is the dominant trace fossil. Within the clastic succession, there are interbeds and lenses of spiculitic deposits. They are composed of siliceous sponge spicules showing advanced stages of dissolution and replacement by diagenetic silica. Matrix silicification was a common process in these lithologies. It led to the formation of nodular and/or banded chert horizons with microlaminated quartz cement. The cherts are also observed in the siliciclastic sediments. The content of spiculites in the Van Keulenfjorden Member increases north-eastward in Sørkapp Land.

Bergnasen (KS) and Keilhaufjellet (KL) sections of the Bravaisberget Formation

The Passhatten, Somovbreen, and Van Keulenfjorden members are recognized on the mountain slopes between Kistefjellet and Keilhaufjellet, where they form a nearly flat-lying sedimentary succession (Fig. 8). However, the Passhatten Member is mostly covered by scree, and its contact with the underlying Triassic deposits is obscured. The same succession can be seen in a fallen tectonic block in the coastal area between Skjemmeneset and Moloen, though it is poorly exposed and separated from the Kistefjellet block by a system of echelon faults.

The sections of the Bravaisberget Formation measured on the eastern slope of Bergnasen (KS section) and at the foot of western slope of Keilhaufjellet (KL section) are presented in Figures 9 and 10, respectively.

The KS section displays about 5 m of the uppermost phosphatic shale succession of the Passhatten Member, which is overlain by a succession of calcite-cemented, fine-grained sandstones and siltstones of the Somovbreen Member, 60 m thick (Fig. 11A). Phosphate deposits are common over the lower 12 m of the succession, making recurrent horizons of pristine and allochthonous nodules separated by winnowed surfaces (Fig. 11B, C). In the upper part of the succession, there are recurrent horizons enriched in phosphatic ammonoids. The Somovbreen Member is overlain with a sharp boundary by a 30-m-thick succession of silica-cemented sandstones, sandy siltstones, and shales of the



Van Keulenfjorden Member. This succession is in turn overlain by shales with flora detritus of the lower part of the Kapp Toscana Group.

The KL section encompasses the upper part of the Somovbreen Member (about 30 m thick), with phosphatic horizons concentrated in intervals between the 6-m and 12-m levels, and between the 22-m and 25-m levels (Fig. 11D). These horizons contain almost exclusively phosphatic ammonoids and products of their mechanical reworking (Fig. 11E, F). The overlying silica-cemented sandstones and shales of the Van Keulenfjorden Member are 20 m thick, being sharply overlain by shales of the Kapp Toscana

Fig. 7. Facies development of the Van Keulenfjorden Member in southern Spitsbergen. **A.** Succession of the upper part of the Bravaisberget Formation at Treskelodden (inner Hornsund), showing position of the Van Keulenfjorden Member. This member is separated from the underlying Somovbreen Member by a thin, discontinuous horizon of condensed phosphorite conglomerate containing phosphatic ammonoids of the family Nathorstitidae (?*Stolleyites* sp.). The condensed horizon marks the boundary between the Somovbreen and Van Keulenfjorden members in the fold belt (from Austjøkultinden on the south to Bravaisberget on the north; see Fig. 3). It is replaced by reworked, fossiliferous phosphatic horizons in the sandy succession of the uppermost part of the Somovbreen Member in the south-western outcrop belt in Sørkapp Land (Fisneset–Keilhaufjellet). The Van Keulenfjorden Member is represented by siliceous sandstones, siltstones and shales with spiculitic deposits. The Treskelodden outcrop belongs to the eastern limb of the Hyrnefjellet Anticline (Birkenmajer, 1964) that represents the Sassendalen Group deposited north of the Sørkapp-Hornsund High. This succession rests upon the Hyrnefjellet and Treskelodden formations (Gipsdalen Group) covered by a thin Kapp Starostin Formation (Tempelfjorden Group), and is overlain by the Kapp Toscana Group containing in its lower part the shaly interval classified as the Tschermakfjellet Formation. **B.** Sandstone bed in the silty/shaly package in the middle part of the Van Keulenfjorden Member at Bautaen, inner Hornsund. The sandstone shows sedimentologic features indicating a beach environment. The common trace fossil *Polykladichnus* cuts lensoidal and ripple laminations of the sandstone. Dark shaly siltstones below and above the sandstone bed show the presence of banded and nodular chert, respectively. The chert deposits reflect silicification of the sediment as a result of diagenetic mobilization of spiculitic silica. **C.** Nodular chert in silty sandstone in the upper part of the Van Keulenfjorden at Bautaen. **D.** Photomicrograph of very fine-grained sandstone of the Van Keulenfjorden Member at Kistefjellet. The sandstone consists of quartz grains (*q*) cemented by microcrystalline quartz cement (*qc*). **E.** Photomicrograph of spiculite in the lower part of the Van Keulenfjorden at Bautaen. The rock is composed of siliceous sponge spicules (*s*) replaced and cemented by microcrystalline quartz cement (*qc*). (D, E) – diagenetic dolomite rhombs (*d*) occur as subordinate cement. Transmitted-light microscopy; (D) – crossed nicols; (E) – parallel nicols. Scale in (D) for both photos.

Group. The topmost part of the Triassic succession at Keilhaufjellet is affected by a small-scale overthrust, which doubles the thickness of the upper part of the Kapp Toscana Group (including the Smalegga Formation) higher up on the mountain slope.

Phosphatic ammonoids in the Somovbreen Member

All ammonoids found in the Bravaisberget Formation of southernmost Sørkapp Land came from the upper part of the Somovbreen Member. They are preserved in the form of phosphatic moulds of phragmocones, developed as a result of phosphate cementation of the original animal skeletons, as well as their sediment infillings (Fig. 12). The cementation was a very early process occurring close to the water/sediment interface in loose, clastic sediment. The major phosphate phase in the phosphatic ammonoids and elsewhere in the phosphate fraction has been x-ray identified as carbonate fluorapatite. Microscopic observations suggest that the crystallization of apatite was preceded by the precipitation of an amorphous calcium phosphate precursor. It led to the formation of fringe cement on the skeletal surfaces, preserving their fine anatomical details (see also Weitschat, 1986; Weitschat and Bandel, 1991; Zakharov and Shkolnik, 1994). The dynamic environmental agents contributed to the winnowing of the upper sediment layer and the exhumation of the ammonoids at various stages of phosphatization. Consequently, the state of preservation of the ammonoids varies widely, even within the same phosphatic horizon. The best preserved are those forming pristine nodules, i.e. the ones that experienced a single episode of phosphogenesis and remained at their original position in the sediment. The formation of fringe apatite cement included pulses of phosphate precipitation separated by pulses of precipitation of pyrite micrograins and/or framboids. In the clastic infillings of the phragmocones, the apatite cement forms envelopes around sediment grains and impregnates organic-rich particles, such as faecal pellets and microfossils. The central parts and voids in the phragmocones are filled with calcite cement, which usually is blocky and/or granular sparite. Calcite cement also fills mouldic pores, developed after dissolution of the aragonitic skeletons. Paragenetic relationships between apatite, pyrite, and calcite indicate that the calcite cementation occurred after the formation and reworking of the phosphatic moulds during their final burial in the sediment column.

Stolleyites planus

More than forty ammonoid specimens were collected along the outcrop belt of the Somovbreen Member between Kistefjellet and Keilhaufjellet. However, most of them show poor preservation. The general features of the phragmocone moulds allow classification of them into the family Nathorstitidae. Five well-preserved specimens from sections KL and KS were determined to be *Stolleyites planus* (Fig. 13). Details of the location of these discoveries are shown in Figures 9 and 10.

Stolleyites planus (Frebold) is characterized by a very distinct umbilical depression in the early and middle ontogenetic stages and by the presence of strongly pronounced umbilical bullae in the middle and late ontogenetic stages. It is similar to its probable ancestor *Nathorstites lindstroemi*, from which it differs mainly in the presence of distinct bullae up to the latest ontogenetic stages.

Samples of the fauna under consideration were first described by Stolley (1911) as two new species: *Nathorstites tenuis* and *N. gibbosus*. These two species were later divided into two different genera. *N. tenuis* was assigned to the genus *Paraindigirites* by Popov (1961). *N. gibbosus* was assigned to the new genus *Stolleyites* by Arkhipov (1974). The genus *Stolleyites* differs from other genera of the family Nathorstitidae in its ontogenesis and the characteristic cross-section of volutions. *Nathorstites gibbosus,* var. *plana*, according to the rules of zoological nomenclature, was renamed *Stolleyites planus* (Frebold, 1929), because var. *plana* was mentioned first by Frebold.

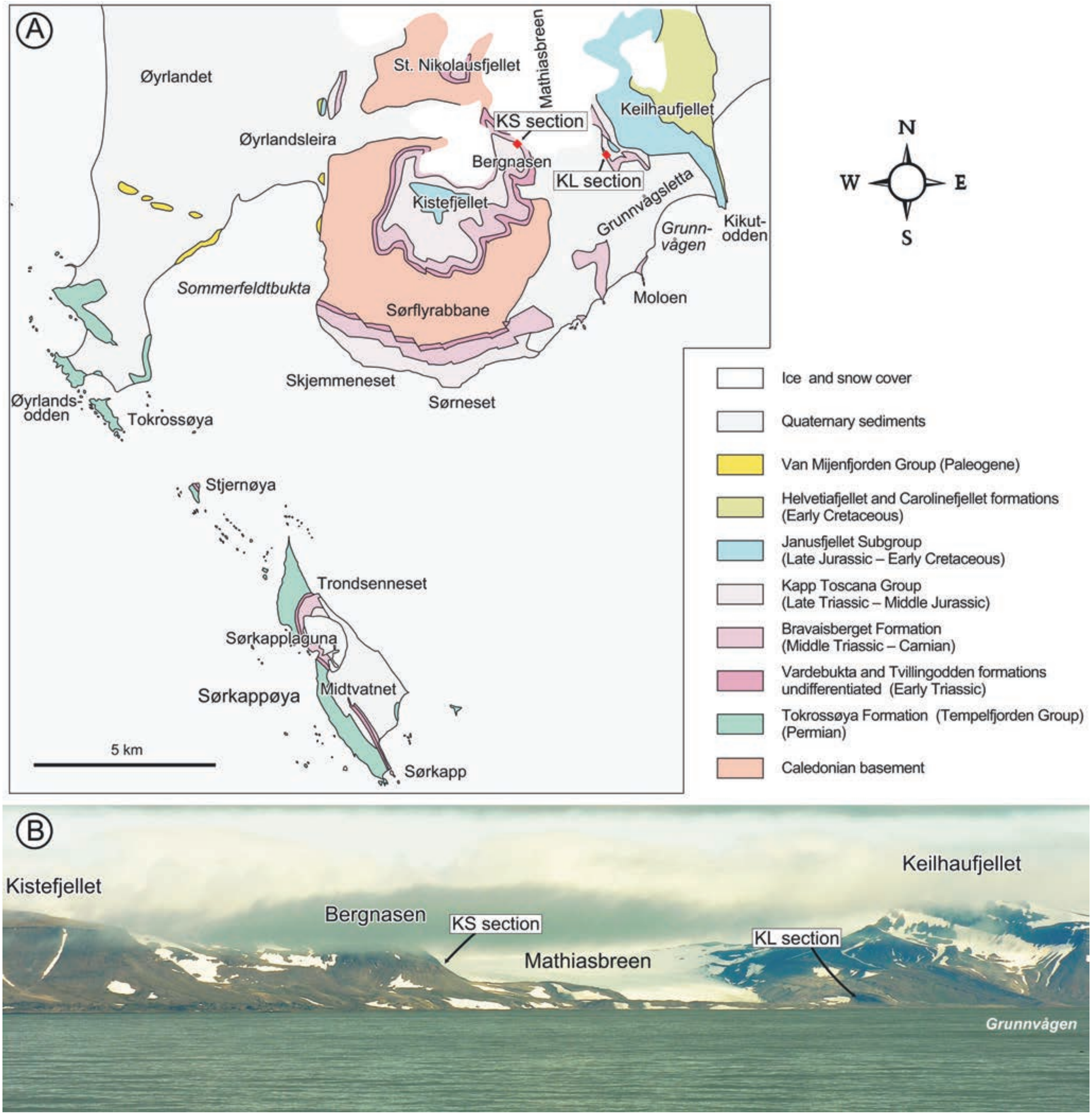


Fig. 8. The Bravaisberget Formation (Middle Triasic–Carnian) in southernmost Spitsbergen. **A.** Geological map of the southernmost part of Spitsbergen showing location of the Bergnasen (KS) and Keilhaufjellet (KL) sections of the Bravaisberget Formation. Geology after Winsnes *et al.* (1993), Dallmann *et al.* (1993b, 2002), and unpublished materials of the present authors, simplified. **B.** Panoramic photograph of the southern coast of Sørkapp Land, showing location of KS and KL sections on the western and eastern sides of Mathiasbreen, respectively. Photograph taken from Sørkappøya.

DISCUSSION

The Middle Triassic sedimentary cycle in Svalbard shows a transgressive-regressive facies arrangement (Mørk *et al.*, 1989; Pčelina, 1998; Mørk and Worsley, 2006; Basov *et al.*, 2009), though the shallow-shelf Bravaisberget Formation is characterized by much more complex and variable facies distribution than the deep-shelf Botneheia Formation (Fig. 3). This reflects a general difference in bathymetry between the depositional areas of the formations, but also a different character of dominant clastic source for the shelf sedimentation. It is plausible that the facies contrast between the formations was enhanced by a northward tectonic displacement of the West Spitsbergen Fold-and-Thrust Belt and the associated tectonic structures relative to the Eastern Svalbard Platform (Dallmann *et al.*, 1993a; Faleide *et al.*, 2008; Høy and Lundschien, 2011; Leever *et al.*, 2011). This displacement would have juxtaposed the repositories of the

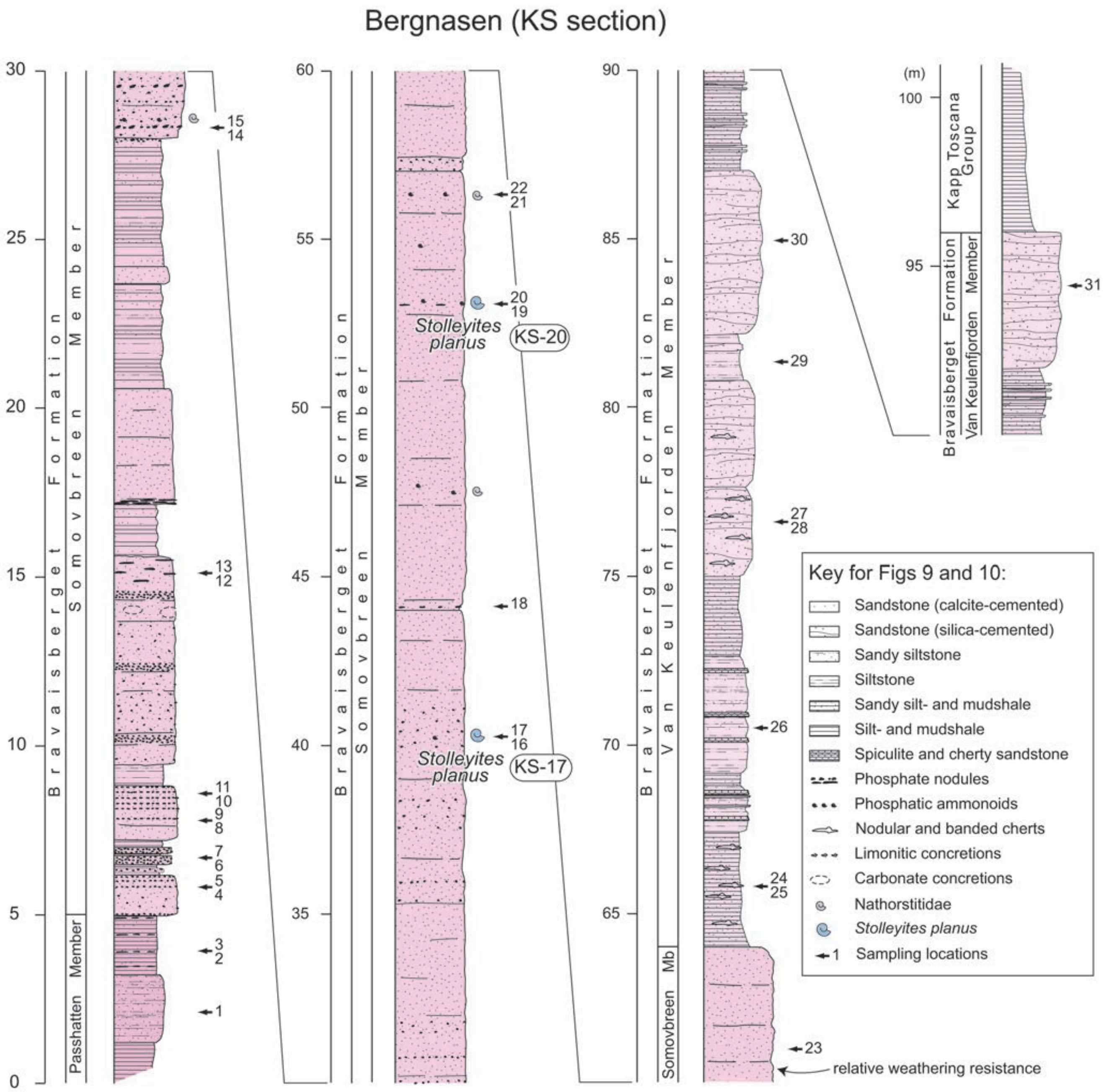


Fig. 9. Bergnasen (KS) section of the Bravaisberget Formation. Findings of *Stolleyites planus* are indicated. For further explanation, see text.

formations that originally occupied different locations on the Triassic Barents Shelf (Fig. 1A).

The Botneheia Formation was built up of sediments transported from distant deltaic systems on the south-eastern Barents Shelf (Gløstard-Clark *et al.*, 2010; Høy and Lundschien, 2011), which formed a major embayment north of the Fennoscandinavian Shield (Laursen *et al.*, 2006; Basov *et al.*, 2009; Gløstard-Clark *et al.*, 2011). The influence of local sediment sources was subordinate in Spitsbergen and negligible in eastern Svalbard. As a consequence, the Botneheia Formation shows subtle facies changes in the fine-grained sediments, influenced mostly by interplay between the distal prodelta and the open-shelf depositional systems (Krajewski, 2013). For the Bravaisberget Formation, the major sediment source was located in close proximity (west and southwest of the present coast of Spitsbergen), most probably in the land area of northern Greenland (Riis *et al.*, 2008; Worsley, 2008). In southern Spitsbergen, the land terminated along the Sørkapp-Hornsund High. The facies development of the Bravaisberget Formation points to a supply of fine-grained clastics during the transgressive and high-stand phases of the Middle Triassic cycle, which reflected a tectonically quiescent period in the land area. Deposition was controlled by subsidence in western Spitsbergen and by the stable position of the Sørkapp-Hornsund High, a part of which formed an emergent structure after its initial flooding in Dienerian (Nakrem and Mørk, 1991). The sudden appearance of the deltaic deposits

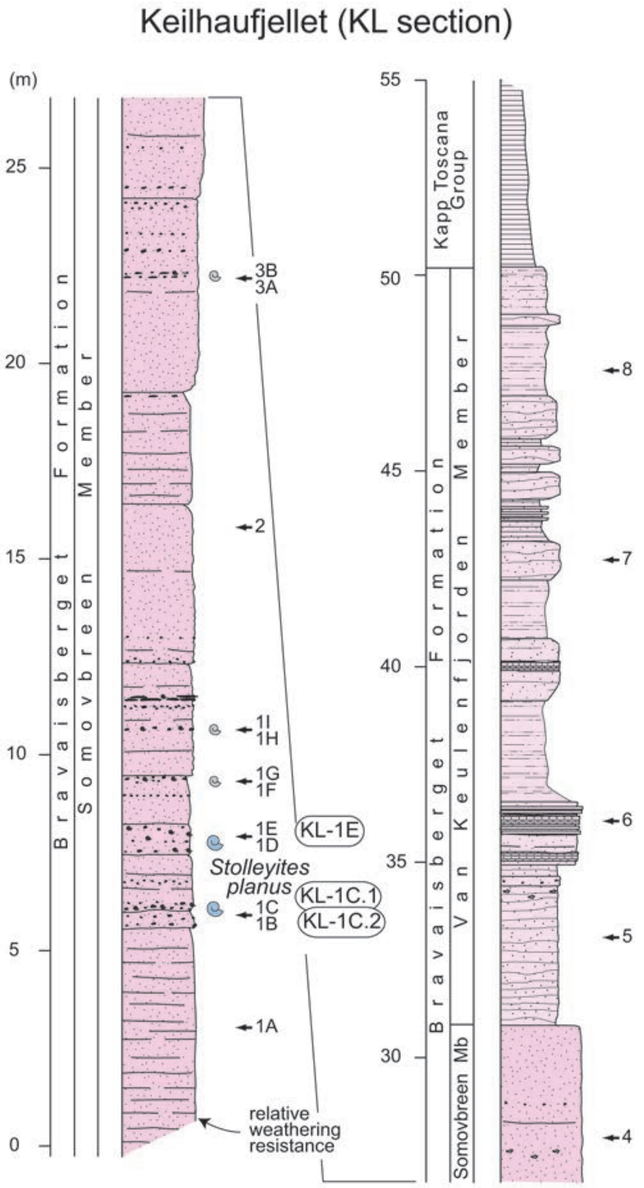


Fig. 10. Keilhaufjellet (KL) section of the Bravaisberget Formation. Findings of *Stolleyites planus* are indicated. For further explanation, see Fig. 9 and text.

of the Karentoppen Member above the organic-rich Passhatten Member or directly on older strata in Sørkapp Land indicate an event of tectonic activity in the source area and rapid supply of clastics to the south-western margin of the Svalbard basin. This supply changed the nature of marine sedimentation in southern Spitsbergen, from mostly muddy environments before the event to sandy ones after it.

The source area for the deltaic deposits seems to be missing in the present geological structure of the NW Barents Shelf, owing to Late Cretaceous–Cenozoic rifting and the separation of Greenland from the East European Craton (Faleide *et al.*, 1993; Riis *et al.*, 2008; Worsley, 2008; Smelror *et al.*, 2009). A part of it (about 40 km wide) could be located on the margin of the Barents Shelf, off the western coast of Sørkapp Land (Nøttvedt *et al.*, 1988, 2008; Faleide *et al.*, 1991), though there is limited knowledge on the Triassic evolution of this tectonic unit (Czuba *et al.*, 2008; Faleide *et al.*, 2008; Henriksen *et al.*, 2011).

The sandy facies of the Somovbreen Member straddles the Sørkapp-Hornsund High and extends basinward over a distance of about 50 km (north and east of Bellsund). Its outline marks the maximum marine redistribution of sediments delivered to the Svalbard basin by the south-western deltaic system. Despite the coarse-grained nature of the deltaic deposits of the Karentoppen Member, the sandstones of the Somovbreen Member are fine-grained and frequently silty, grading into siltstones and mudstones. They are extensively bioturbated, showing common traces of winnowing and sediment reworking. The microscopic survey revealed that they are quartz-dominated with an admixture of glauconite, and contain intervals of concentration of detrital zircon and rutile. This facies development suggests a prolonged period of low sedimentation rates and common sediment recycling in a shallow-shelf environment after the deltaic input. Gravely beach deposits observed at Røysneset indicate the presence of a rocky shore in close proximity to the delta outlets.

The general change of the nature of clastic sedimentation from the Passhatten Member to the Somovbreen Member did not affect phosphogenic conditions in the shelf environments of southern and western Spitsbergen (Krajewski, 2000a, c; Krajewski *et al.*, 2007; Pčelina and Korčinskaja, 2008). This is a strong evidence of the continuation of high biological productivity, related to nutrient supply from the oceanic basin during and after the event of deltaic input (Krajewski, 2011). The inflow of fresh water into the shelf basin was insufficient to impact on the authigenic processes in the marine facies, which supports the supposition of short-lived activity of the south-western deltaic system.

It has been suggested that the maximum flooding surface during the Middle Triassic cycle in Svalbard (both Botneheia and Bravaisberget formations) was located in a sedimentary interval showing the highest concentration of marine organic carbon (Karcz, 2010; Krajewski, 2013). This interval reflects advanced stagnation and oxygen deficit in the drowned shelf environments underlying a surficial zone of high biological productivity (Basov *et al.*, 2009; Krajewski, 2013). The highest concentration of marine organic carbon was noted in the middle part of the Blanknuten Member of the Botneheia Formation (massive phosphatic mudstone facies of Krajewski, 2013), which was dated as early Ladinian in central and eastern Svalbard (Weitschat and Lehmann, 1983; Weitschat and Dagys, 1989; Hounslow *et al.*, 2008). This age is consistent with the suggested age of the Middle Triassic maximum flooding surface in deltaic systems of the southern Barents Shelf (Gløstard-Clark *et al.*, 2010; Høy and Lundschien, 2011). The massive phosphatic mudstone in the Blanknuten Member occurs between the 75-m and 90-m levels in the 105-m-thick section of the Botneheia Formation at Blanknuten (Krajewski, 2008), and between the 90-m and 110-m levels in the 130 m thick section at Vikinghøgda (Krajewski and Weitschat, unpubl. ms.; see also Hounslow *et al.*, 2008, fig. 5). The maximum concentration of marine organic carbon was noted in the upper part of the Passhatten Member of the

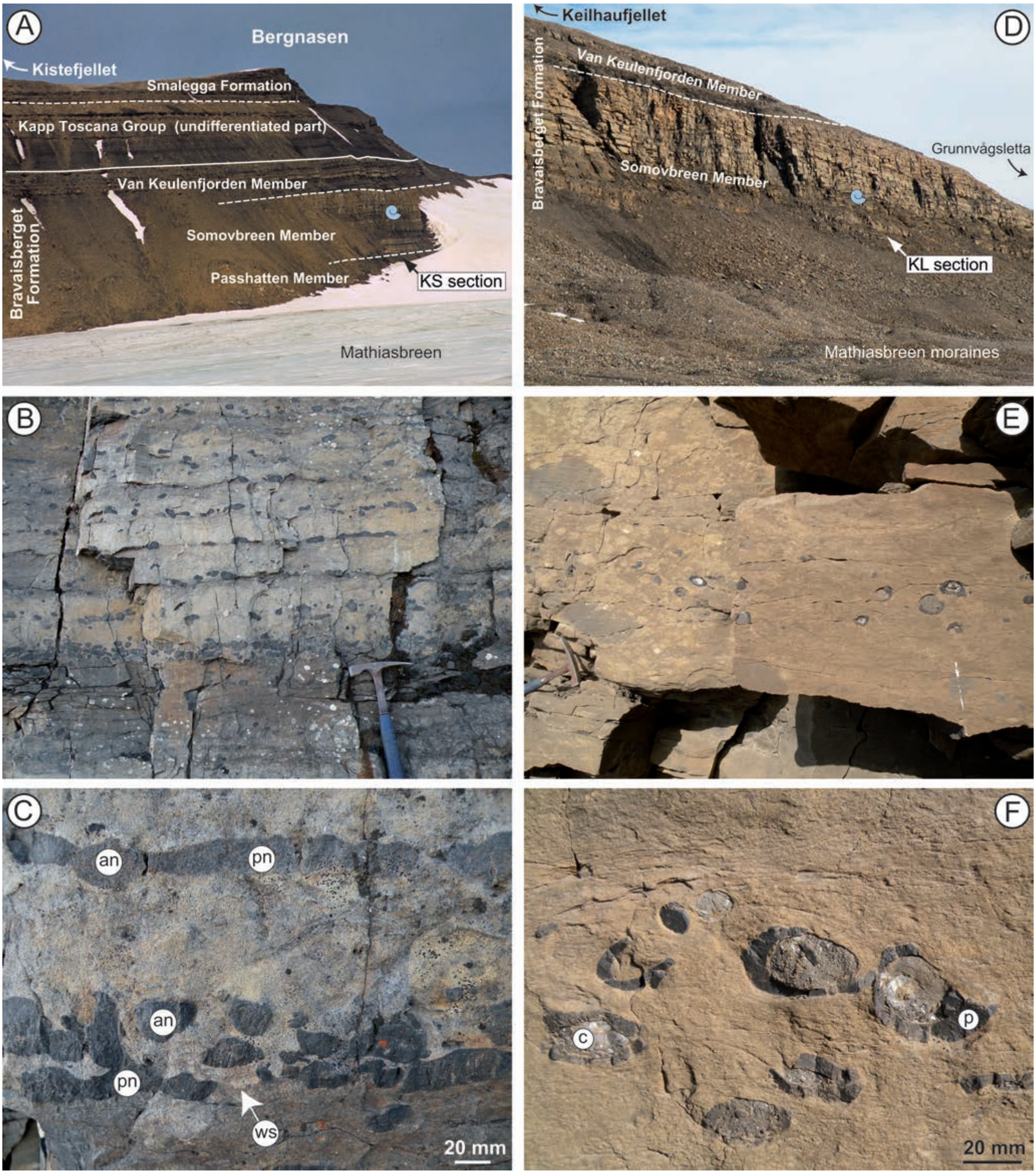


Fig. 11. Lithostratigraphy and facies of the Bravaisberget Formation in the vicinity of Mathiasbreen. **A.** Eastern slope of Bergnasen showing lithostratigraphic subdivision of the Triassic succession and the direction of KS section of the Bravaisberget Formation. Location of findings of *Stolleyites planus* is indicated. **B.** Lower part of the Somovbreen Member at Bergnasen showing succession of fine-grained sandstone with recurrent rows of phosphate nodules. Hammer is 40 cm long. **C.** Rows of pristine (*pn*) and allochthonous (*an*) phosphate nodules separated by winnowed surface (*ws*) in the lower part of the Somovbreen Member at Bergnasen. **D.** Rocky cliff at foot of the western slope of Keilhaufjellet showing direction of KL section of the Bravaisberget Formation. Location of findings of *Stolleyites planus* is indicated. **E.** Phosphatic horizon in the upper part of the Somovbreen Member at Keilhaufjellet consists of phosphatic ammonoids preserved at various stages of mechanical reworking. Section perpendicular to bedding. Hammer is 40 cm long. **F.** Ammonoids in phosphatic horizon shown in (E). The external parts of the fossil moulds are cemented by phosphate (*p*), and the internal rings are filled with later blocky calcite (*c*).

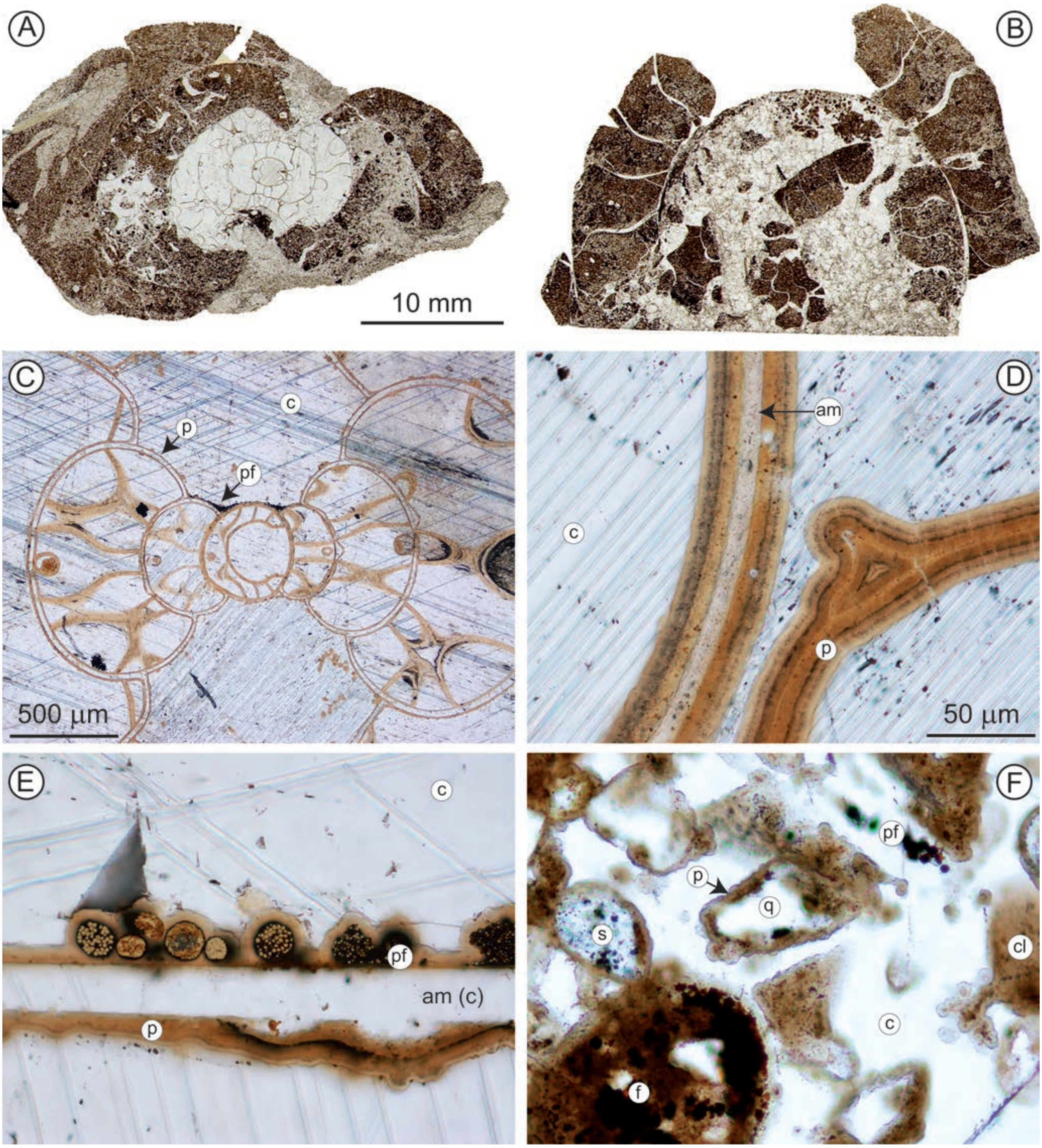


Fig. 12. Phosphatic ammonoids in the Somovbreen Member of the southernmost Sørkapp Land. **A.** Pristine phosphatic ammonoid in KL section. Note the compactional injection structure of sandy sediment developed in the lower part of internal rings before calcite cementation of the voids. **B.** Reworked phosphatic ammonoid in KL section. Mechanical fragmentation of the phosphatic infilling occurred before calcite cementation of the voids. **C.** Carbonate fluorapatite fringe cement (*p*) in internal rings of phosphatic ammonoid contributes to perfect imprint of the original phragmocone anatomy. Note small geopetal structures made of polyframboidal pyrite (*pf*). The remaining pore space and mouldic pores after dissolution of the skeleton are filled by blocky calcite cement (*c*). **D.** Multilayered apatite fringe cement with seams of pyritic microcrystals (*p*) coating ammonoid septum (*am*). The septum was dissolved during early diagenesis and infilled by a sequence of phosphate and calcite cement. Void space in the phragmocone was infilled by later blocky calcite (*c*). **E.** Apatite fringe cement (*p*) with pyrite framboids (*pf*) developed on ammonoid septum (*am*). The mouldic pore after dissolution of the septum and the internal void were infilled with later blocky calcite (*c*). **F.** Clastic sediment filling ammonoid phragmocone shows apatite fringe cement (*p*) on detrital quartz grains (*q*) and moulds of siliceous sponge spicules (*s*), and apatite impregnations of faecal pellets (*f*). Cluster-like apatite cement (*cl*) and polyframboidal pyrite (*pf*) are seen in inter-particle pore space. The remaining voids were filled by calcitic sparite (*c*). (A, B) – thin-section photographs; (C–F) – combined transmitted- and reflected-light photomicrographs, parallel nicols. Scales in (A) and (D) are for (A, B) and (D–F), respectively.

Fig. 13. *Stolleyites planus* (Frebold). **A**, **B.** Sample KL-1C.1 from KL section at Keilhaufjellet (see Fig. 10 for sample location). Calcite-filled middle ontogenic stage. The suture lines are accentuated by thin apatite fringe cement.

Bravaisberget Formation in Bellsund (the interval between the 100-m and 118-m levels in the 160-m-thick section of the Passhatten Member at Bravaisberget; Karcz, 2010) and close to the top of this member in Hornsund (the interval between the 50-m and 53-m levels in the 54-m-thick section of the Passhatten Member at Treskelen; Krajewski, 2000c). These organic-rich intervals in the Passhatten Member lack biostratigraphic dating. However, it is reasonable to assume that they constitute an isochronous horizon related to the maximum flooding of Spitsbergen during the Middle Triassic cycle, which should correlate with a similar horizon in the Blanknuten Member (Fig. 14). These data suggest that the supply of deltaic clastics to southern Spitsbergen occurred shortly after the maximum flooding of the basin, i.e. at the end of or after the early Ladinian. Hence, the oldest marine clastics of the Somovbreen Member should be roughly of the same age.

The discoveries of *Stolleyites planus* in phosphate-bearing horizons of the upper part of the Somovbreen Member in the Kistefjellet-Keilhaufjellet area bear witness to the continuation of marine sedimentation and phosphogenic conditions through the Middle-Late Triassic boundary. In Svalbard, *Stolleyites planus* defines the lower Stolleyites planus Subzone of the S. tenuis Zone, which is the first biostratigraphic zone of the Carnian (Weitschat and Dagys, 1989; Dagys and Konstantinov, 1992; Dagys and Weitschat, 1993; Korčinskaja, 2000). The fossiliferous phosphate-bearing horizons observed in the Kistefjellet-Keilhaufjellet area are also found at Fisneset north of Stormbukta, indicating that this development of the upper part of the Somovbreen Member is typical for south-western Sørkapp Land. It provides the most complete record of sedimentation of the Somovbreen Member. These horizons join one another to form a condensed phosphorite horizon occurring at the top of the Somovbreen Member further northeast in the fold belt. This is thought to reflect decreasing depositional rates and increasing condensation together with increasing distance from the coastal environments. The condensed horizon contains phosphatic ammonoids of the family Nathorstitidae (?*Stolleyites* sp.). It can be traced from Austjøkultinden in NE Sørkapp Land through inner Hornsund (Bautaen–Hyrnefjellet) to Bellsund (Bravaisberget–Bravaisodden).

Stolleyites planus has been found at several places in central and eastern Spitsbergen (Milne Edwardsfjellet, Teistberget, Roslagenfjellet) in a thin, discontinuous phosphatic black shale unit (blue-weathering), occurring just above the cliff of the Blanknuten Member of the Botneheia Formation (Weitschat and Dagys, 1989; Dagys and Weitschat, 1993; Dagys *et al.*, 1993; Hounslow *et al.*, 2007). Korčinskaja (2000) reported the presence of *Stolleyites planus* and *Daxatina canadensis* from the same stratigraphic level on Edgeøya. This thin shale was considered to be the basal deposit of the Tschermakfjellet Formation. The top of the cliff-forming succession of the Blanknuten Member contains a condensed phosphorite horizon that underlies the discontinuous phosphatic shale unit. The overlying sideritic (purple-weathering) shales of the Tschermakfjellet Formation contain *Stolleyites tenuis* in the lower part of the succession (Korchinskaya, 1972a; Korčinskaja, 1972b, 1982; Dagys and Weitschat, 1993; Dagys *et al.*, 1993). In the

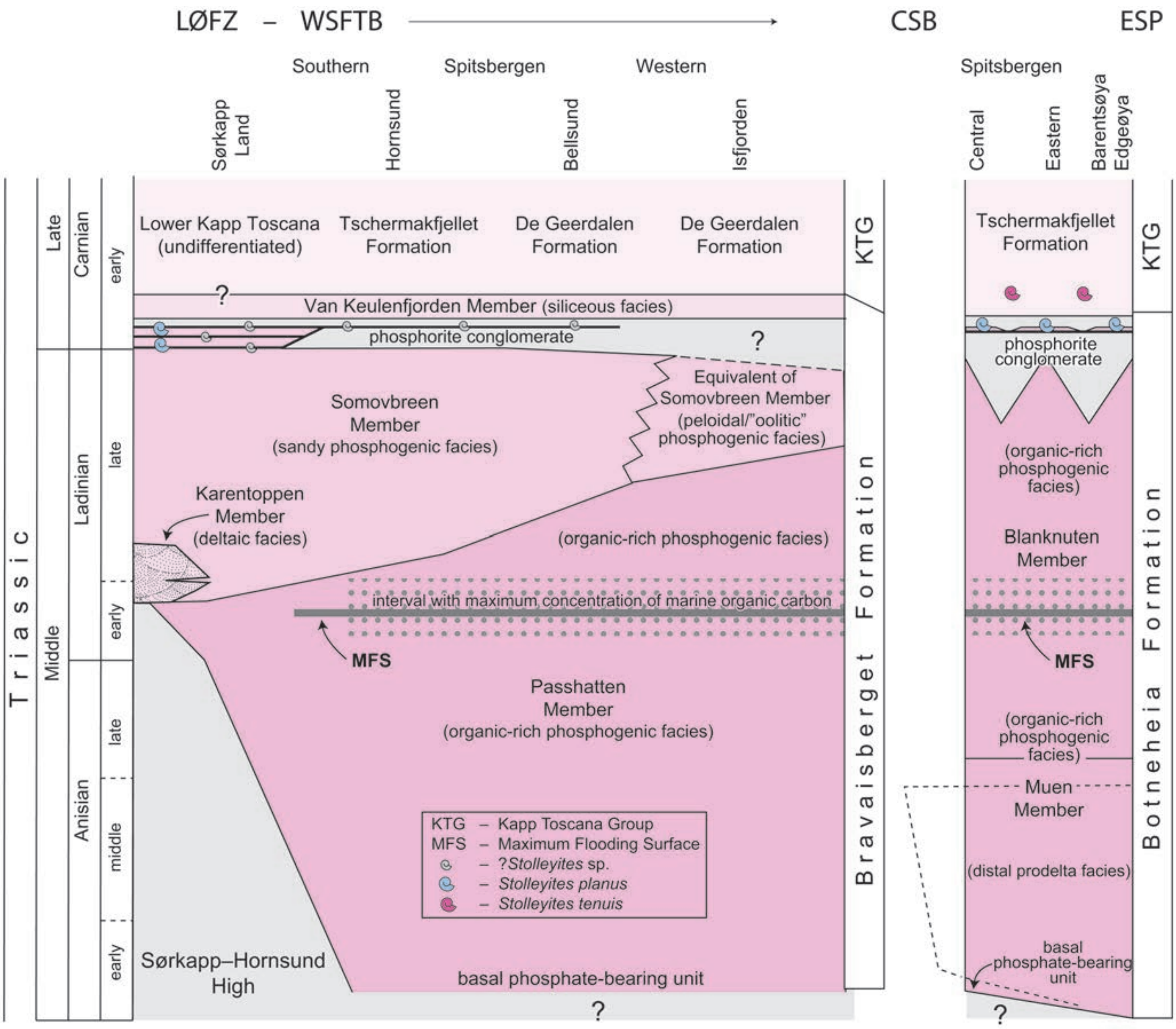


Fig. 14. Stratigraphic scheme of the Bravaisberget Formation of southern and western Spitsbergen and its suggested correlation with the Botneheia Formation of central and eastern Spitsbergen and eastern Svalbard. LØFZ – Lidfjellet-Øyrlandsodden Fold Zone; WSFTB – West Spitsbergen Fold-and-Thrust Belt; CSB – Central Spitsbergen Basin; ESP – Eastern Svalbard Platform (including central Spitsbergen). For further explanation, see text.

opinion of the authors, the classification of the thin phosphatic shale to the base of the Tschermakfjellet Formation was a consequence of failure to discriminate between the Botneheia and Tschermakfjellet shales in the boundary interval, which at many places is complicated, owing to listric faulting and décollement structures (Hounslow *et al.*, 2007, 2008). Microscopic and geochemical investigations indicate that this shale has characteristics typical of the Botneheia shales, i.e. it contains large amounts of marine organic matter (up to 11 wt.% total organic carbon – TOC) and *Tasmanites* algae (kerogen type II/I), phosphate nodules, phosphatic fossil moulds, and authigenic pyrite; and it lacks siderite concretions and cement (Krajewski, 2008, 2013). X-ray diffraction of a *Stolleyites planus* collected from this shale at Roslagenfjellet in Agardhbukta (eastern Spitsbergen) indicates that carbonate fluo- rapatite is the dominant mineral phase of the fossil mould. This contrasts with the low organic content of the overlying shales of the Tschermakfjellet Formation (c. 1 wt.% TOC), which contain almost exclusively woody organic matter (kerogen type III), siderite cement, concretions, and fossil moulds; and are very poor in authigenic pyrite and devoid of sedimentary phosphate. These findings are consistent with the recent investigations of Xu *et al.* (2014) who located the Ladinian-Carnian boundary in the uppermost part of the Botneheia Formation. Hence, the substantial hiatus suggested for the boundary between the Botneheia and Tschermakfjellet formations (Hounslow *et al.*, 2006a, b, 2007) should be located below the condensed phosphorite horizon in the uppermost part of the Botneheia Formation (Fig. 14). On southern Barentsøya and possibly at other places on the Eastern Svalbard Platform, the deposition of this horizon was preceded by an erosional event that removed a part of the cliff-forming succession (Krajewski, 2013). The changing position of the upper Ptychid Layer with *Aristoptychites*, *Ussurites* and *Daonella* (late Ladinian) in sections of the Blanknuten Member in central and eastern Spitsbergen (from 14 m to 2 m below the phosphorite conglomerate), and the presence of reworked moulds of *Aristoptychites* and *Ussurites* in the phosphorite conglomerate in Spitsbergen, on Edgeøya and southern Barentsøya indicate that the erosion/condensation was a regional event during termination of the phosphogenic environments in Svalbard (Köhler-Lopez and Lehmann, 1984; Weitschat and Dagys, 1989; Dagys *et al.*, 1993; Krajewski and Weitschat, unpubl. ms.).

The data presented above suggest that the uppermost interval of the Somovbreen Member of the Bravaisberget Formation in south-western Sørkapp Land, which grades into the condensed phosphorite horizon in the remainder of southern and western Spitsbergen, can be correlated with the condensed phosphorite horizon and the associated phosphatic shale at the top of the Blanknuten Member of the Botneheia Formation in central and eastern Svalbard (Fig. 14). These deposits represent the youngest phosphogenic environments in Svalbard that are already of the earliest Carnian age. Hence, the Van Keulenfjorden Member that overlies the Somovbreen Member in southern and western Spitsbergen should be considered to be Carnian in age. It represents clastic sedimentation in marginal- to shallow-marine environments that were characterized by the abundance of siliceous sponges and by the lack of either phosphate or siderite authigenesis. The deposition of the member seems to have been confined to a part of the early Carnian. It included a time period corresponding to the hiatus between the topmost part of the Botneheia Formation (phosphogenic marine facies of the S. planus Subzone) and the lowermost part of the Tschermakfjellet Formation (sideritic prodelta facies of the S. tenuis Subzone) in central and eastern Svalbard. However, on the basis on available palaeontological data (Pčelina, 1967; 1983, 1985, 1996; Korčinskaja, 1972b, 1982) the exact time of termination of deposition of the Van Keulenfjorden Member is difficult to estimate.

CONCLUSIONS

1. The Bravaisberget Formation of southern Spitsbergen (Middle Triassic–Carnian) represents a marginal part of the organic-rich, phosphogenic depositional system that developed in Svalbard in response to an event of high biological productivity on the Barents Shelf. The basin margin was bounded on the southwest by the Sørkapp-Hornsund High, a positive tectonic structure that marked the border of an emergent area located further southwest. North of the high, the subsiding shelf bottom stretched from southern to western Spitsbergen.

2. The Bravaisberget Formation shows a general facies distribution and thickness changes that reflect a transgressive-regressive cycle over the marginal part of the basin. It forms a wedge of organic-rich deposits thinning toward the Sørkapp-Hornsund High, where they are replaced by marine and deltaic sandy facies. However, the detailed facies arrangement is complex, resulting from the interplay between regional processes on the Barents Shelf and local processes, related to tectonic activity along the basin margin and changing conditions in the shallow shelf environments.

3. The following stages of deposition of the Bravaisberget Formation can be discerned:

a) Organic-rich, dominantly fine-grained sedimentation of the Passhatten Member during the transgressive and high-stand phases of the Middle Triassic cycle. This sedimentation extended from western Spitsbergen southward after the Anisian transgression; it reached the topmost part of the Sørkapp-Hornsund High during maximum flooding of the shelf basin in early Ladinian. The supply of fine-grained clastics indicates a tectonically quiescent period of the adjacent land area. Phosphogenic conditions were common in the organic-rich environments and particularly intense on submarine silty-sandy bars that migrated between muddy depressions (Krajewski, 2000c; Krajewski *et al.*, 2007).

b) The sudden appearance of the deltaic deposits of the Karentoppen Member in Sørkapp Land directly after maximum flooding of the shelf basin. This was a consequence of short-lived event of tectonic activity in the south-western source area. Rapid uplift and erosion of this area brought about the input of coarse clastics to the basin margin through narrow delta outlets separated by rocky shores. The eroded substratum was dominated by acidic rocks and/or products of the sedimentary recycling of them. The mountainous landscape, at least in part, was covered by vegetation.

c) Shallow-marine redistribution of the deltaic clastics under suppressed sedimentation rates. Cessation of the deltaic activity and a regional regressive trend in the Barents Shelf in late Ladinian contributed to the reworking of the deltaic clastics into finer fractions and their redistribution in Spitsbergen. The sandstones and siltstones of the Somovbreen Member form a bulge that extended into the shelf basin for a distance of about 50 km. Low sedimentation rates contributed to the formation of glauconite grains, common bioturbation of the sediment, and widespread phosphogenesis. Outside the sandy/silty bulge, there were deposited phosphatic "oolitic" grainstones that required submarine hiatal conditions and recurrent reworking/winnowing of the seabed.

d) Basinward condensation during termination of the deposition of sandy/silty phosphogenic facies of the Somovbreen Member at the Middle-Late Triassic boundary. These environments seem to reflect fluctuating sea-level during a tectonically quiescent period close to the end of the regressive phase. Recurrent flooding of the basin margin affected phosphogenic episodes that contributed to the formation of phosphate-bearing horizons in the coastal environments of south-western Sørkapp Land. They were separated by regressive events that provided clastic supply to the coastal environments, though intense submarine reworking and/or erosion dominated in areas remote from the shore.

e) An event of siliciclastic and spiculitic deposition of the Van Keulenfjorden Member. This event reflects peculiar conditions that developed along the basin margin during the early Carnian. It resulted in the formation of a continuous clastic horizon in southern and western Spitsbergen that shows the abundance of siliceous sponges and common traces of early diagenetic silicification of the sediment. The facies development indicates shallow- to marginal-marine environments. This unit is missing in the remainder of Svalbard; it is not recognized in other parts of the Triassic Barents Shelf.

3. At least two correlation horizons between the Bravaisberget and Botneheia formations can be suggested (Fig. 14):

a) Tracking a horizon with maximum concentration of marine organic carbon in the fine-grained facies of the Passhatten and Blanknuten members would help to reveal the position of the maximum flooding surface during the Middle Triassic transgressive-regressive cycle. Its suggested location is in the middle part of the Blanknuten Member in eastern Svalbard and central Spitsbergen and in the upper part of the Passhatten Member in western Spitsbergen.

b) The facies and palaeontological data indicate stratigraphic correlation of the condensed phosphorite conglomerates at the top of the sandy phosphogenic facies of the Bravaisberget Formation (top of the Somovbreen Member) and at the top of the muddy phosphogenic facies of the Botneheia Formation (top of the Blanknuten Member). With the exception of south-western Sørkapp Land, these horizons were associated with a substantial hiatus in the phosphogenic environments that reflected complex non-depositional/erosional processes during the regressive phase of the cycle. On the main islands of Svalbard, the condensed horizons are of earliest Carnian age.

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