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# PHOSPHORITE-BEARING SEQUENCE OF THE WILHELMÖYA FORMATION AT HORNSUND AND ALONG WESTERN COAST OF SÖRKAPP LAND, SPITSBERGEN[2]

(Figs 1–6; Pls I–XIII)

ABSTRACT. The Smalegga Member (Lower-Middle Jurassic) of the Wilhelmöya Formation at Hornsund and in western Sörkapp Land is represented by a marginal to shallow marine clastic sequence containing recurrent phosphorite horizons. The member was deposited as a result of starved coastal facies development and intervening transgressive episodes in the western margin of the Early Jurassic Svalbard seaway. Phosphorite deposition was associated with transgressive episodes and appeared over the southern Spitsbergen area in a series of events. It is inferred that enhanced phosphorus flux to the environment was reinforced by ascending of phosphorus-enriched deeper shelf waters from an open marine basin connecting the Svalbard seaway. The nature of sedimentary to diagenetic processes contributing to the sequence development as well as published paleontological datings allow to classify the Smalegga Member as a facies equivalent of the phosphorite-bearing Brentskardhaugen Bed of central Spitsbergen.

## INTRODUCTION

The Wilhelmöya Formation (Rhaetian-Middle Jurassic) in southern Spitsbergen is represented by a thin sequence of phosphorite-bearing quartzitic sandstones overlying deltaic deposits of the De Geerdalen Formation. This

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sequence is defined as the Smalegga Member and it shows fairly uniform development in Sörkapp Land and south-western Torell Land (Mörk *et al.*, 1982). It is accepted that this member was deposited in a shallow to marginal marine starved environment in response to transgressive episodes developed onto the abandoned deltaic system of the western land area (Steel & Worsley, 1984 and references therein). However, the nature of this environment and the sedimentary to diagenetic processes leading to phosphate concentration in the sequence are up to now poorly understood.

The objective of this study was to investigate phosphorite-bearing units of the Wilhelmöya Formation in southern Spitsbergen in an attempt to clarify their facies position, genesis, and paleoenvironmental significance. The present paper contains results of geological research carried out in the Hornsund area and the western coast of Sörkapp Land.

## GEOLOGICAL SETTING

The sedimentary sequence attributed to the Wilhelmöya Formation in southern Spitsbergen can be traced in NW-SE trending Alpine orogenic belt (Birkenmajer, 1972; 1981). In the study area, it stretches out from the interior of Torell Land (Różycki, 1959), across the inner part of Hornsund (Birkenmajer, 1960; 1964; 1975; 1977), into north-eastern Sörkapp Land (Worsley & Mörk, 1978). Strong tectonic deformations and highly glaciated area make the exposures of the Wilhelmöya Formation poor and isolated. Limited occurrences of the formation are also known from the western coast of Sörkapp Land (El-Kammar & Nysaether, 1980; Bäckström & Nagy, 1985) and the Kistefjellet-Keilhaufjellet massif in southernmost Spitsbergen (the latter not included in this paper). These are confined to a few mountain tops and tectonized coastal bedrock exposures.

Eight sections of the Wilhelmöya Formation have been studied in southern Spitsbergen (Fig. 1*A*, *B*). They are referred to as sections 1 to 8 in the present paper and occur in two parallel exposure belts. The sections 1 – 5 are located in the Triassic-Jurassic belt of inner Hornsund (Fig. 2*A*); the remaining ones are located in the western coast of Sörkapp Land (Fig. 2*B*); Detailed locations of the sections are as follows: (1) southern slope of Braemfjellet above Kvalfangarbreen; (2) eastern crest of Triasnuten above Wibeskardet; (3) eastern crest of Hyrnefjellet east of point 627; (4) eastern coastal exposures at Treskelodden; (5) north-western crest of Smalegga above Bautabreen; (6) gully in the north-western slope of Lidfjellet and northern tributary creek of Liddalen; (7) skerries at Röysneset; and (8) topmost crags and plateau on Karentoppen. It should be noted that the uppermost part of the Wilhelmöya Formation at Treskelodden and the whole sequence at Röysneset are accessible during extremely low tides only.

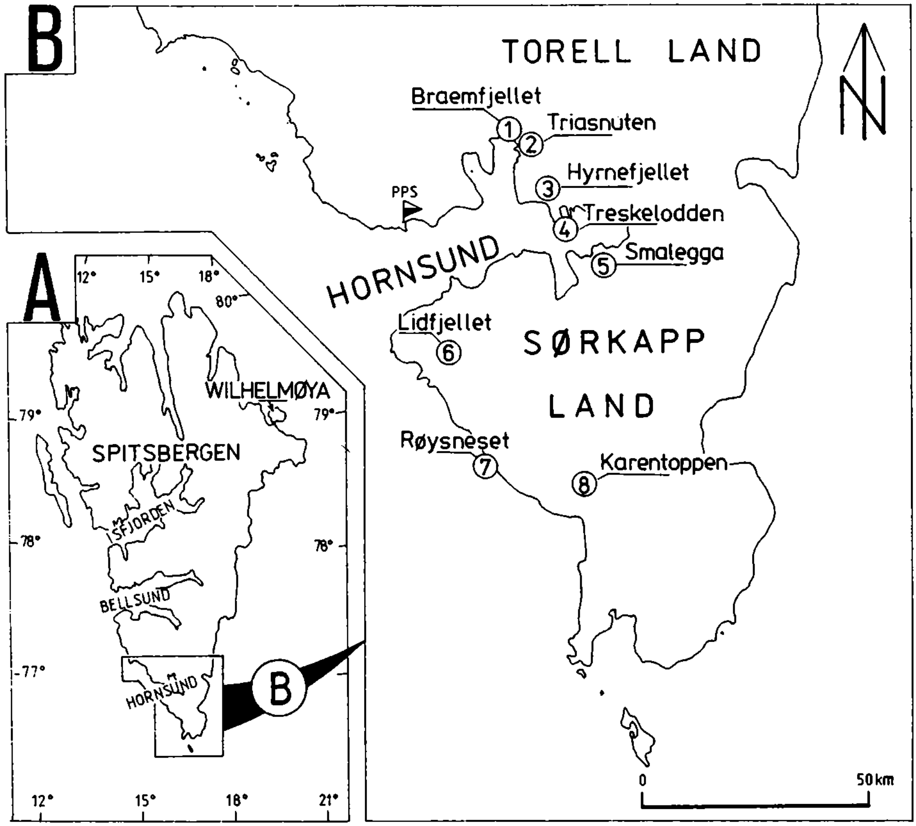



Fig. 1. *A*. Sketch-map of Spitsbergen and location of Hornsund and Sörkapp Land (*B*) *B*. Map of southern Spitsbergen showing locations of the profiles studied in the Hornsund area (*1–5*) and western coast of Sörkapp Land (*6–8*)

*PPS* – Polish Polar Station at Isbjörnhamma

## FACIES CHARACTERISTICS

The Wilhelmöya Formation in the Hornsund area and in the western coast of Sörkapp Land is represented by a sequence of sandy coastal deposits showing thickness variation from 12 up to 30 metres (Fig. 2*A*, *B*). This sequence can be divided into five sub-facies: (*i*) major sandstone, (*ii*) sandstone/shale, (*iii*) conglomeratic sandstone/conglomerate, (*iv*) stromatolite/oncolite, and (*v*) phosphorite. The former three sub-facies reflect spatial and temporal differentiation of the shore-zone depositional system. The stromatolite/oncolite sub-facies is poorly developed in the study area, but usually it is associated with conglomeratic units. The phosphorite overlaps the shore-zone sediments regardless of their original facies differentiation and pattern. It forms several horizons in the sandy sequence and also occurs in the form of reworked components within individual coastal sedimentary units.

The characteristics of the sub-facies of the Wilhelmöya sequence can be summarized as follows:

(*i*) The major sandstone is the most common sediment variety in the Wilhelmöya sequence (Pl. I*A*). This is medium to coarse-grained massive, parallel-, and ripple-laminated quartzitic sandstone with occasional cross-bedded units. Marine trace fossils *Arenicolites, Monocraterion,* and *Teichichnus* as well as scattered wood fragments and trunks are frequently found in this sandstone (Pl. I*B*; II*A*). Phosphate nodules, if present, are usually confined to discrete horizons associated with omission surfaces (Pl. I*C*). Truncation surfaces covered by fine gravel or gravelly sandstone also occur in the sandstone sequence. This sub-facies is indicative of the shoreface depositional regime with strong wave and current interactions with the sandy bottom and recurrent storm event sedimentation. The prominent maturity of the sandy sediment and the originally well- to very well-rounded quartz grains suggest low sedimentation rates and frequent reworking. Thicker sequences of the major sandstone reflect a number of shoreface depositional episodes associated with partial to ultimate destruction of formerly deposited sandy beds. A horizon of rhizoliths in the upper sandstone sequence at Treskelodden (Pl. II, *B*), and presumably also some truncation surfaces at Röysneset indicate subaerial interludes during the deposition of this sub-facies;

(*ii*) The sandstone/shale subfacies is composed of medium to fine-grained sandstone beds 1 – 15 cm thick alternating in various proportions with silty shale (Pl. III, *A*). A range of sequences of the sandstone/shale is observed in the study area, from thicker sandstone beds separated by thin (0.5 – 1 cm) shale intercalations to nearly pure shaly units 0.5 – 1 m in thickness. The sandstone beds are bioturbated with dominant *Diplocraterion*, and they contain dispersed plant debris and changing amounts of silt material (Pl. III, *B*). The silty shale is dark grey to black owing to content of disseminated organic matter of undoubtedly terrestrial origin (mature to overmature kerogen type III and kerogen type IV, Polish Polar Research Programme, unpublished data). Rare bands of sideritized sediment occur within thicker shaly units (e.g., at Hyrnefjellet). The sandstone/shale sub-facies represents transitional zone from the shoreface to offshore environments. It was deposited below the normal wave base under conditions of slow sedimentation and negligible sediment supply from the shore-zone. Individual sandstone beds indicate abrupt contribution of sediment, probably by settling of sand clouds suspended by storm waves, followed by reduction in flow energy and prolonged reworking by organisms. Fair weather intervals were represented by fine-grained sedimentation and increased settlement of minute particles of coast-derived organic matter. Shallow burial diagenesis of organic matter led to the accidental sideritization of shaly interbeds;

(*iii*) The conglomeratic sub-facies encompasses interbeds of thin-bedded sandstone with gravel admixture, conglomeratic sandstone, and conglomerate (pl. IV, *A*). These interbeds are most common in the Karentoppen section,

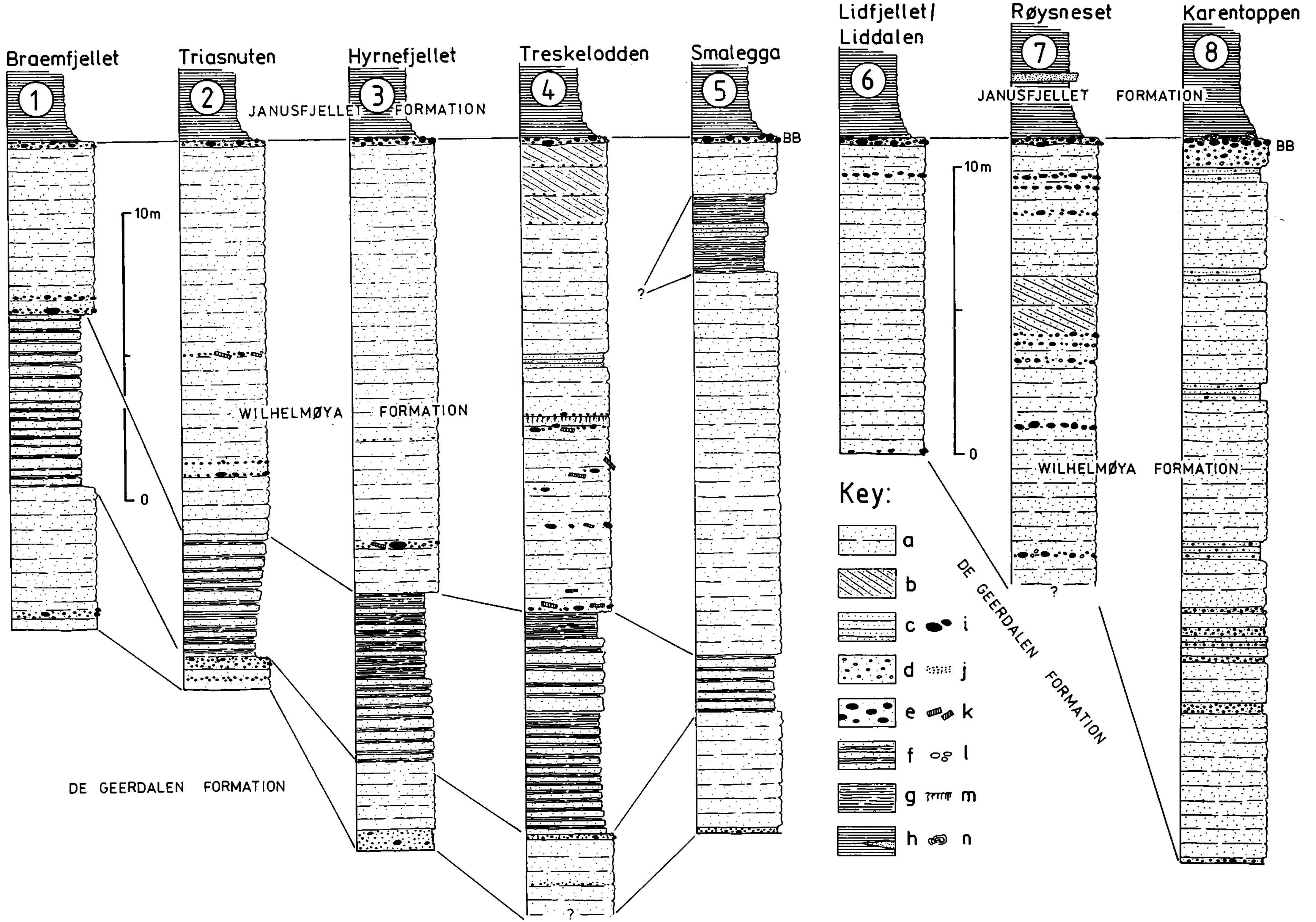



Fig. 2. Profiles of the Wilhelmöya Formation in the Hornsund area (*A*) and along the western coast of Sörkapp Land (*B*)

*BB* – Brentskardhaugen Bed of southern Spitsbergen. For location of the profiles – see Fig. 1. *B*; *a* – major sandstone (massive, parallel- and ripple-laminated quartzitic sandstone with common bioturbations); *b* – major sandstone (cross-bedded units); *c* – conglomeratic subfacies (thin-bedded sandstone with gravel admixture); *d* – conglomeratic subfacies (polymictic conglomerate and conglomeratic sandstone); *e* – phosphorite subfacies (sandy, conglomeratic, and silty phosphatic nodules, and microsporite clasts concentrated in layers, horizons, and conglomeratic beds); *f* – sandstone/shale subfacies (alternating fine-grained sandstone and silty shale); *g* – sandstone/shale subfacies (silty shale enriched in terrigenous organic matter); *h* – black shale with rare sandstone beds of the Janusfjellet Formation; *i* – phosphate nodules; *j* – *phosphoclasts;* *k* – large wood fragments; *l* – pebbles of quartz, quartzite, chert, and silicified limestone; *m* – rhizoliths; *n* – oncoids becoming thin and irregular in the remaining part of the study area. The sandstone shows planar lamination with low-angle discordances accentuated by gravelly layers. It contains lenses and sheets of coquinoid bivalve accumulations (Pl. IV, *B*), but neither trace fossils nor bioturbations have been noted. The sandstone interbeds grade laterally into conglomeratic horizons. The latter are composed of diverse rock fragments among which quartz, quartzite, chert, and silicified limestone predominate (Pl. V, *A*). Redeposited solitary corals from the Upper Palaeozoic rock sequence also occur at some levels (Pl. V, *C*). The gravelly components are preserved at various stages of coastal reworking and encompass both discoidal and equant pebbles. Some of the discoidal pebbles show external zones severely altered and ferruginized due to subaerial weathering prior to their final deposition (Pl.V, *B*). The conglomeratic sub-facies is indicative of the upper shoreface to foreshore depositional environment reinforced by coarse sediment supply from coastal bedrock exposures of Upper Palaeozoic and Precambrian formations;

(*iv*) The stromatolite/oncolite sub-facies is known from reworked pebbles and rock fragments occurring in the conglomeratic beds and layers. The only exception is the topmost part of the Wilhelmöya sequence on Karentoppen where oncoids form irregular bed at the base of the Janusfjellet black shale (Pl. VI, *A*). The structure and fabric of stromatolite and oncoid fragments are strikingly similar to the *in situ* preserved stromatolite crusts known from the Wilhelmöya Formation in Van Keulenfjorden (Krajewski, 1991a). By comparison with that area, it could be suggested that the microbial structures proliferated in some parts of the shoreface upon pebbly tongues redeposited from the swash zone. However, prolonged periods of non-deposition were necessary to establish conditions favourable for microbial mat proliferation and its preservation in the form of stromatolites and oncoids. These structures underwent subsequent destruction in the high-energy coastal environment and were reworked, and then incorporated, into the conglomeratic sub-facies:

(*v*) The phosphorite sub-facies is represented by a range of phosphatic components which are concentrated in individual beds and discrete horizons. Although up to twelve superimposed phosphorite horizons occur in the Wilhelmöya sequence in southern Spitsbergen, only two of them tend to be continuous. These are usually found in the lower part and at the top of the Wilhelmöya sequence. The upper horizon is ascribed to the Brentskardhaugen Bed in the lithostratigraphic scheme of southern Spitsbergen (Birkenmajer, 1975; 1977; Worsley & Mörk, 1978). The horizons occurring in the middle part of the sequence are more or less reworked into the coastal deposits. They are laterally discontinuous, intermixed with the conglomeratic sub-facies and/or represent scattered nodules in the major sandstone.

The phosphatic components of the phosphorite sub-facies encompass a large variety of nodular bodies, clasts, and grains accompanied by phosphatized biogenic remnants (Pl. VI, *B-D*). However, all these components contain x-ray uniform phosphate mineral which is carbonate fluorapatite

(CFA) with F values ranging from 1.1 up to 2.0%. Petrographic analysis reveals that the phosphate is sub- to microcrystalline CFA resulting from partial to ultimate recrystallization of the original botryoidal and globular phosphate matter (Pl. VII, *A-C*). Depending upon the nature of phosphatic components, the CFA occurs as inter- and intra-particle cement, microsphorite (phosphate mudstone), and replacement structures in carbonate clasts. The CFA also replaces the original hydroxyapatite of vertebrate bones, and organic-carbon cellular walls in wood fragments (Pl. VI, *B, C*).

The phosphate nodules are represented by conglomeratic, sandy, and silty bodies which reflect early phosphate diagenesis of several different sediment types (Pls VIII, *A*, *B*; IX; X *A*). The sandy nodules definitely predominate in the Wilhelmöya sequence. They are cemented by rim to void-filling CFA cement and are fossiliferous as a rule. The clasts of microsphorite are the second most common component of the phosphorite sub-facies (Pls X, *B*; XI, *A*, *B*). The microsphorite is a compact phosphate mudstone containing admixtures of disseminated clay minerals (mostly illite) and quartz grains in fine to coarse silt fraction. The clasts form individual beds, mainly in the lower part of the sequence, and/or occur as added components within coarse grained phosphorite horizons. Other phosphatic components, including phosphatic faecal pellets, ooids, arenaceous foraminiferal tests with CFA-filled chambers, bio--phosphomicritized biogenic particles, and replaced wood and bone fragments, are far less important. These usually are incorporated into larger nodules and clasts and only episodically occur as individual phosphate grains and their accumulations.

The content of phosphorus pentoxide in the phosphatic components fluctuates from 4 to 35% owing to changing capacity of the original and secondary porosity and the advancement of CFA cementation/replacement processes. It is evidently the highest in the replaced wood and bone fragments (27–35% $P_2O_5$) and clasts made of microsphorite (21–28% $P_2O_5$). Conglomeratic nodules show wide variation in the phosphorus content but usually they contain 4–9% $P_2O_5$. The most common sandy nodules are characterized by intermediate values averaging at 15% $P_2O_5$. It should be pointed out that the above values represent concentration grades of separated phosphorite fraction. The phosphorus values of total rock samples derived from the phosphorite horizons (feed grade) are lower and vary between 2 and 12% $P_2O_5$.

The lower phosphorite of the Wilhelmöya Formation is a polymictic conglomeratic bed 0.2–0.7 m thick (Pl. X, *B*). It either directly overlies sandy to shaly units of the De Geerdalen Formation or occurs upon a thin and discontinuous sequence of the major sandstone. The conglomerate is composed of both phosphatic and non-phosphatic grains occurring in coarse sand to fine gravel fraction, which are cemented by fine sand and silt. The phosphatic components are represented by clasts of microsphorite and occasional silty and sandy nodules or their reworked fragments. The non-phosphatic components encompass sandstone and siltstone clasts, and quartz, quartzite, and chert pebbles. The sandstone/siltstone clasts represent reworked fragments of impure and poorly sorted sandstones and sandy siltstones containing dispersed feldspar and illite, which undoubtedly were derived from the underlying deltaic succession of the De Geerdalen Formation. However, some of these clasts underwent subsequent phosphatization and cementation of secondary and/or rudimentary porosity. The phosphorite bed is bioturbated as a rule with burrows filled with mature quartz sand of the overlying major sandstone. The bed is in places heavily altered due to late diagenetic calcitization.

The uppermost phosphorite bed of the Wilhelmöya Formation (Brentskardhaugen Bed) is 0.2 – 1.2 m thick and is usually composed of coarse gravel fraction (Pl. X, *A*). Pebbles of quartz, quartzite, chert, and silicified limestone are intermixed in various proportions with sandy phosphate nodules. The matrix of the bed consists of medium to coarse sandstone with minor admixture of finer sediment fractions. The phosphorite overlies a clear-cut non-deposition surface at the top of the major sandstone. It is covered by the black shale facies of the Janusfjellet Formation. Thicker sequences of the Brentskardhaugen Bed show vertical fractionation of the gravelly components with quartz and rock pebbles dominating the middle part and phosphate nodules concentrated in the upper part and also at the bottom of the conglomerate. The fossils occurring in phosphate nodules include skeletons, moulds, and debris of ammonites, belemnites, pelecypods, brachiopods, gastropods, crinoids, and foraminiferal tests (see Kopik, 1968; Birkenmajer & Pugaczewska, 1975; Bäckström & Nagy, 1985). Paleoenvironmental context of the phosphorite sub-facies will be discussed later on in this paper.

## FACIES PATTERN

The facies of the Wilhelmöya Formation in southern Spitsbergen considerably integrate with one another forming complex vertical sequences of sandy coastal deposits. Isolated exposures in the Hornsund area and western coast of Sörkapp Land do not provide sufficient evidence to develop three-dimensional models of the sandstone bodies. Thus it is difficult to distinguish between the mainland and barrier island depositional sequences, although the latter could be ill-defined owing to reversed shoreline migration within starved coastal environment. However, a facies trend parallel to depositional strike, resulting in shore-parallel sediment bodies is characteristic. It is generally accepted that the major land area during Late Triassic-Early Jurassic was situated to the west of the western outcrop belt of Sörkapp Land (Birkenmajer, 1977; Steel & Worsley, 1984). Exposures in this belt contain almost exclusively shoreface sequences of the major sandstone. The location of the Karentoppen section in close proximity with high mainland coast can be suggested by common conglomerate interbeds set within the shoreface sequence. This sandy sequence splits into two horizons of the major sandstone separated by transitional facies in the inner Hornsund outcrop belt; this indicates increased contribution of offshore environments in the eastern portion of the area. A general transgressive-regressive facies development could be suggested on the basis of vertical sediment sequences. The detailed analysis, however, points to much more complex facies superpositions which reflect a number of coastal sedimentation episodes with interludes of non-deposition and reworking. At least three features of the facies pattern in this outcrop belt should be outlined. First, the lower horizon of the major sandstone is poorly preserved and discontinuous, resulting from the subsequent transgressive reworking. Secondly, the transitional facies shows wide lateral variation and it wedges out southeastwards in the study area (see also Worsley & Mörk, 1978). Thirdly, the overlying upper sandstone encompasses several depositional units with point to sand-bar development at Treskelodden.

## STAGES OF PHOSPHORITE FORMATION

The superimposed phosphorite horizons in the Wilhelmöya sequence yield sufficient evidence to reconstruct processes leading to phosphate concentration within the coastal depositional system of southern Spitsbergen. From the facies development and pattern it seems clear that phosphorite deposition was associated with a series of events which interrupted the starved coastal sedimentation and introduced temporary non-deposition conditions. Equalization of environmental conditions during the formation of phosphorite and general lack of conformity between coastal facies under- and overlying phosphorite horizons suggest a regional extent of the phosphoritzation events. The mechanism proposed in this paper involves changes in sea-level to explain the cyclicity of phosphorite formation and coastal facies development, with maximum phosphate concentration during high sea-level stands. Each phosphoritization event, however, consisted of a succession of stages which provided varying feedback effects on one another, thus resulting in a variety of final burial sequences (Fig. 3).

The formation of omission surfaces always predated major phases of phosphate emplacement within the Wilhelmöya sequence. This process reflected inhibition of terrigenous sediment supply and general diminution of intensity of the shore-zone dynamic agents. Increased biological manifestation upon the omission surfaces is evidenced by local development of highly bioturbated horizons and molusc shell accumulations (Pl. XI, *C*). There are some lines of evidence suggesting that the original phosphate emplacement proceeded within a narrow subsurface zone regardless of compositional variations of coastal sediments (Pls XII, *A*, *B*; XIII *A*, *B*). Conglomeratic, sandy, and silty phosphate nodules and microsphorite clasts were formed within the conglomerate, major sandstone, and sandstone/shale sub-facies, respectively. Moreover, the phosphatization affected biogenic skeletal remains and wood fragments which frequently served as nucleation sites for the nodule

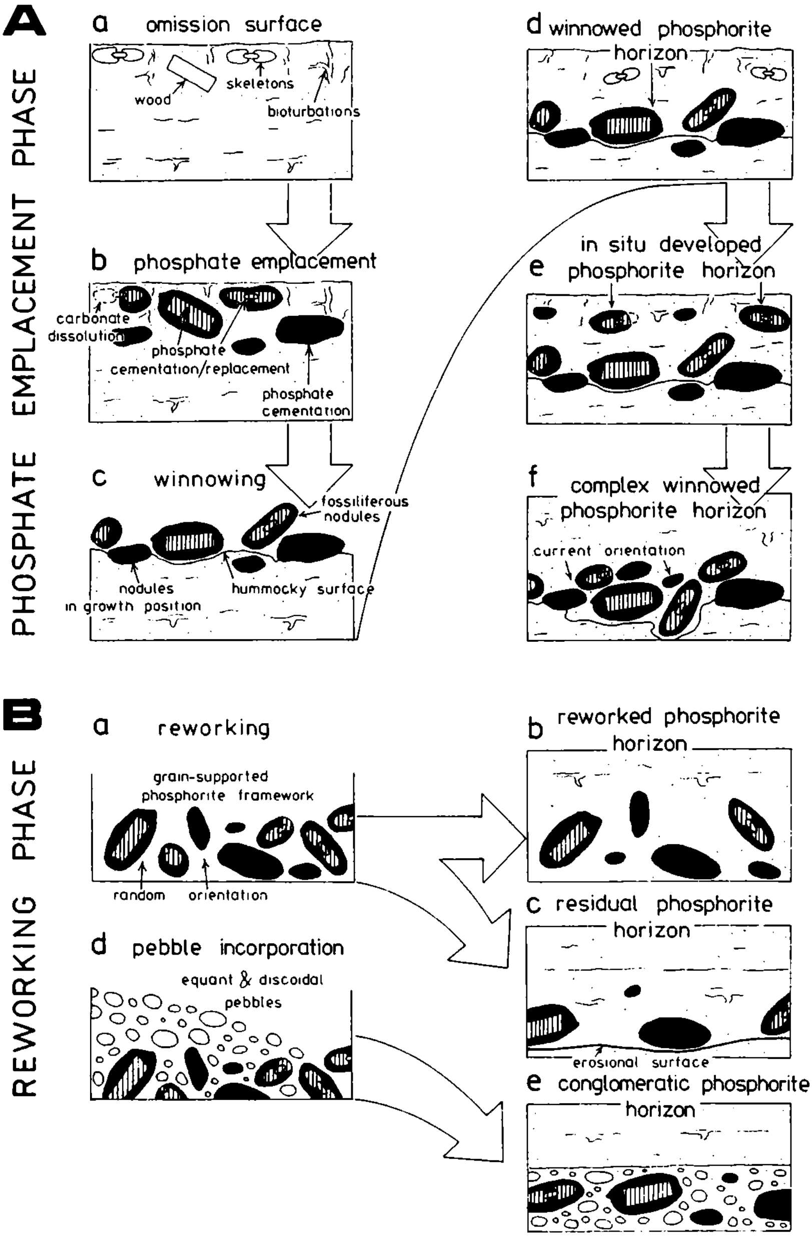



Fig. 3. Succession of stages associated with phosphate emplacement (*A*) and reworking (*B*) phases of phosphoritization events in the Wilhelmöya Formation of southern Spitsbergen. Phosphate structures and resultant phosphorite-bearing sequences shown in the scheme refer to phosphoritization processes proceeding in major sandstone subfacies

growth. Phosphate cementing rudimentary porosity of fragments of various lithologic units of the De Geerdalen Formation indicates lateral discontinuity of the coastal sediment prism during the phosphoritization events and partial seafloor exposure of the Upper Triassic substratum.

Phosphate emplacement within the Wilhelmöya sequence was always associated with simultaneous mechanical concentration of phosphorite fraction which led to the development of winnowed phosphorite horizons. Well-defined examples at Röysneset show recurrent rows of phosphate nodules preserved in growth position upon hummocky omission surfaces (Pl. XII, *A*, *B*). Advanced stages of this process brought about the ultimate winnowing of unconsolidated sand from between the nodules and phosphorite lag formation (Pl. I, *C*). Complex winnowed horizons contain several generations of phosphate cement in form of nodular to irregular zones which are separated by sediment winnowing and recurrent hummocky surface development (Pl. XIII, *B*). Reworking of the phosphorite fraction, on the other hand, was always associated with the destruction of original sequences containing *in situ* preserved and/or winnowed phosphate nodules. Depending upon the advancement of reworking processes, the phosphorite is either concentrated to form homogeneous framework of nodules and clasts in individual horizons (Pl. X, *A*, *B*), incorporated into conglomeratic beds, or scattered within the major sandstone (Pl. II, *A*). Reworked phosphorite horizons showing high phosphorus content are preferentially preserved in the lower and uppermost parts of the Wilhelmöya sequence in the inner Hornsund outcrop belt, owing to negligible diluting effect of subsequent coastal deposition. Phosphorite-bearing units in the middle part of the sequence usually contain relict nodules and clasts which passed through a series of episodes of coastal reworking.

## DISCUSSION

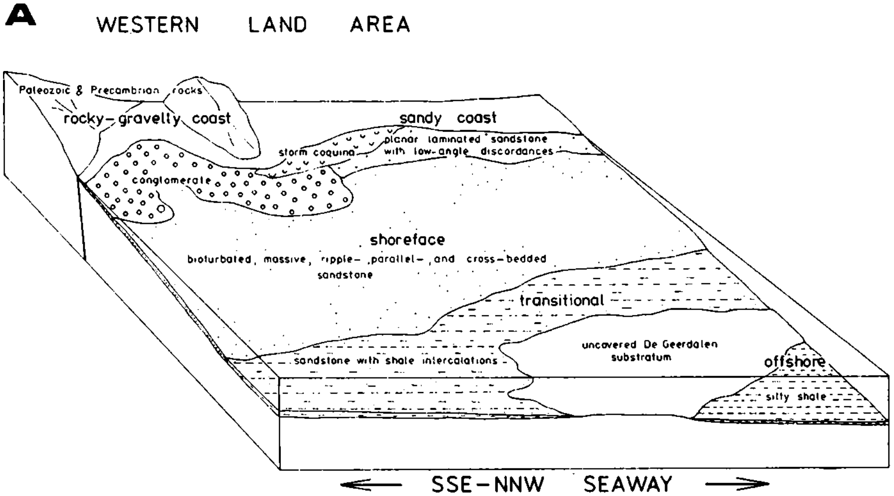
The approximation of facies and processes which contributed to the development of the Wilhelmöya sequence in southern Spitsbergen points to several geological inferences:

(1) The prominent contrast of depositional environment between the Wilhelmöya Formation and the underlying De Geerdalen Formation can be related to a general change in hydrographic regime of the western land area close to the Triassic/Jurassic boundary. Abandonment of fluvial depositional systems and delta outbuildings in western Spitsbergen enabled the development of starved coastal to shallow marine environments in Early Jurassic times (see also discussion in Pčelina, 1965, 1967, 1980 and Mörk *et al.*, 1982). Although infinitesimal terrigenous sediment supply to these environments and aridity of climate in the western land provided favourable conditions for indigenous marine mineral accumulations in the shelf area, the fact remains that the observed phosphate concentrations in the Wilhelmöya Formaton are low, and most high-grade horizons occur in extremely condesced sequences.

The chances are, therefore, that the environments capable of producing indigenous phosphorite accumulations developed rarely during the sequence deposition and appeared in the area following a series of regional events;

(2) There is ample and convincing evidence that the phosphoritization events consisted of two environmentally contrasted phases: (*i*) near-surface concentration of phosphate, and (*ii*) its wide reworking. These phases are paralleled on a general way with transgressive-regressive episodes developed upon the starved coastal depositional system (Fig. 4*A*-*C*). Temporary influence of open marine environment coupled with prolonged non-deposition intervals can be seen as crucial factors controlling phosphate concentration in the sequence. Permanent high-energy conditions resulting from subsequent shallowing of the environment explain extensive reworking which post-dated the major phase of phosphate emplacement. The relationship between transgres-

**A**

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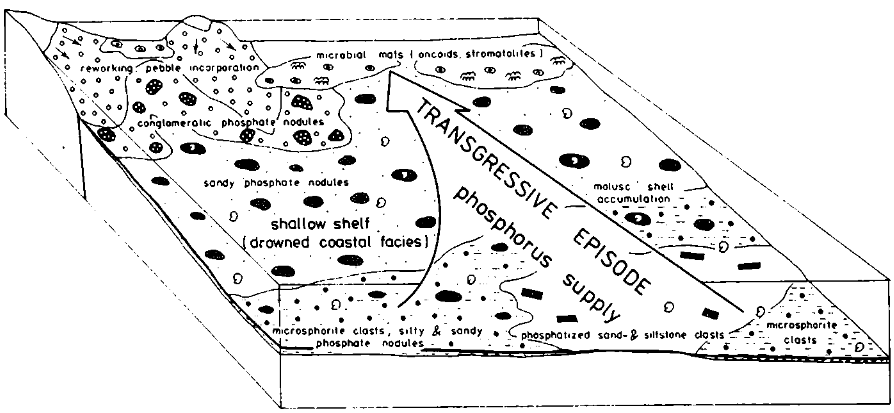

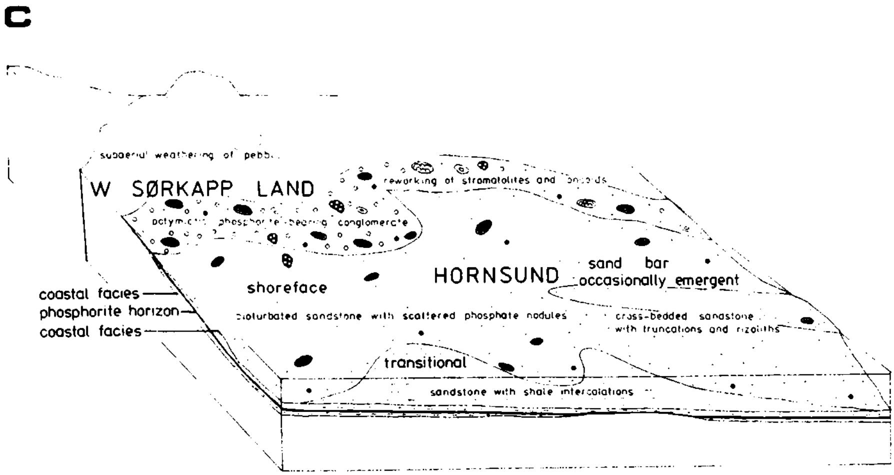


Fig. 4. Palaeonvironmental context of phosphorization events in the Wilhelmöya Formation of southern Spitsbergen. Starved coastal depositional system (*A*) is interrupted by transgressive episode which promotes regional phosphoritization of sediments (*B*). Reworking of phosphorite deposit and coastal facies differentiation are associated with subsequent sea-level fall (*C*)

sive episodes and phosphoritization events implies enhanced phosphorus flux into the environment during high sea-level stands, most probably as a result of ascending of phosphorus-enriched water masses from deeper shelf. It is unlikely, however, that the Early Jurassic narrow seaway in Svalbard (Steel & Worsley, 1984) developed phosphorus reservoir large enough to reinforce regional phosphoritization events. As yet no detailed palaeogeographic reconstructions of the Barents shelf Jurassic have been published, but the nature and extent of phosphoritization events in the Wilhelmöya Formation suggest a broad connection of the Svalbard seaway with open marine basin during the Early Jurassic times;

(3) Sedimentation of the Wilhelmöya sequence in southern Spitsbergen appears to have followed a cyclic pattern with recurrent transgressive episodes separated by regressive phases and intervening periods of coastal sandy facies development. At least four transgressive episodes may be suggested on the basis of burial sequence preservation (Fig. 5). Only two episodes (episodes *I* and *III* in Fig. 5) deposited well-defined phosphorite horizons which occur in the lower part and at the top of the sequence, respectively. The middle episode (*II*) has left less clear sequence with recurrent low-grade horizons. Phosphorite deposition in the area during the episode *IV* is disputable. However, the uppermost phosphate nodule row with oncoids and phosphate ooids at the top of the Brentskardhaugen Bed on Karentoppen might be linked with the onset of this episode;

(4) The nature of cyclic development of phosphoritization events in the sequence is strikingly similar to that one described from the Brentskardhaugen Bed in its type area of Sassenfjorden (Krajewski, 1991b). The latter sequence,

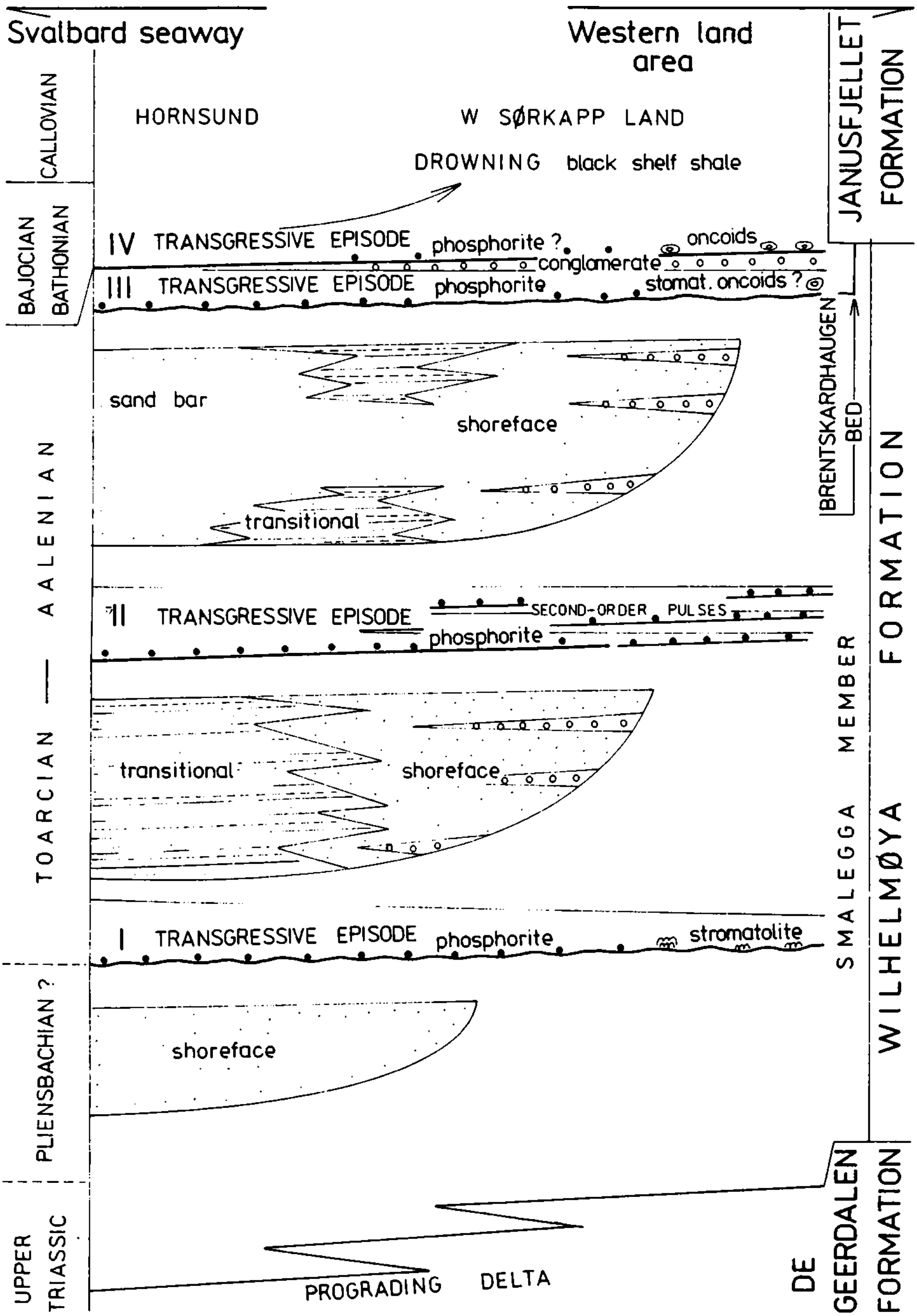


Fig. 5. Vertical facies changes of the Wilhelmöya Formation in southern Spitsbergen. The facies succession is indicative of recurrent transgressive episodes with phosphorite deposition developed onto starved coastal sedimentary system of the western margin of Early Jurassic Svalbard seaway

however, shows higher degree of condensation which led to intermixing or direct overlapping of phosphorite generations in a thin sandy-conglomeratic unit. This, in conjunction with the occurrence of Toarcian ammonite fauna in the lower phosphorite horizon in southernmost Sörkapp Land (Pčelina, 1980), and Toarcian-Aalenian and possibly Bajocian forms in the uppermost phosphorite horizon at Hornsund and in W Sörkapp Land (Brentskardhaugen Bed of southern Spitsbergen, Kopik, 1968; Birkenmajer & Pugaczewska, 1975; Bäckström & Nagy, 1985), suggest that the Smalegga Member of southern Spitsbergen could be considered *a facies equivalent* of the Brentskardhaugen Bed as defined in Sassenfjorden (Fig. 6; see also Wierzbowski *et al.*, 1981). The age of discontinuous unit of the major sandstone which occurs beneath the lower phosphorite horizon is not defined. By comparison with similar sandstone underlying the condensed phosphorite in Van Keulenfjorden, this unit could be of Pliensbachian age (see Krajewski, 1991a). The validity of tentative correlation shown in Figure 6 is open to dispute since the datings are scarce and somewhat conflicting between different localities. However, the interpretation accepted in this paper suggests that the Wilhelmöya Formation in southern Spitsbergen is represented almost exclusively by the Toarcian-Aalenian sedimentary sequence.

## CONCLUSIONS

The Smalegga Member of the Wilhelmöya Formation at Hornsund and in western Sörkapp Land is represented by marginal to shallow marine clastic sequence containing recurrent phosphorite horizons. It was deposited as a result of starved coastal facies development and intervening transgressive episodes in the western margin of the Early Jurassic seaway in Svalbard. The sequence is divided into five sub-facies: (*i*) major sandstone, (*ii*) conglomerate, (*iii*) sandstone/shale, (*iv*) stromatolite/oncolite, and phosphorite. The former three sub-facies reflect differentiation of coastal depositional system during low sea-level stands and they form sediment bodies which conform generally with shore-parallel alignment. Shoreface, transitional zone, and sand bar environments are considered essential in the deposition of conglomerate/sandstone/shale facies sequences. The phosphorite sub-facies and rare remnants of stromatolites and oncoids are associated with transgressive episodes which inundated the coastal facies and introduced temporary non-deposition conditions to southern Spitsbergen. Stromatolites and oncoids were restricted to shallow nearshore environments with conglomeratic tongues and sheets redeposited from the high-coast parts of the western land area. The phosphorite horizons are widespread, resulting from regional events of phosphoritization which affected the coastal facies regardless of their original differentiation and pattern. Phosphate emplacement within various types of coastal sediments and accumulated biogenic remnants led to the development of a range of fossiliferous nodules and clasts. The phosphorite fraction was

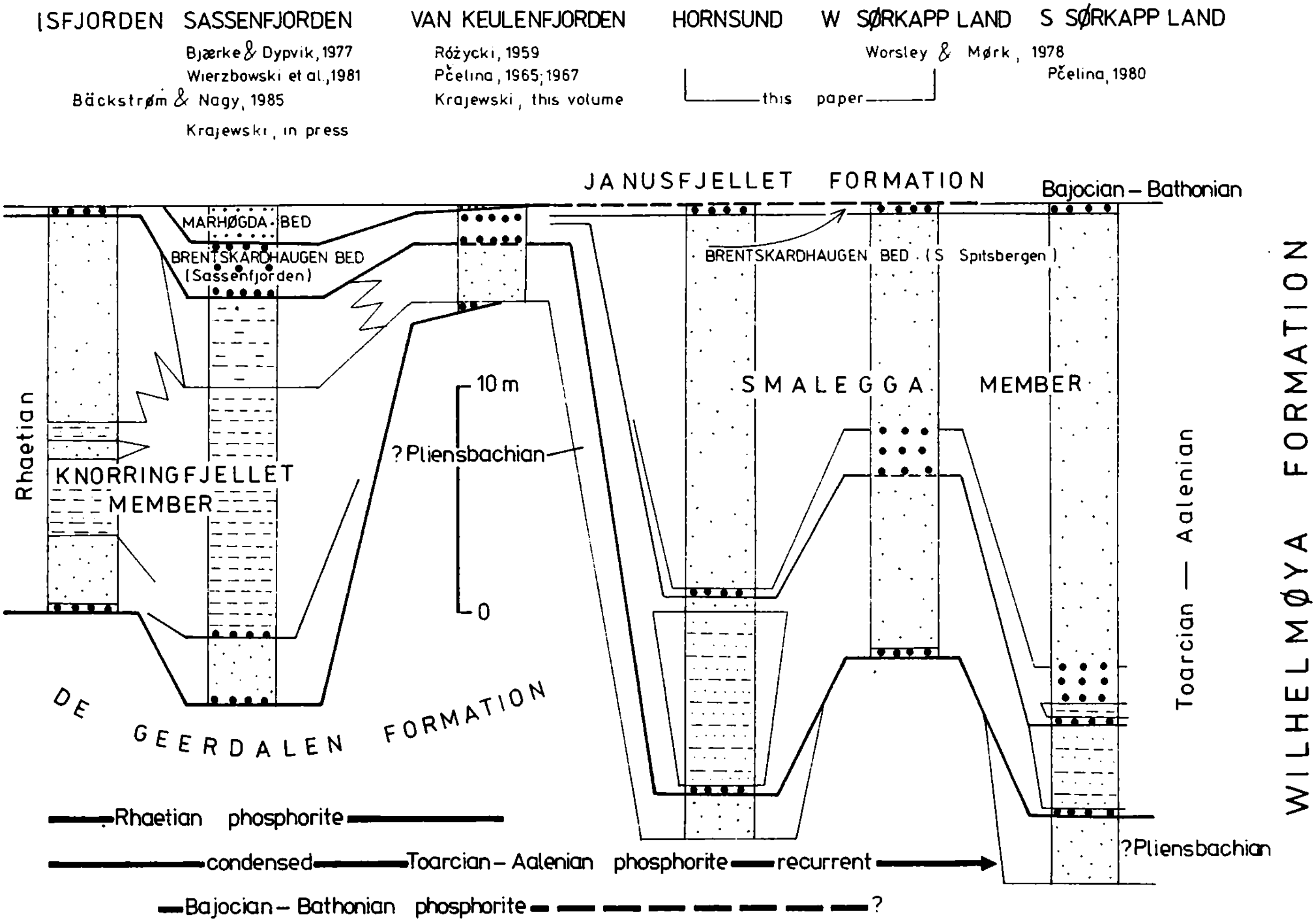


Fig. 6. Tentative correlation of sedimentary units of the Wilhelmöya Formation along western coast of Spitsbergen. The phosphorite-bearing Smalegga Member of southern Spitsbergen is considered to be facies equivalent of the Brentskardhaugen Bed in central Spitsbergen

concentrated due to winnowing process and was subsequently reworked into conglomeratic beds and major sandstone units. It is inferred that enhanced phosphorus flux to the environment during transgressive episodes was reinforced by ascending phosphorus-enriched deeper shelf waters from an open marine basin connecting the Svalbard seaway. At least four transgressive episodes contributed to the development of phosphorite-bearing units of the Smalegga Member. The upper two episodes were responsible for deposition of a well-known phosphorite marker horizon separating the Wilhelmöya from the overlying Janusfjellet Formation, which is ascribed to the Brentskardhaugen Bed in the lithostratigraphic scheme of southern Spitsbergen. The evidence presented in this paper supported by published palaeontologic datings suggest that this horizon is only a part of the Brentskardhaugen Bed defined in its type area in central Spitsbergen. It is proposed that the Smalegga Member is a facies equivalent of the latter bed in the southern Spitsbergen area.

## ACKNOWLEDGEMENTS

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*Krzysztof P. Krajewski*

## FOSFORYTONOŚNA SEKWENCJA FORMACJI Z WILHELMÖYA W REJONIE FIORDU HORNSUND I NA ZACHODNIM WYBRZEŻU SÖRKAPP LAND NA SPITSBERGENIE

Streszczenie

Formacja z Wilhelmöya w rejonie fiordu Hornsund oraz na zachodnim wybrzeżu Sörkapp Land na Spitsbergenie jest reprezentowana przez piaszczyste ogniwo ze Smalegga (dolna-środkowa jura) zawierające przewarstwienia i horyzonty fosforytowe. Ogniwo to zostało osadzone w przybrzeżnym środowisku morskim o niskim tempie sedymentacji, które było poddane wpływom powtarzających się epizodów transgresywnych. Sekwencje zbioturbowanych piaskowców kwarcytycznych, piaskowców zlepieńcowatych i zlepieńców oraz drobnoziarnistych piaskowców z przewarstwieniami łupków wzbogaconych w detrytus roślinny, odzwierciedlają zróżnicowanie przybrzeżnej strefy sedymentacji. Horyzonty i warstwy fosforytowe przykrywają przybrzeżne facje klastyczne niezależnie od ich pierwotnego zróżnicowania i zdają się być związane z powtarzającymi się epizodami transgresywnymi. W pracy jest wyrażone przypuszczenie, że nadmierna ilość fosforu niezbędna do powstania obserwowanych nagromadzeń fosforytu była dostarczana

z otwartego zbiornika morskiego w środowiska przybrzeżne za pomocą systemu prądów wstępujących. Nadmiar fosforu był systematycznie redukowany poprzez wytrącanie węglanowego fluoroapatytu w próżniach porowych kląstycznych osadów dennych, a powstałe w ten sposób konkrecje i klasty fosforytowe były koncentrowane na dnie morskim w wyniku wymiatania luźnego osadu. Co najmniej cztery epizody transgresywne przerywane okresami regresji i rozbudowy facji przybrzeżnych zaznaczyły się w trakcie sedymentacji ogniwa ze Smalegga. Cykliczność sedymentacji i współzależne występowanie generacji osadu fosforytowego oraz przegląd publikowanych oznaczeń paleontologicznych sugerują, że ogniwo ze Smalegga południowego Spitsbergenu jest facjalnym odpowiednikiem fosforytonośnej warstwy z Brentskardhaugen w centralnym Spitsbergenie.

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## EXPLANATIONS OF PLATES

### Plate I

*A* — Shoreface sequence of the Wilhelmöya Formation at Röysneset. The sequence is composed of major sandstone with recurrent horizons of sandy phosphate nodules

*B* — Bioturbated major sandstone with *Teichichnus* and *Monocraterion* from the Wilhelmöya sequence at Röysneset. Note intervals of strong biological reworking alternating with homogeneous sandy layers. Polished surface photograph

*C* — Winnowed horizon of sandy phosphate nodules occurring in the middle part of the Wilhelmöya sequence at Röysneset

### Plate II

*A* — Reworked sandy phosphate nodules (*p*) and a trunk fragment (*t*) in the upper major sandstone unit of the Wilhelmöya Formation at Treskelodden

*B* — Fragment of a horizon with rhizoliths (*r*) in the upper major sandstone unit at Treskelodden. Weathered surface photograph

### Plate III

*A* — A part of the Wilhelmöya sequence at Treskelodden showing the lower major sandstone unit (*ms*) overlain by the transitional sandstone/shale subfacies (*ss*). The boundary between the two units is accentuated by phosphorite conglomerate horizon (*pc*)

*B* — Fine-grained sandstone with dispersed plant detritus and *Diplocraterion* trace fossils from the sandstone/shale subfacies of the Wilhelmöya Formation at Treskelodden. Polished surface photograph

### Plate IV

*A* — Fragment of typical conglomeratic sequence occurring in the lower part of the Wilhelmöya

Formation at Karentoppen. The sequence is composed of alternating conglomerate layers and thin-bedded sandstone with gravel admixture. Polished surface photograph

*B* – Fragment of storm-like coquinoid accumulation of bivalve shells occurring in the form of elongate lens within the conglomeratic sequence on Karentoppen. Polished surface photograph

## Plate V

*A* – Polymictic conglomerate composed of quartz (*q*), quartzite (*qz*), chert (*ch*), and other rock pebbles, which occurs in the middle part of the Brentskardhaugen Bed on Karentoppen. Polished surface photograph

*B* – Discoidal pebble of silicified limestone from the Brentskardhaugen Bed on Karentoppen. External zone is severely altered (black) owing to subaerial weathering prior to the final pebble deposition. Thin section photograph

*C* – Silicified solitary coral occurring as a reworked pebble in the Brentskardhaugen Bed on Karentoppen. The coral shows ferruginization and leaching of inter-septal voids (black) followed by phosphatization of the remainder porosity (dark-grey). Thin section photograph

## Plate VI

*A* – Sideritized oncoid from the uppermost part of the Brentskardhaugen Bed on Karentoppen. The oncoid shows plotted fabric of microbial laminae and arenaceous tests of encrusting foraminifera. Thin section photograph

*B–D* – Sections across fossiliferous sandy phosphate nodules from the Brentskardhaugen Bed containing bone (*B*) and wood (*C*) fragments, and ammonite phragmocones (*D*). *B* – Lidfjellet; *C* – Karentoppen; *D* – Smalegga. Polished surface photographs

## Plate VII

*A* – Phosphate (*p*) in sandy nodule of the Brentskardhaugen Bed cements quartz grains (*q*) and forms incipient replacement structures in a shell debris (*r*). Botryoidal morphology of phosphate cement (*b*) is visible in incompletely cemented inter-particle pores

*B* – Microglobular nature of botryoidal phosphate cement. Note the original phosphate matter of microglobules recrystallized into minute aggregates of CFA crystals

*C* – Internal structure of phosphate microglobules showing radial recrystallization of apatite crystals

*A–C* – Hyrnefjellet; SEM photomicrographs of preparations after artifical removal of carbonate

## Plate VIII

*A* – Conglomeratic phosphate nodule from the middle phosphorite horizon on Braemfjellet composed of quartz pebbles (*q*) cemented by phosphate (*p*). Thin section photograph

*B* – Sandy phosphate nodule from the Brentskardhaugen Bed on Hyrnefjellet containing abundant phosphatized crinoid ossicles. Thin section photograph

## Plate IX

Sandy phosphate nodule from the Brentskardhaugen Bed on Smalegga containing phosphatized bivalves (*b*), gastropods (*g*), wood fragments (*w*), and dispersed shell debris. Thin section photograph

## Plate X

*A* – The uppermost phosphorite conglomerate (Brentskardhaugen Bed) of the Wilhelmöya Formation on Hyrnefjellet composed of sandy phosphate nodules and quartz pebbles set in sandy matrix. Polished surface photograph; sample by courtesy of Prof. K. Birkenmajer

*B* – The lowermost phosphorite conglomerate of the Wilhemöya Formation on Hyrnefjellet composed of phosphoclasts made up of microsphorite which are cemented by bioturbated sandy siltstone. Polished surface photograph

## Plate XI

*A*, *B* – Microsphorite clasts (black) in silty (*A*) and sandy (*B*) matrices of the lower phosphorite conglomerate of the Wilhelmöya Formation. *A* – Hyrnefjellet; *B* – Treskelodden. Thin section photographs

*C* – Fragment of highly bioturbated horizon underlying phosphorite conglomerate in the upper part of the Wilhelmöya Formation on Lidfjellet. Polished surface photograph

## Plate XII

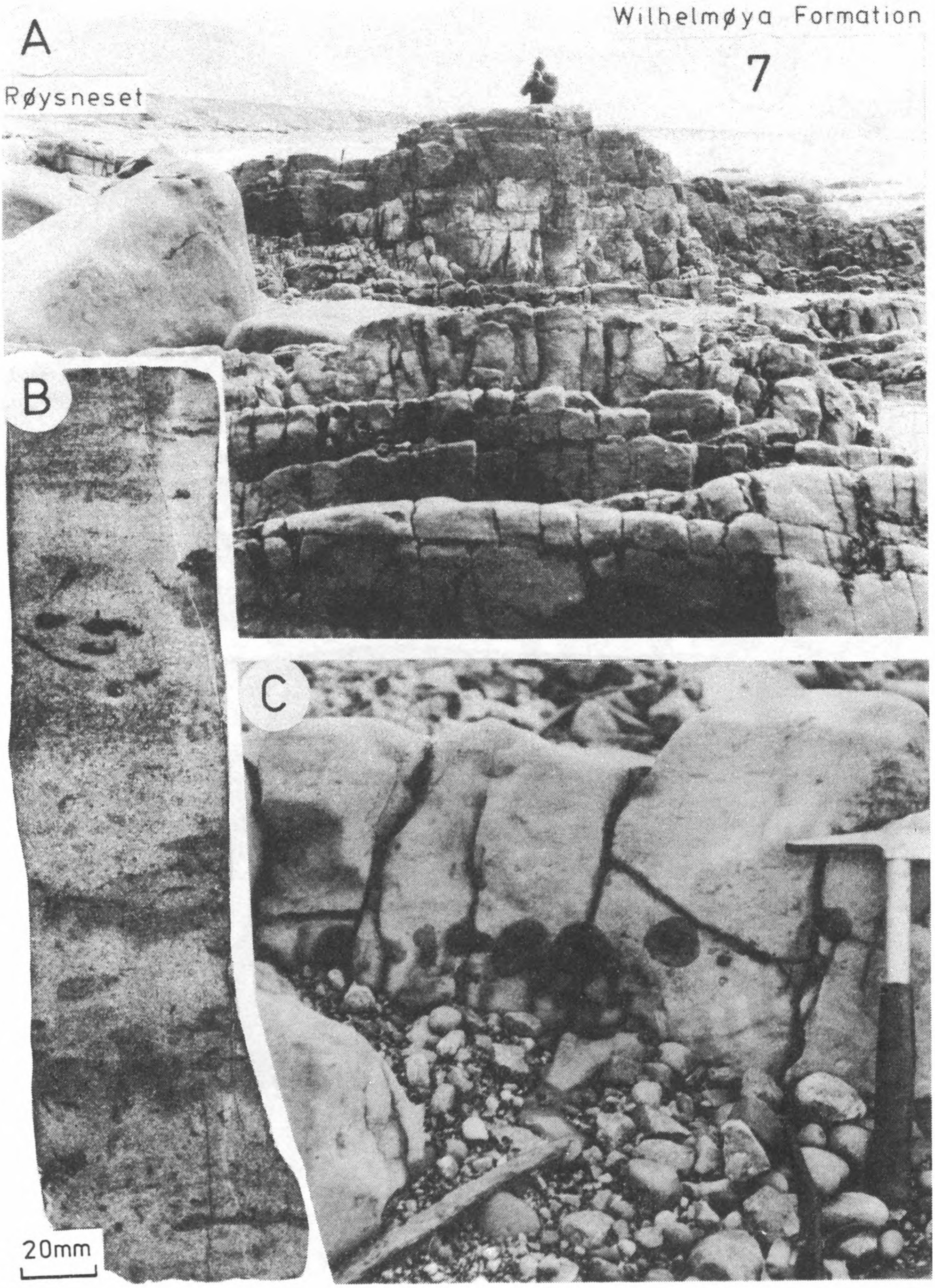
*A* – Phosphate nodules in growth position (arrowed) in winnowed phosphorite howizon of the Wilhelmöya Formation at Röysneset. Polished surface photograph

*B* – Phosphate nodules in growth position from the winnowed phosphorite horizon shown in *A*. Note intact lower boundaries of the nodules and the preferential preservation of biogenic remnants within nodular matrices. Upper parts of the nodules were synsedimentarily exposed due to winnowing of co-existing sandy sediment. Thin section photograph

## Plate XIII

*A* – Initial site of phosphate nodule growth (black) within sandy-conglomeratic bed of the Wilhelmöya Formation on Braemfjellet. Thin section photograph

*B* – Sequence of CFA cement generations (*p1*, *p2*, *p3*, and *p4*) separated by hummocky surfaces in complex winnowed phosphorite horizon of the Wilhelmöya Formation at Röysneset. Polished surface photograph

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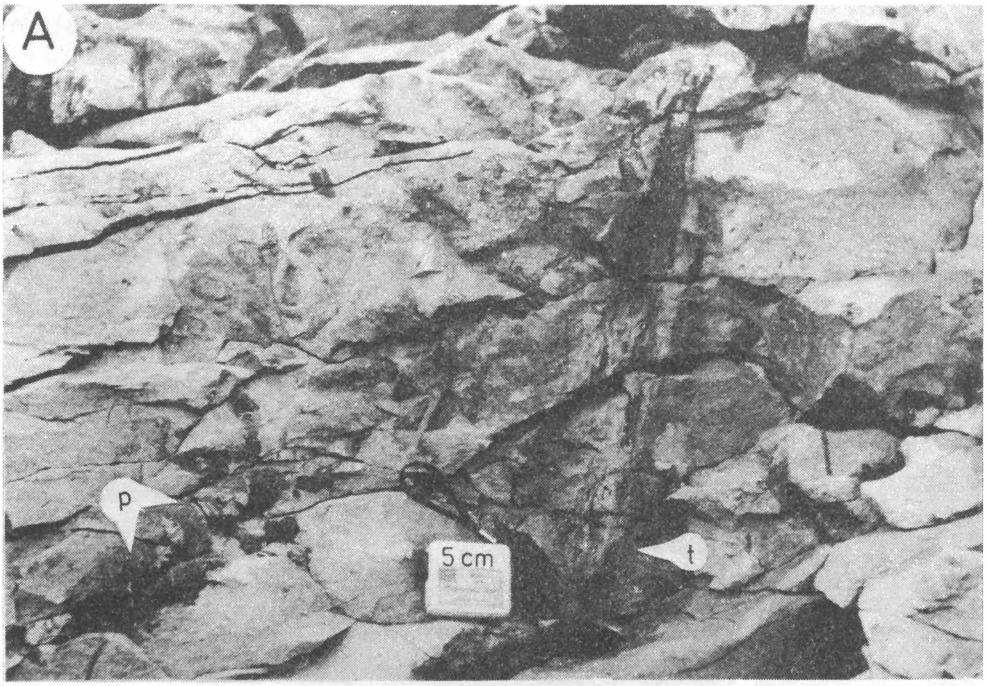


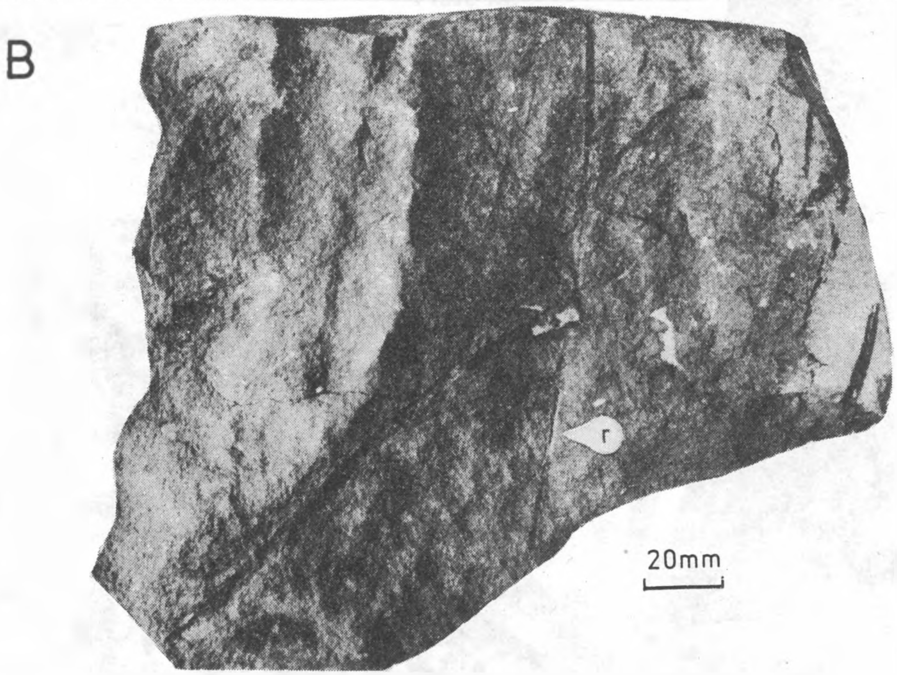


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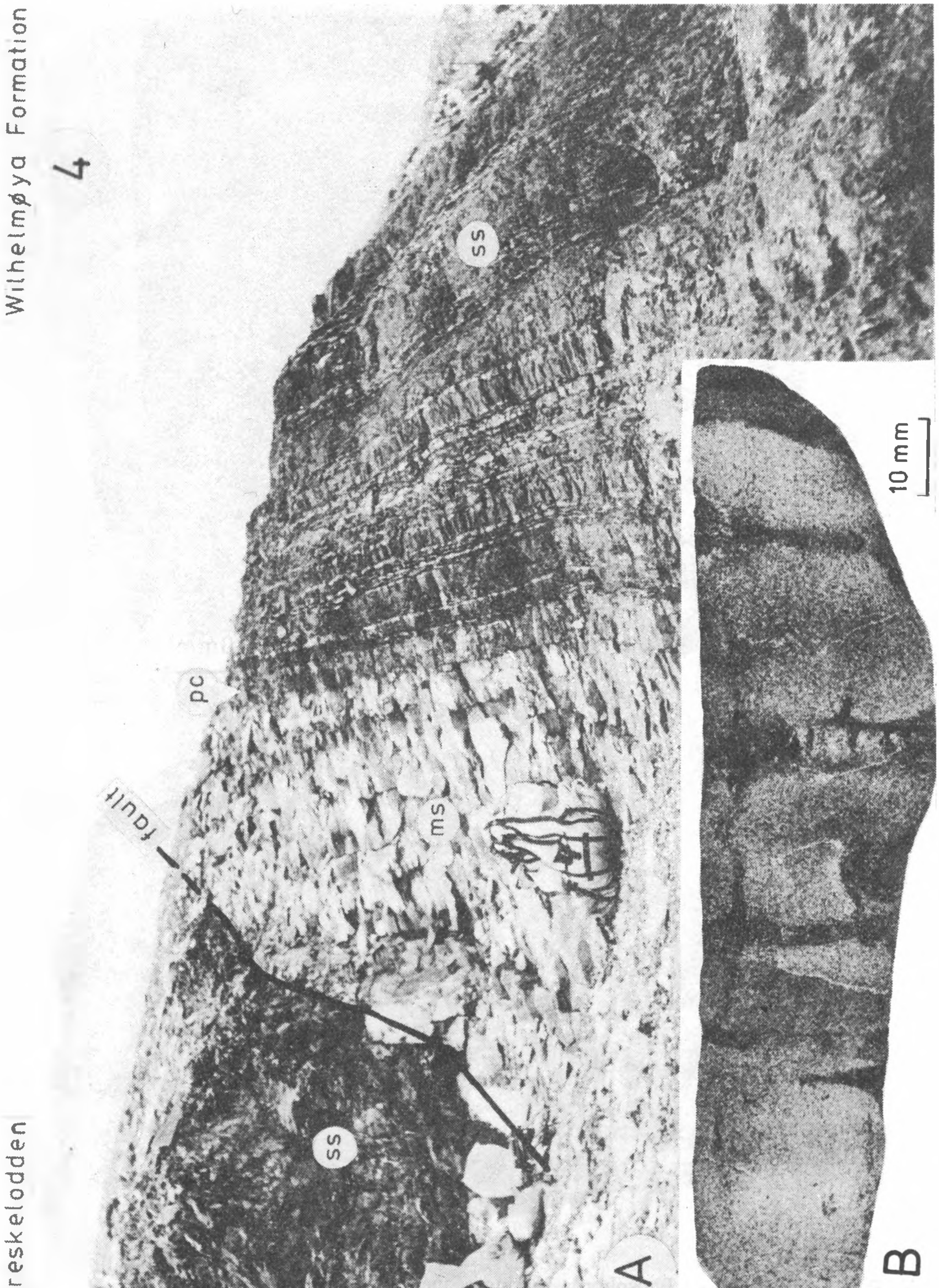


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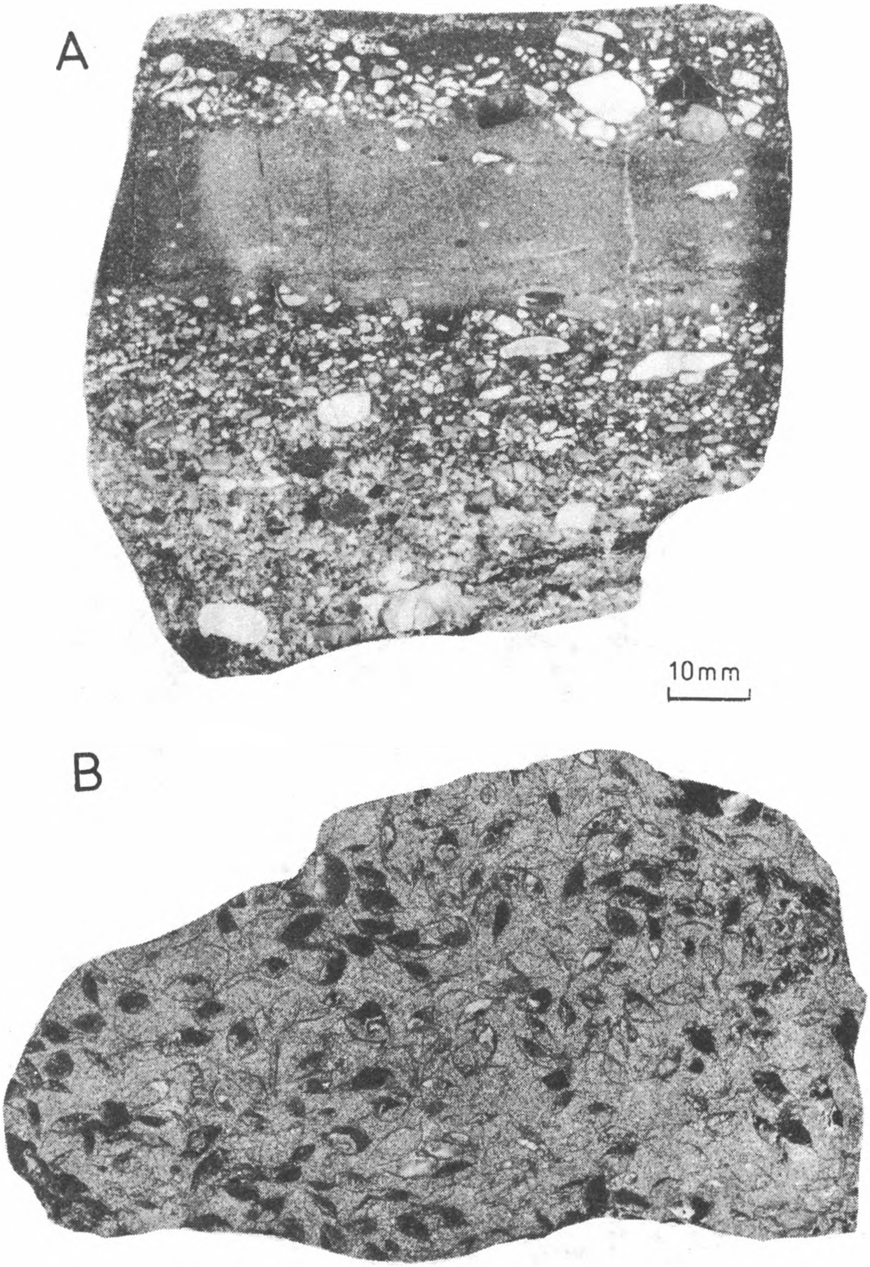


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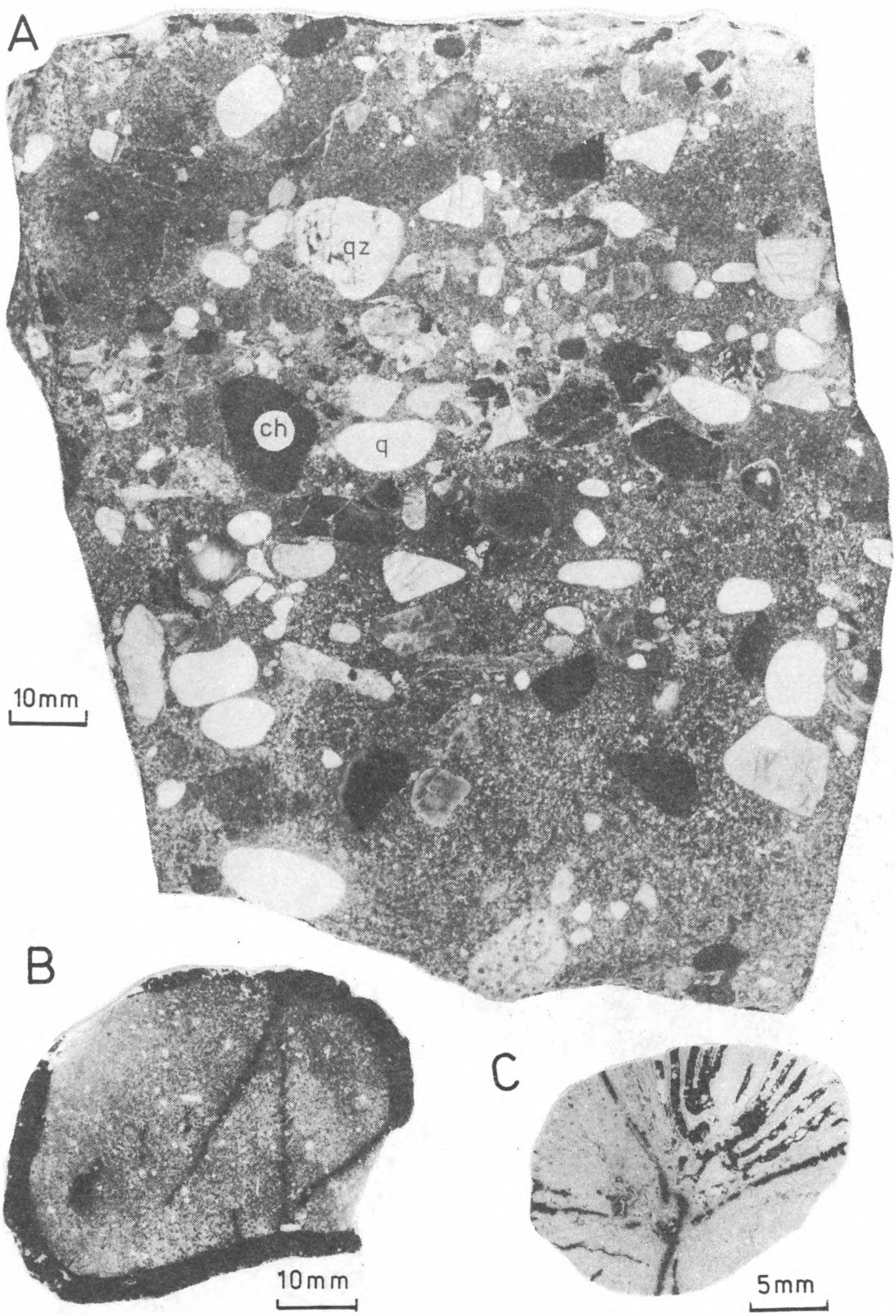


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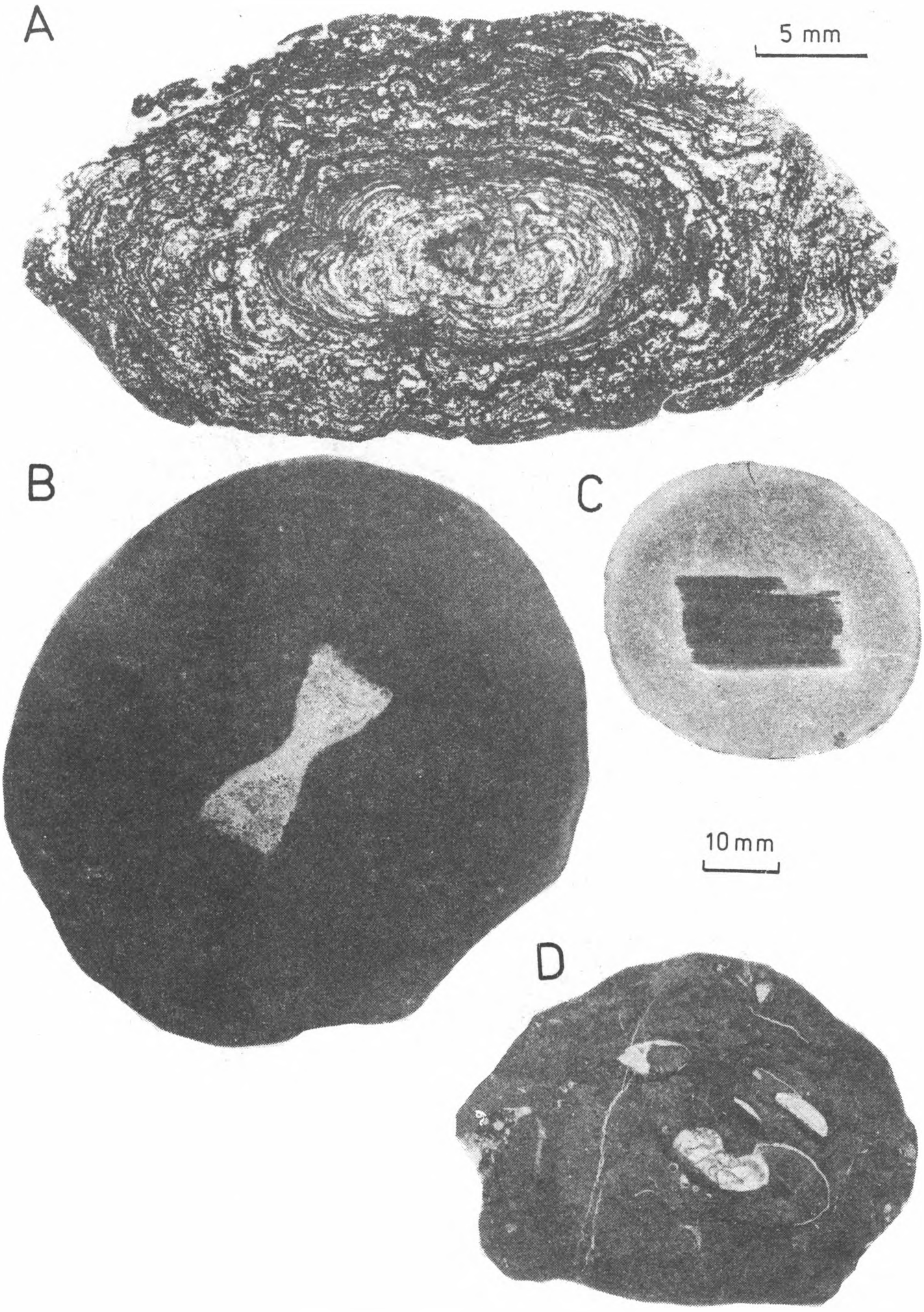


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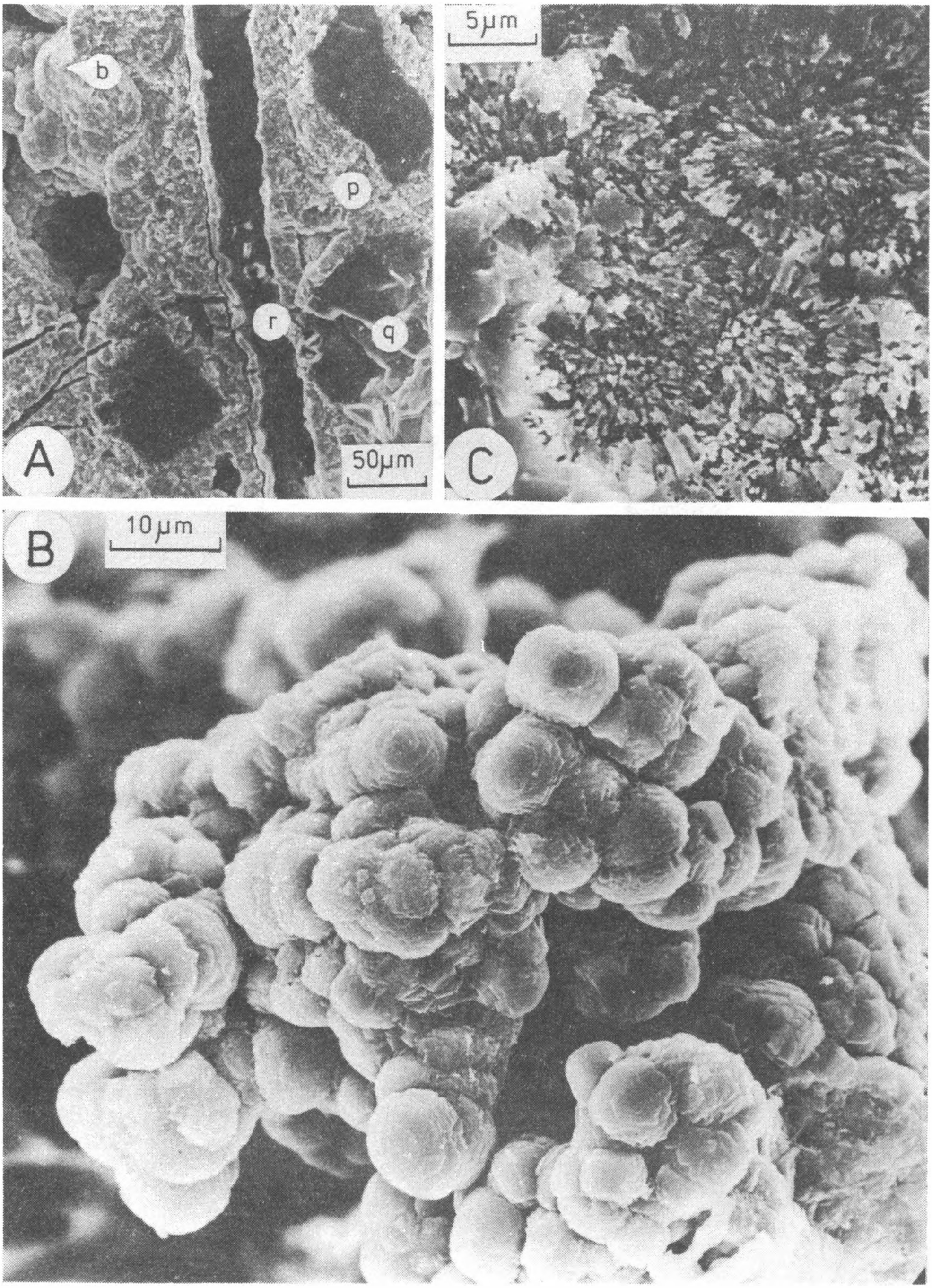


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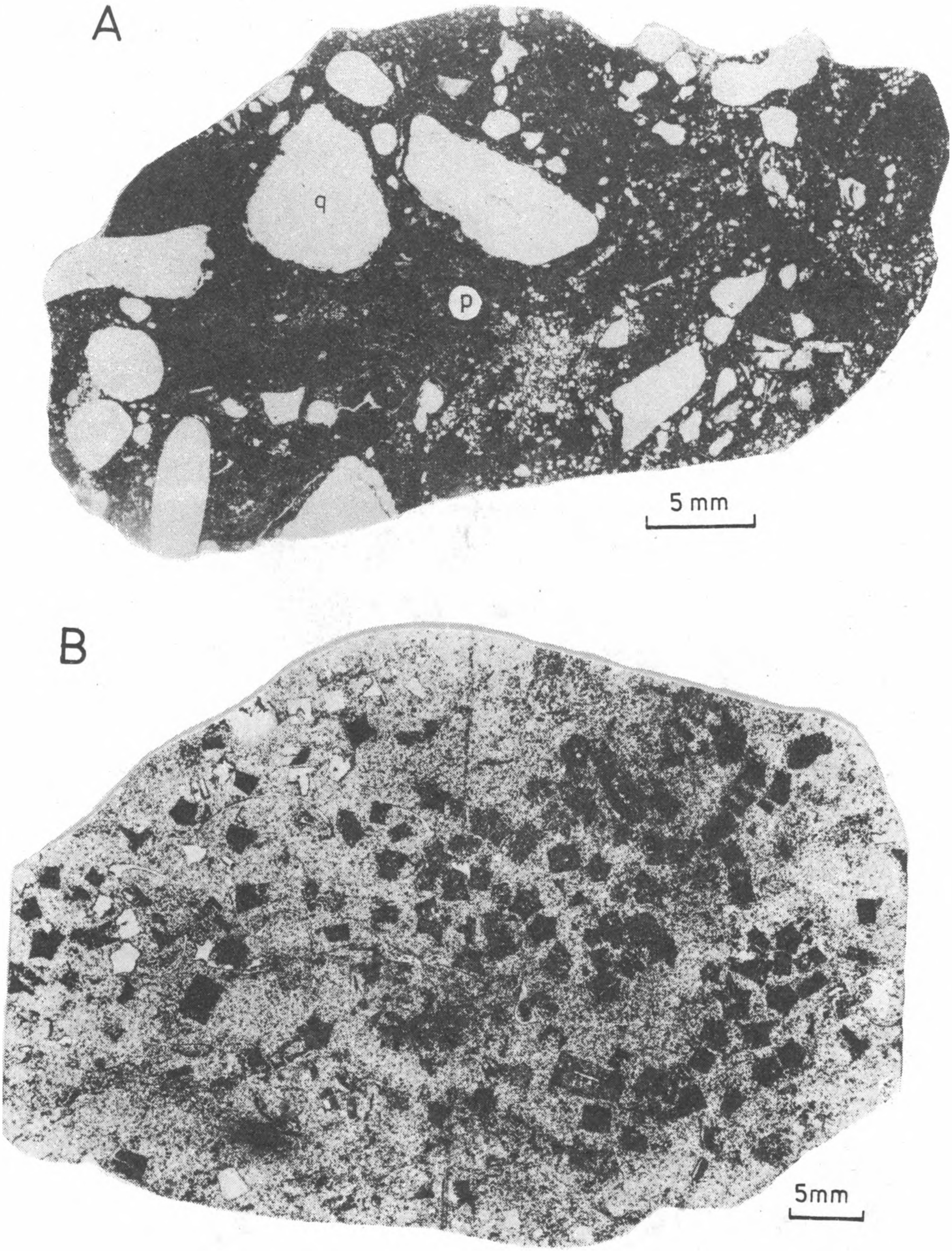


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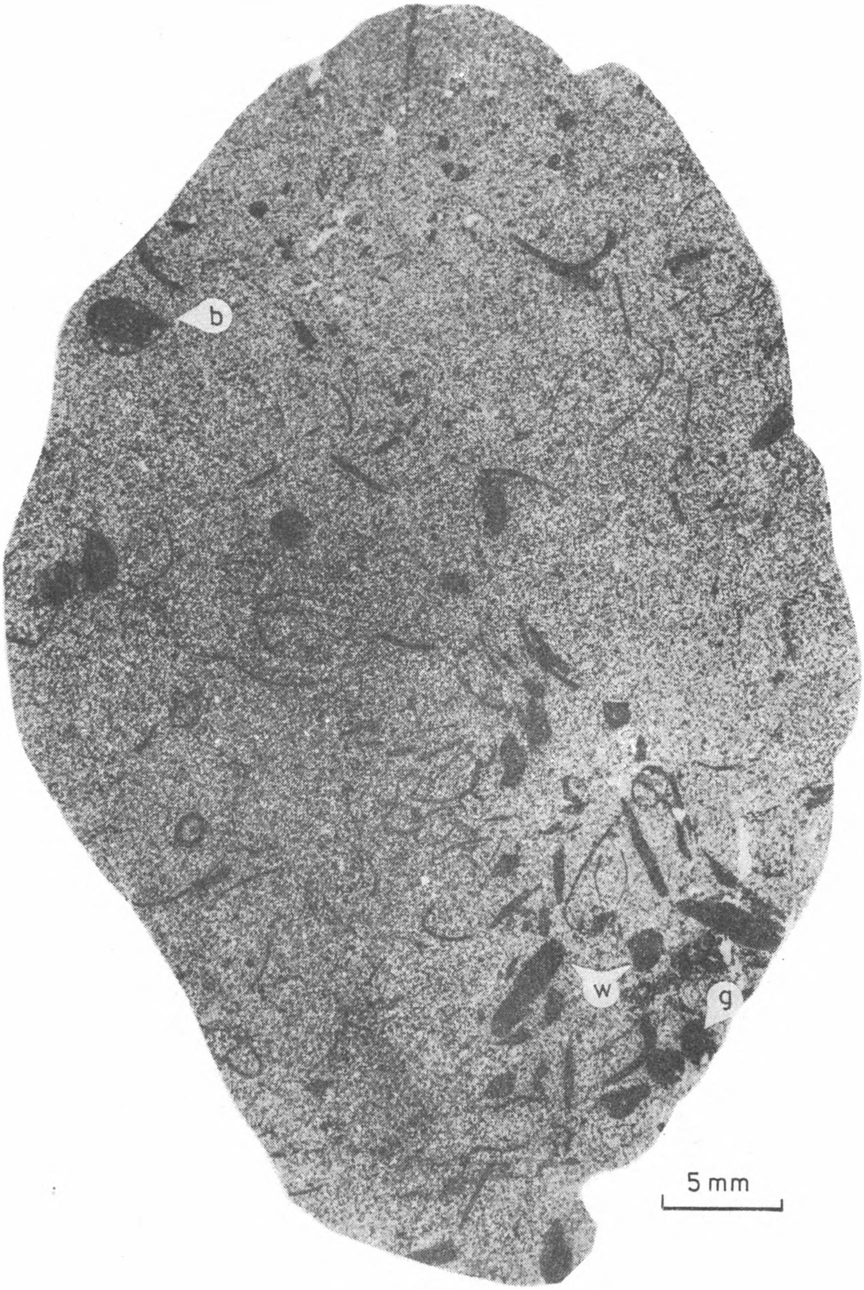


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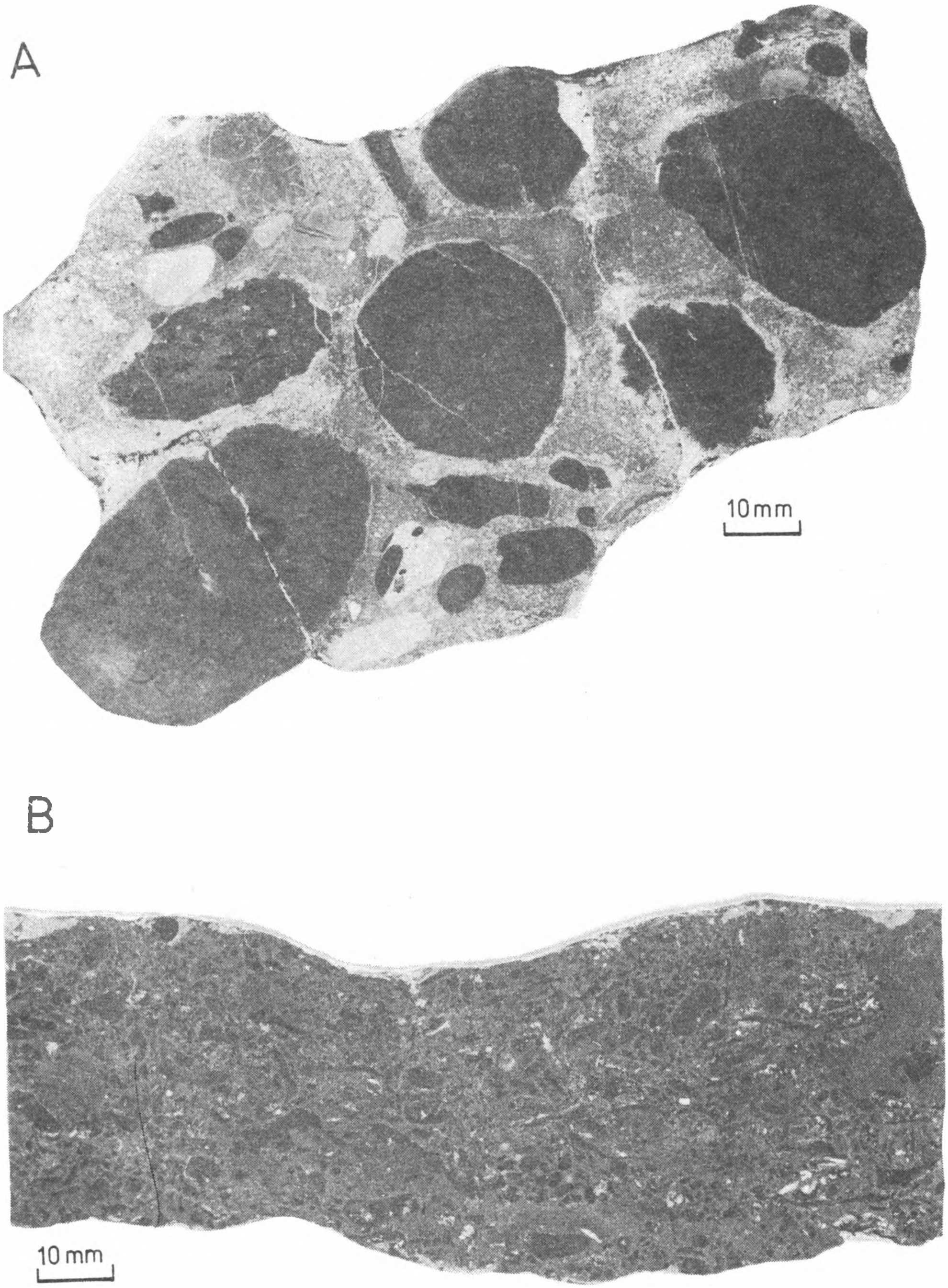


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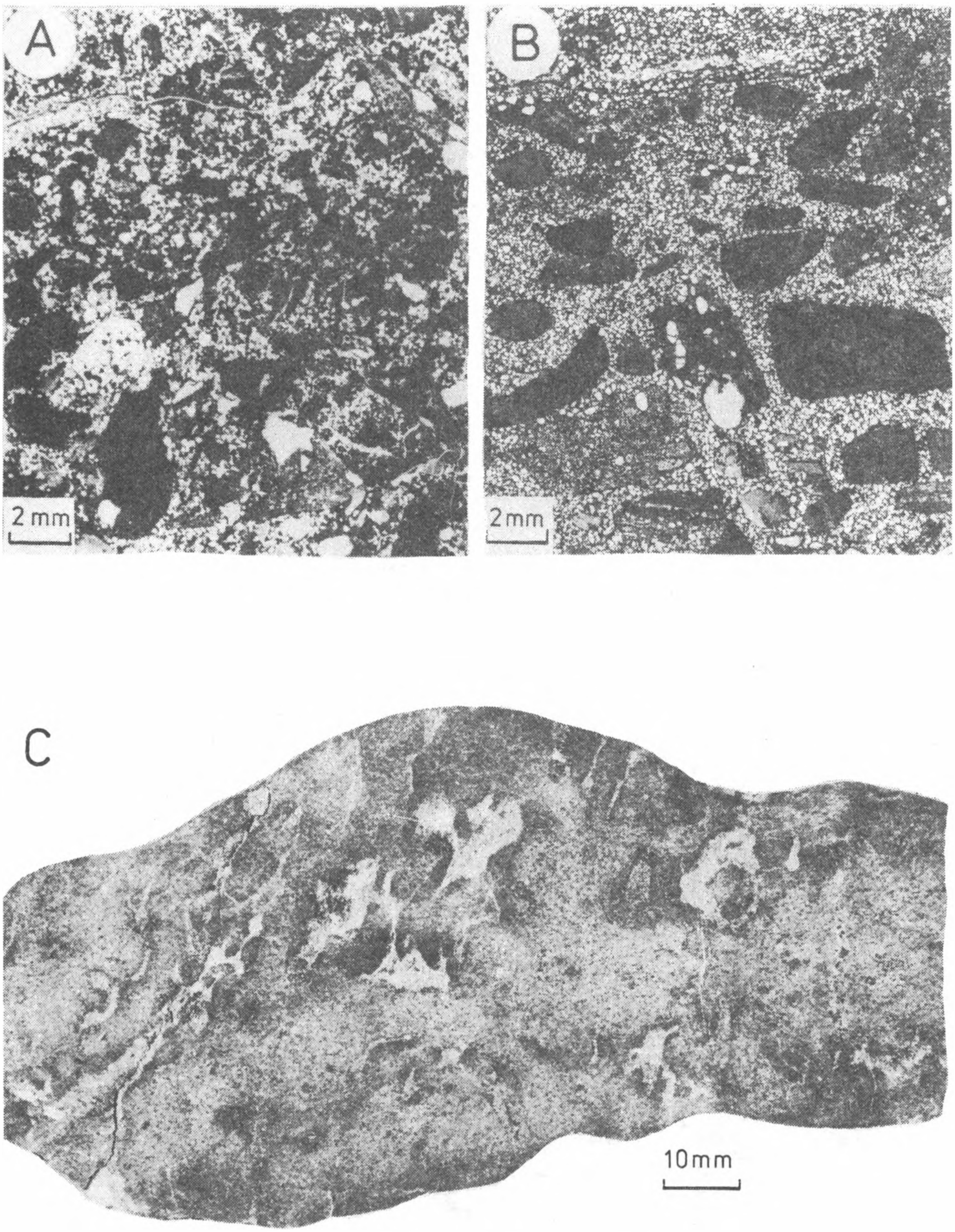


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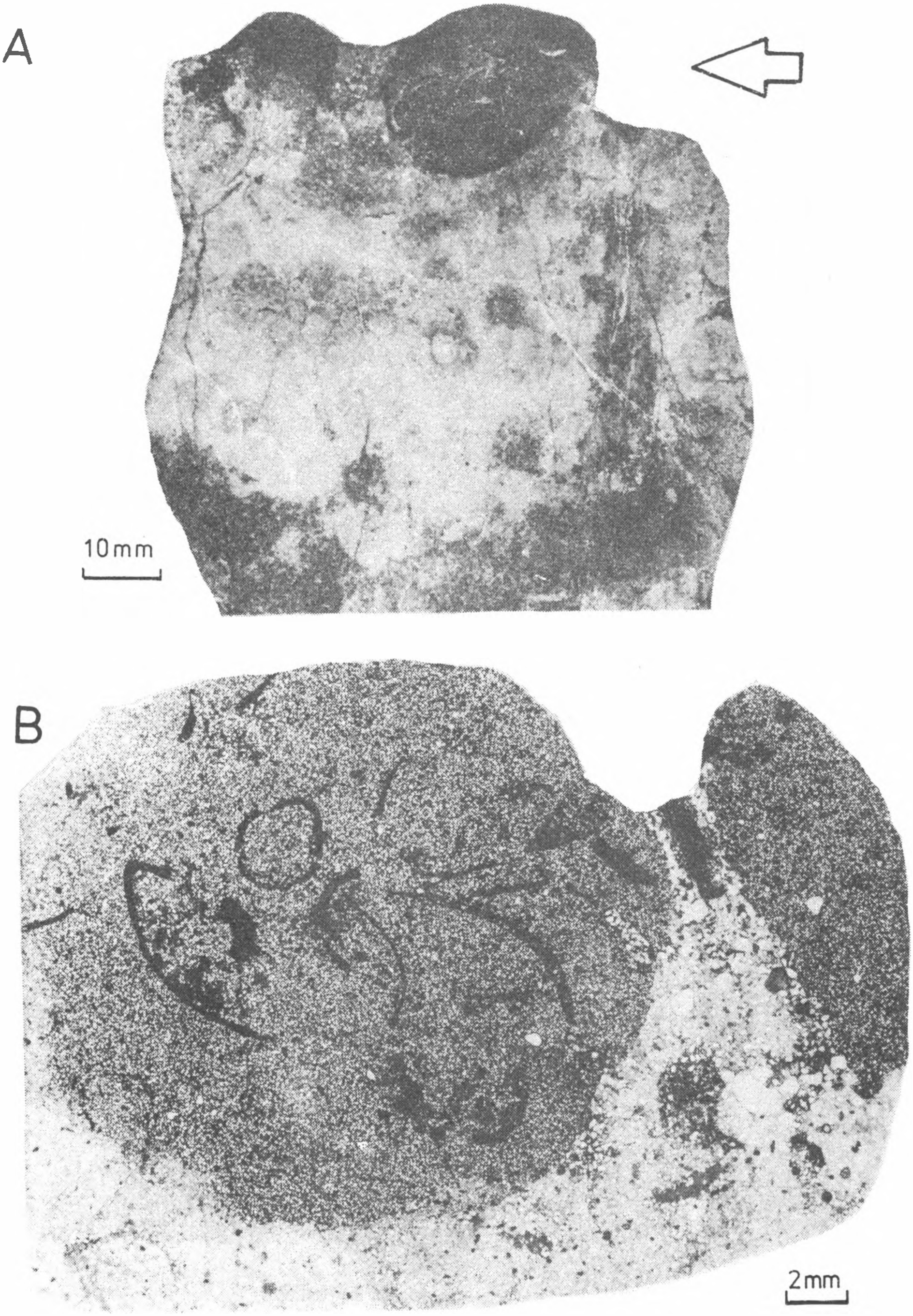


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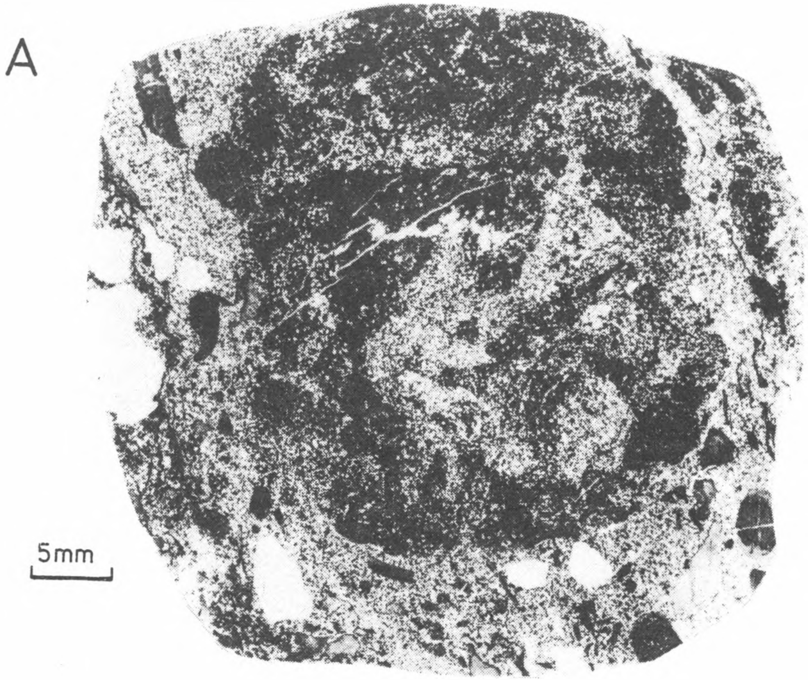


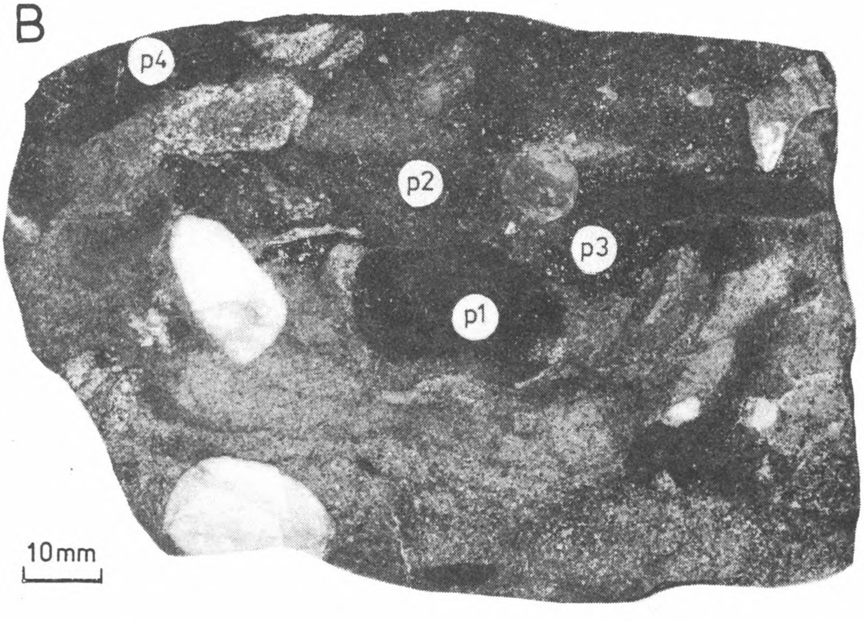


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