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Phosphoritization in a starved shallow shelf environment: the Brentskardhaugen Bed (Toarcian-Bajocian) in Spitsbergen

ABSTRACT: The condensed Brentskardhaugen Bed (Toarcian-Bajocian) in central Spitsbergen is a low-grade phosphate-bearing horizon (4—12%P_2O_5) occurring at the base of the Jurassic transgressive shelf succession. This condensed sequence was deposited in a shallow marine environment of restricted sedimentation which, occasionally, was capable of producing indigenous sandy to conglomeratic phosphate nodules. The nodules grew within the sediment as a result of precipitation of microglobular carbonate fluorapatite (CFA) during a very early stage of diagenesis.

It is inferred that the development of successive phosphate nodule generations was associated with recurrent sea-level rises ascending deeper shelf waters into the shallow environment and the consequent high biological productivity events. The enhanced phosphorus flux to the shelving bottom during these events reinforced widespread sea-floor phosphoritization. Rare episodes of intense CFA emplacement rather than slow phosphate fixation within the seabed are considered essential for the phosphorus concentration in this condensed sequence.

Key words: Arctic, Spitsbergen, Jurassic, sedimentology, condensed phosphorite.

Introduction

The condensed phosphate-bearing facies (*disconformity* or *unconformity* phosphorites) usually occur at bases of large transgressive units in the shelf and epicontinental settings (Bushinski 1966, Cook 1984, Riggs 1986). They are inherently associated with shallow marine environments of restricted sedimentation and represent small but common phosphorus sinks in the geological column. However, the detailed nature of phosphate concentration in these facies is poorly understood. The marked contrasts between the long periods of the condensed phosphorites formation and the resulting low-grade and low-volume phosphate rocks may be explained either by slow or by episodic phosphorus fixation within the seabed. Since the two mechanisms seem to be controlled by different sets of environmental to diagenetic processes (Bentor 1980, Froelich *et al.* 1982 for references), reconstructions of the nature and rates of phosphate emplacement would be of primary importance in elucidating the genesis of these deposits.

This paper presents analysis of a condensed phosphate-bearing facies associated with regional disconformity, which occurs at the base of the Jurassic transgressive shelf succession in Spitsbergen. This facies is classified into the Brentskardhaugen Bed in the local lithostratigraphic scheme (Parker 1967). It has been a subject of paleontologic, sedimentologic, and facies analyses (Frebold 1929, Różycki 1959, Pcelina 1965a, 1965b, 1967, 1980, Kopik 1968, Birkenmajer 1972, 1975, 1977, Birkenmajer and Pugaczewska 1975, Bjaerke and Dypvik 1977, Worsley and Mörk 1978, Wierzbowski *et al.* 1981a, 1981b, Bäckstrom and Nagy 1985). However, it lacks a detailed reconstruction of the mechanisms of phosphate concentration. The purpose of the present paper is to shed light on this topic, in an attempt to clarify phosphoritization processes operating in the starved clastic shelf environments of the Spitsbergen Jurassic.

Geological setting

The widespread transgressive shelf succession of the Wilhelmöya and Janusfjellet Formations (Rhaetian-Jurassic) in Spitsbergen (Fig. 1A—C) was deposited on the deltaic system of the De Geerdalen Formation (Upper Triassic). The lower part of this succession comprises two superimposed clastic sequences which correspond to the second-order transgressive pulses in the Svalbard shelf (Mörk *et al.* 1982). Both the sequences contain condensed basal phosphorite horizons (Steel and Worsley 1984). The lower phosphorite is confined to the western portion of the Svalbard shelf where it shows rather patchy distribution. The upper phosphorite has been recognized throughout Spitsbergen. This phosphorite is classified into the Brentskardhaugen Bed and accepted as a marker horizon separating the Wilhelmöya from the overlying Janusfjellet Formation.

The exposures of the Brentskardhaugen Bed in the type area in central Spitsbergen (southern margin of Sassenfjorden. Fig. 1A—B) allow the definition of this bed as a sandy to conglomeratic phosphate-bearing sediment which yields diverse fossil assemblages of the Toarcian-Bajocian age (Bäckstrom and Nagy 1985). In eastern Spitsbergen and on Wilhelmöya, subordinate delta outbuildings into the Svalbard shelf influenced thicker development of this phosphate-bearing facies (Fig. 1C). Here, the Brentskardhaugen Bed splits into several indistinct phosphatic horizons set in the upper part of the Tumlingodden Member, Wilhelmöya Formation (Worsley 1973). A decrease in the facies condensation is also observed in southern Spitsbergen where the foreshore

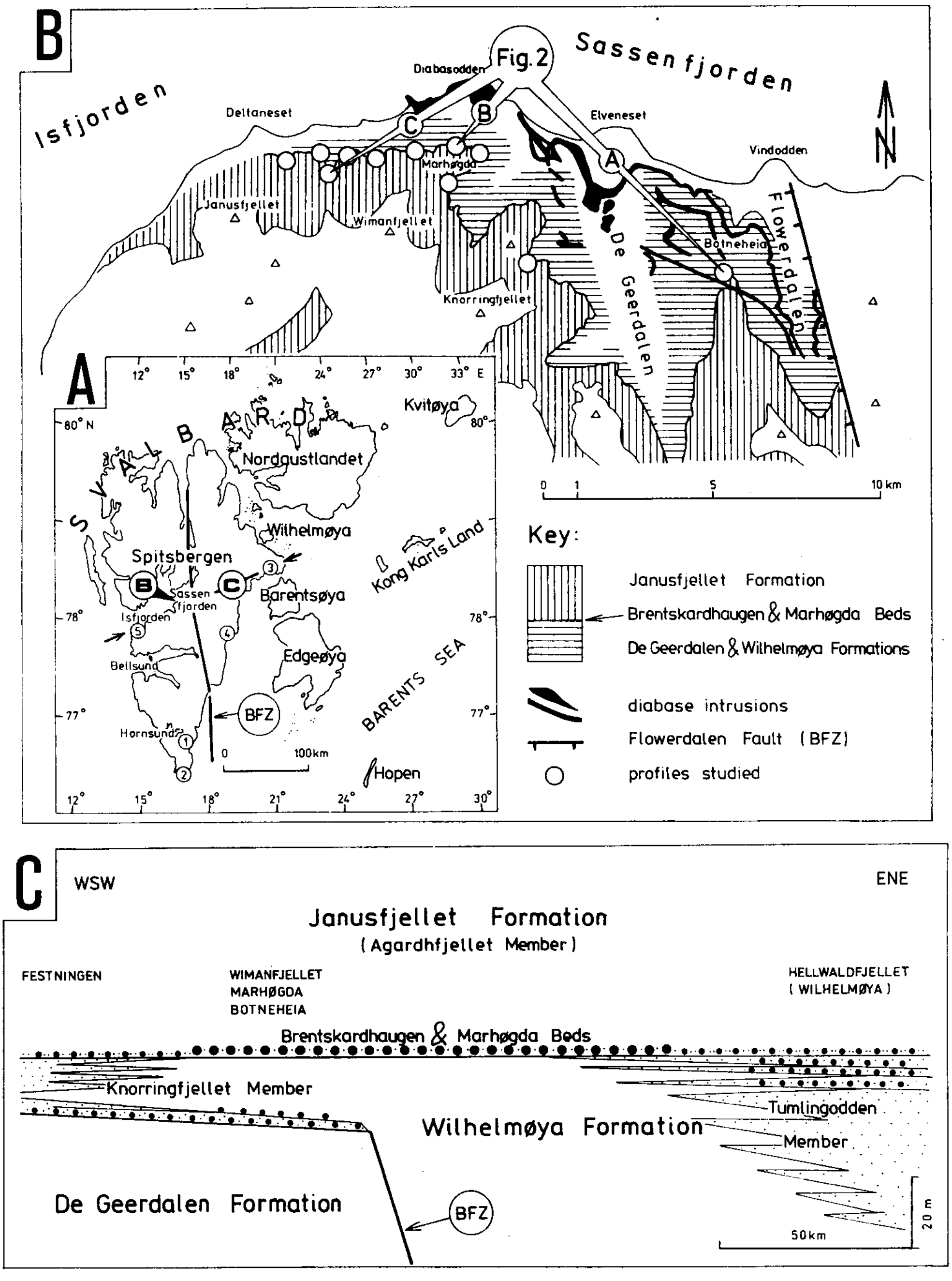

Fig. 1. A—sketch-map of Svalbard archipelago showing the location of southern margin of Sassenfjorden in central Spitsbergen (B) and the direction of Upper Triassic-Jurassic facies section (C): 1—Smalegga, 2—Sörkapp, 3—Helwalldfjellet, 4—Agardhbukta, 5—Festningen, BFZ—Billefjorden Fault Zone. B—geological map of the southern margin of Sassenfjorden showing location of the profiles studied; geology after Major and Nagy (1972), simplified. C—interpretative section of the Upper Triassic-Jurassic facies and formations across Spitsbergen showing the position of the Brentskardhaugen phosphorite. For detailed explanations see text.

sequence of the Smalegga Member, Wilhelmöya Formation (Mörk *et al.* 1982, Sörkapp Formation of Pcelina 1980) contains up to 12 individual phosphorite horizons. This sequence can be considered a lateral equivalent of the Brentskardhaugen Bed as defined in the type area of Sassenfjorden. However, the uppermost horizon of the sequence is best developed and ascribed to the Brentskardhaugen Bed in the lithostratigraphic scheme of southern Spitsbergen (Birkenmajer 1975, 1977, Worsley and Mörk 1978).

The present paper refers to the Brentskardhaugen Bed occurring in the southern margin of Sassenfjorden, central Spitsbergen (Fig. 1B) where condensation of the phosphate-bearing facies is well defined, and detailed bio- and lithostratigraphic relations are best known. The material illustrated in the text is also derived from central Spitsbergen outcrops. However, comparative observations in southern Spitsbergen (Bellsund, Hornsund and Sörkapp Land) as well as analysis of material from eastern Spitsbergen (Agardhbukta) were helpful in the elaboration of ideas and models proposed here.

Condensed facies characteristics

The condensed phosphate-bearing sequence in central Spitsbergen rests disconformably upon various lithologic units of the Knorringfjellet Member, Wilhelmöya Formation. It clearly marks the base of upward fining rhythm of the Agardhfjellet Member, Janusfjellet Formation (Fig. 2). The sequence is bipartite and composed of the lower sandy-conglomeratic and the upper mudstone-oolite depositional units. These units are attributed to the Brentskardhaugen Bed and the Marhögda Bed, respectively (Bäckstrom and Nagy, 1985). The sequence is enriched in calcium phosphate which has been determined as carbonate fluorapatite (CFA). P_2O_5 values of total rock samples fluctuate between 4 and 12%. A vertical differentiation in the phosphorite fraction representation is observed everywhere in the sequence, with phosphate nodules dominating the lower sandy part and phosphatic ooids concentrated in the upper muddy part (Pl. 1B). However, the upper part of the sequence exhibits strong diagenetic alteration resulting from siderite and ankerite replacements, which makes the original CFA fabrics rare and poorly preserved.

The sandy Brentskardhaugen Bed possesses common traces of intraformational reworking and shows variations in thickness (from 0.3 to 2.0 m) and internal complexity. The host sediment of this bed is composed of quartz grains occurring in the medium sand to fine gravel fraction with changing admixture of quartz, quartzite, and chert pebbles and fine green pellets identified to be glauconite and chlorite. The detrital grains are well — to very well — rounded and they are cemented by carbonate cements including ankerite, dolomite, calcite and siderite.

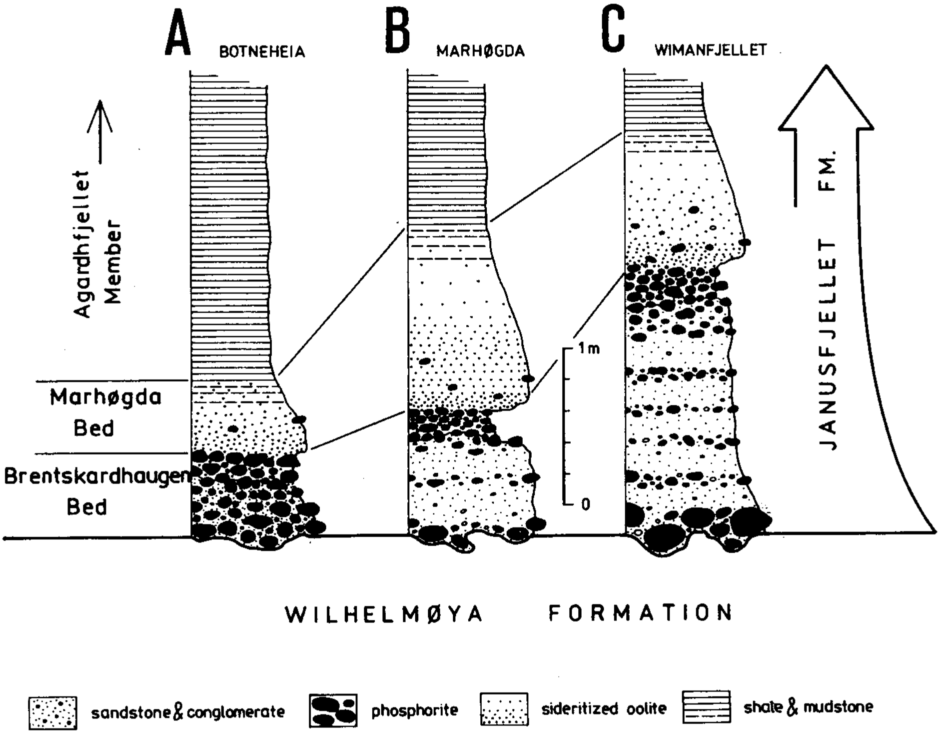

Fig. 2. Typical profiles of the Brentskardhaugen-Marhögda phosphate-bearing sequence at the southern margin of Sassenfjorden, central Spitsbergen. For detailed location of the profiles see Fig. 1B.

The Brentskardhaugen Bed usually contains recurrent horizons of phosphate nodules. The horizons occurring at the bottom and at the top of the bed tend to be continuous in the central Spitsbergen area (Fig. 2B—C). Thinning of this bed is associated with mixing of the horizons to form homogeneous phosphorite framework, and also with the overall increase in the content of phosphate nodules (Fig. 2A). The nodules contain abundant and well-preserved fossils and this contrasts with the scarcity of biogenic remnants in the sandy host sediment (Pl. 1A). The fossils are indicative of several biostratigraphic zones of the Early Jurassic and they suggest stratigraphic condensation of the phosphate-bearing sequence (Wierzbowski *et al.* 1981b, Kopik and Wierzbowski 1988).

Phosphate nodules

The phosphate nodules comprise a spectrum of sandy to conglomeratic bodies showing variations in shape, size, and internal composition (Pl. 2). The

CFA principally occurs as interparticle cement and it constitutes from 30 to 60% of the nodule capacity. Several stages of the cement development are observed, from thin rim ovules binding the detrital grains to ultimate infillings of the interparticle pore space. This is reflected in changing grade of the phosphorite fraction from 9 up to 22% P_2O_5.

The CFA is the first and predominant cement generation in the diagenetic succession of the nodules (Pl. 3). It exhibits ubiquitous globular microstructure when examined under SEM. Recrystallization of this original fabric supports the development of secondary radiaxial CFA crystals aligned with their c-axes normal to the cemented surfaces, though the external globule morphologies remain preserved. Other CFA fabrics, including replacements of biogenic particles and faecal pellets, impregnations of mollusc skeletons, bone and wood fragments, are far less important. Rare phosphatic ooids developed around quartz and/or glauconite grains occur within the nodules. In the upper part of the phosphate-bearing sequence the number of the ooids increases rapidly at the expense of sandy phosphate nodules marking the transition from the Brentskardhaugen Bed to the overlying Marhögda Bed.

The nodules are preserved at various stages of their early diagenetic development which is reflected in stages of the expansion of CFA cementation zones outward scattered sites of initial phosphate nucleation (Pl. 2). The cementation within a homogeneous sandy sediment usually led to the development of spheroidal, compact nodular bodies (Pl. 1B). The nodules formed in finely laminated sand are platty, whereas those ones occurring within conglomeratic sediment become irregular and sometimes pass into mamillated cementation zones (Pl. 2F—G). In some nodules, the cement precipitated within external rings leaving the nodule centres non-phosphatic and unconsolidated during early diagenesis. Advanced stages of the nodule growth encompass a series of phosphorite aggregates in which two or more neighbouring nodules join one another following undisturbed expansion of the CFA cementation zones (Pl. 4A). External surfaces of the phosphate nodules usually are sharp, and sometimes they are abrasionally glazered (Pl. 4B).

Phosphorite horizons

The phosphate nodules in the Brentskardhaugen Bed tend to concentrate within distinct horizons. The horizons can be classified into four types (Fig. 3).

1. *In situ* developed phosphorite horizons contain nodules which are preserved in growth position within sandy to conglomeratic sediment (Fig. 3A, Pl. 3A). These horizons provide virtually the only fossil evidence of the original CFA emplacement within the condensed facies. However, they are rarely found in the sequence owing to their common destruction by subsequent dynamic processes. *In situ* developed horizons are observed at the northern slopes of

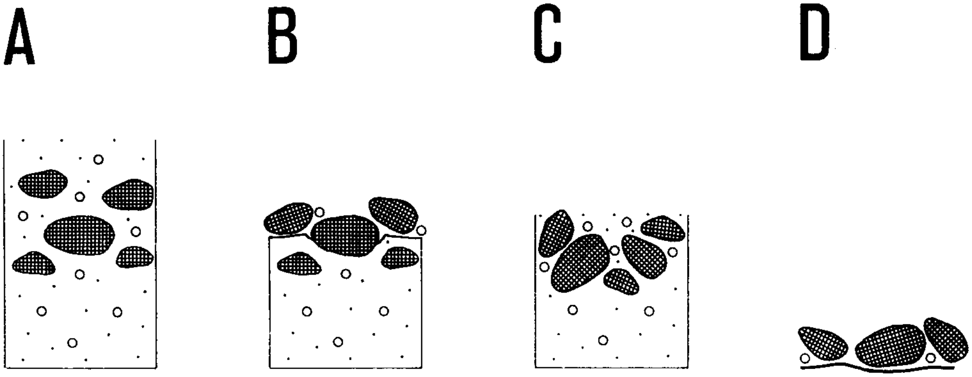

Fig. 3. Diagram showing main types of phosphorite horizons in the Brentskardhaugen Bed in central Spitsbergen

Janusfjellet, Wimanfjellet, and Marhögda where they tend to concentrate in the uppermost part of the Brentskardhaugen Bed (Figs. 1B, 2B—C, Pl. 2).

2. Winnowed phosphorite horizons are made of phosphate nodules developed *in situ* and subsequently concentrated by winnowing of unconsolidated sediment from between the nodules (Fig. 3B). Various nodules of older generations also are incorporated within these horizons. Most frequently, the horizons cover destructed sequences which contain nodules preserved in the growth position. Advanced stages of sediment winnowing led to the development of grain-supported phosphorite framework resting upon a hummocky surface. The nodules are aligned with their longer axes parallel to this surface and display current orientation (*see also* Bäckstrom and Nagy 1985). The winnowed horizons form the prominent topmost bench composed of loose nodules on Wimanfjellet, and also they occur on Botneheia and Marhögda (Figs. 1B, 2A—C).

3. Reworked phosphorite horizons consist of phosphate nodules of various sizes which are intermixed and randomly oriented within the horizons (Fig. 3C). These are the most common phosphorite accumulations in the Brentskardhaugen Bed. The grain size distributions within the nodules and the host rock suggest reworking and homogenization without noticeable lateral transport of the sediment. These horizons are discontinuous and they pass laterally into winnowed and/or *in situ* developed phosphorite sequences.

4. Residual phosphorite horizons are composed of large phosphate nodules (up to 30 cm in size) showing prominent compositional and textural contrasts towards the surrounding sediment (Fig. 3D, Pl. 4B). These horizons occur in the lowermost part of the Brentskardhaugen Bed where they cover the basal discontinuity surface (Fig. 2B—C). They show patchy distribution, frequently being confined to pockets and depressions on this surface. The nodules

preserve relics of sediments which are not discerned in the host sediment of the Brentskardhaugen Bed. Three types of sediment dominate: (*i*) quartz sandstone enriched in phosphatized crinoid ossicles (Pl. 5A), (*ii*) phosphatic coquinoid sandstone with *Pleuromya* (Pl. 5B), and (*iii*) well-sorted, laminated sandstone with irregular vertical burrows (Pl. 6A, p1). The residual phosphorite horizons provide evidence of former sediment generations of the condensed facies which were early diagenetically phosphatized and subsequently encountered ultimate environmental destruction.

Phosphorite generations

The superposition of the phosphorite horizons in the Brentskardhaugen Bed suggests that several phosphate generations were emplaced within the sediment during the condensed facies development. This presumption is consistent with the presence of nodules showing two or more growth stages separated by clear-cut erosional boundaries (Pl. 6). It is difficult to estimate the number of phosphorite generations which contribute to the final burial shape of the Brentskardhaugen Bed because of incomplete record of the condensed facies in central Spitsbergen and its highly reworked nature. The paleontologic evidence from this region is not precise enough to subdivide the phosphorite generations (A. Wierzbowski, *personal communication*). Neither the composition of the CFA shows noticeable variations within the nodule generations (*see also* El-Kammar and Nysaeter 1980).

The exposures of the Brentskardhaugen Bed at the northern slopes of Wimanfjellet suggest the presence of six superimposed phosphorite horizons showing considerable differences in the type of sediment subjected to CFA cementation. Moreover, the residual horizon occurring at the base of the sequence comprises relics of at least three older generations (*see also* Krajewski *in press*).

Discussion

The condensed phosphate-bearing facies of the Brentskardhaugen Bed developed as a result of rapid transgressive pulse put onto the partly exposed Svalbard shelf. This transgression introduced shallow starved environments to the prevailing part of Spitsbergen (Steel and Worsley 1984). The central Spitsbergen area, which is characterized by maximum condensation of the phosphorite facies, was remote from the foreshore environments of southern Spitsbergen and the subordinate delta outbuildings in northeastern Svalbard. In this area, the minimum *net* sedimentation and frequent reworking of the seabed led to the development of a thin phosphorite bed, which elsewhere splits into several phosphatic horizons set in the thicker nearshore sequences.

The remnants of *in situ* developed phosphorite horizons in central Spitsbergen indicate that the starved shelf environment was capable of producing indigenous accumulations of phosphate nodules. The presence of phosphorite generations suggest recurrent sea-floor phosphoritization episodes. The vast majority of fossils in the Brentskardhaugen Bed is preserved within the phosphorite fraction where the early phosphate cementation and replacement prevented them from dissolution and/or mechanical destruction. Therefore, it is sensible to expect that the preserved fossils reflect particular periods of sea-floor phosphoritization rather than the whole interval of the facies deposition. The paleontologic analysis reveals the concentration of ammonite and bivalve assemblages indicative of several intervals of the Early Jurassic, including the *bifrons, variabilis,* and the lower part of the *thouarsense* Zones of the Toarcian, the *opalinum* Zone of the Aalenian, and also an indefinable part of the Bajocian (Wierzbowski *et al.* 1981b. Bäckstrom and Nagy 1985, Kopik and Wierzbowski 1988). In particular, the abundant and widespread Toarcian faunas indicate enhanced phosphate diagenesis during this period.

The environmental episodes of high energy were responsible for destruction of the original phosphorite-bearing sequences and the consequent dynamic concentration of the phosphate nodules. At least two different mechanisms are supposed to have contributed to these processes: (*i*) strong bottom current action leading to winnowing of finer sediment fractions and a relative concentration of phosphate nodules, and (*ii*) rapid high energy events leading to intermixing of phosphorite fraction without important lateral transport of the sediment.

Changes in sea-level are plausible to explain the overall cyclicity of the phosphorite formation and its reworking in the central Spitsbergen area. They are consistent with the recurrent facies migration in the foreshore zone of southern Spitsbergen as well as with the alternation of phosphorite sedimentation and delta outbuilding episodes in the northeastern Svalbard. The variations of the sediment types, depositional structures, and the associated benthic communities in the Brentskardhaugen Bed in central Spitsbergen suggest a differentiation of the shallow shelf environment during low sea-level stands. These stands were prone to reworking and sediment redeposition owing to the enhanced wave and current interactions with the seabed. In contrast, the development of successive phosphorite generations regardless of the former environment differentiation suggests that the sea-floor phosphoritization appeared over the central Spitsbergen area in a series of events. These events were associated with temporary equalization of the depositional conditions and may well indicate recurrent and rapid sea-level rises.

At least three different mechanisms leading to the within-sediment phosphate concentration have been proposed for the contemporary shelf environments of restricted mineral sedimentation. These are: (*i*) phosphorus uptake by hydrated ferrous oxides in the water column and its subsequent liberation under reducing conditions close to the sediment/water interface (Marshall 1983), (*ii*) phosphorus assimilation from seawater by bacterial communities and its concentration within cellular structures (O'Brien *et al.* 1981), and (*iii*) phosphorus transport *via* planktonic particulate matter and its intrasedimentary release and precipitation (Baturin 1978). The former two mechanisms are characterized by a slow and rather continuous phosphorus flux into the seabed which brings about the very slow accretion of phosphate nodules. Therefore, they are unlikely to offer a satisfying explanation for the studied sequence. The latter mechanism may well explain the phosphorus concentration in the Brentskardhaugen Bed since it is associated with episodes of enhanced organic matter deposition and the consequent development of phosphorite generations (Baturin and Bezrukov 1979, Yanshin and Zharkov 1986).

High biological productivity is necessary to supply abnormal amounts of marine organic matter to the shelving, shallow ocean bottom. Within modern shelf environments, this process is reinforced by upwelling of cold, nutrient-rich waters from intermediate depths of outer shelf and slope (Sheldon 1981, Parrish 1982). Rapid sea-level rises are responsible for episodic ascending of deeper water masses into shallow shelf environments otherwise characterized by lowered nutrient input (Birch 1979, Diester-Haass and Schrader 1979; Shniukov *et al.* 1985). The restricted mineral sedimentation in these environments coupled with the high deposition of organic matter lead to the rapid sea-floor phosphoritization (Giresse 1980, Baturin *et al.* 1985). The organic matter contributes to intrasedimentary release of phosphorus (Romankevich and Baturin 1972, 1974; Romankevich 1984) which, in the form of globular phosphate gel, precipitates within the topmost sediment layer (Baturin and Dubinchuk 1974, 1979).

It seems that similar mechanism might affect the episodic sea-floor phosphoritization and interdependent development of phosphorite generations in the Brentskardhaugen Bed. However, the low-grade phosphate rock of this bed suggests that the processes of sea-floor phosphoritization were marginally significant during the condensed facies development.

The recent paleogeographic reconstructions of the Svalbard shelf (Steel and Worsley 1984) show that the Brentskardhaugen phosphorite covered an area of at least 24,000 km^2. This area, considered against the average thickness of 0.7 m, the average phosphorus content of 2.62%, and the mean volumetric weights of the phosphorite and the sandy host rock of 2.67 and 2.52 g cm^{-3}, respectively, gives 1.14×10^6 t P buried in the Svalbard shelf during the condensed facies deposition. Taking for granted that the rates of phosphorus burial within the sediment during the episodes of sea-floor phosphoritization were comparable to the rates calculated for the SW African shelf (5×10^{-3} t P km^{-2} yr^{-1} on the basis of Russian data summarized by Baturin 1978), the time-span necessary to achieve the estimated phosphorus volume would be less than 10,000 years. This, considered against the interval of the Bed deposition from the Middle Toarcian up to the end of Bajocian, *i.e.* approximately 15 My according to calculations of Odin (1984) and Westermann (1984), gives less than one thousandth of the time of sea-floor facies exposition. A similar calculation, taking the average burial phosphorus flux of 1×10^{-9} moles-P cm^{-2} yr^{-1} obtained by Froelich *et al.* (1982), gives the phosphoritization time in the Brentskardhaugen Bed nearly one hundredth of the total facies deposition. Clearly, the remainder of this time falls into various reworking and rearrangements of the phosphate-bearing sediment.

The above calculation pretends only rough estimate. However, it is illustrative of the episodicity of phosphoritization in the condensed Brentskardhaugen Bed. It suggests extremely rare events of enhanced biological productivity introduced to the starved shelf environment of the Svalbard Jurassic.

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Streszczenie

Przedmiotem pracy jest analiza sedymentologiczna skondensowanej warstwy z Brentskardhaugen (toark — bajos) na obszarze centralnego Spitsbergenu w Sassenfjorden (fig. 1). Szczególną uwagę poświęcono formom występowania i sposobom koncentracji fosforanu (węglanowego fluoroapatytu — CFA) w tej warstwie. Warstwa z Brentskardhaugen jest niskoprocentowym horyzontem fosforytonośnym (4—12% P_2O_5) występującym u podstawy transgresywnej sekwencji szelfowej środkowej i górnej jury (fig. 2). Horyzont ten jest wzbogacony w piaszczyste i zlepieńcowate konkrecje fosforytowe (pl. 1—2) które tworzyły się w czasie wczesnej diagenezy w podpowierzchniowym środowisku porowym nieskonsolidowanego osadu (pl. 3). Powtarzające się w sekwencji warstwy z Brentskardhaugen horyzonty konkrecji fosforytowych (fig. 3) odzwierciedlają szereg epizodów wczesnodiagenetycznej fosfatyzacji osadu (pl. 5—6). Sugeruje się, że epizody fosfatyzacji były związane z okresami wzmożonej żyzności wód szelfu Spitsbergenu jako rezultat wzrostów miąższości kolumny wody i zwiększonej penetracji wzbogaconych w fosfor wód otwartego szelfu.

PLATE 1

A – Botneheia; polished section of fossiliferous phosphate nodule from the Brentskardhaugen Bed: voids within phosphatized biogenic material are due to epigenetic leaching of late carbonate cement; arrowed is the section of *Harpoceras* phragmocone. B – field appearance of the sandy-conglomeratic Brentskardhaugen Bed at the northern slope of Wimanfjellet; note the dark gray phosphate nodules and the white quartz pebbles; scale in centimetres.

PLATE 2

A—G. Shapes and internal compositions of phosphate nodules preserved in growth position within the topmost part of the Brentskardhaugen Bed at Wimanfjellet; polished section photographs.

PLATE 3

Janusfjellet; initial stage of phosphate nodule growth within the Brentskardhaugen Bed. A – small nodules (arrowed) preserved in growth position within sandy-conglomeratic sediment. B – initial site of CFA cement development; arrowed are gradational transitions towards the surrounding conglomeratic sediment; thin section photograph. C – phosphate rim cement binding quartz grains and showing CFA crystals aligned normal to the cemented surfaces; the remaining pore space was occupied by subsequent void-filling carbonate cement. D – external surface of CFA rim cement showing relics of the original globular fabric. C, D — SEM photomicrographs; preparations after artificial removal of carbonate.

PLATE 4

Marhögda; A – aggregate of two twin nodules developed as a result of CFA cement expasion outward the neighbouring nucleation sites. B – reworked phosphate nodule showing erosional external boundary (arrowed); the nodule centre is occupied by a concentration of fine plant detritus; polished section photographs.

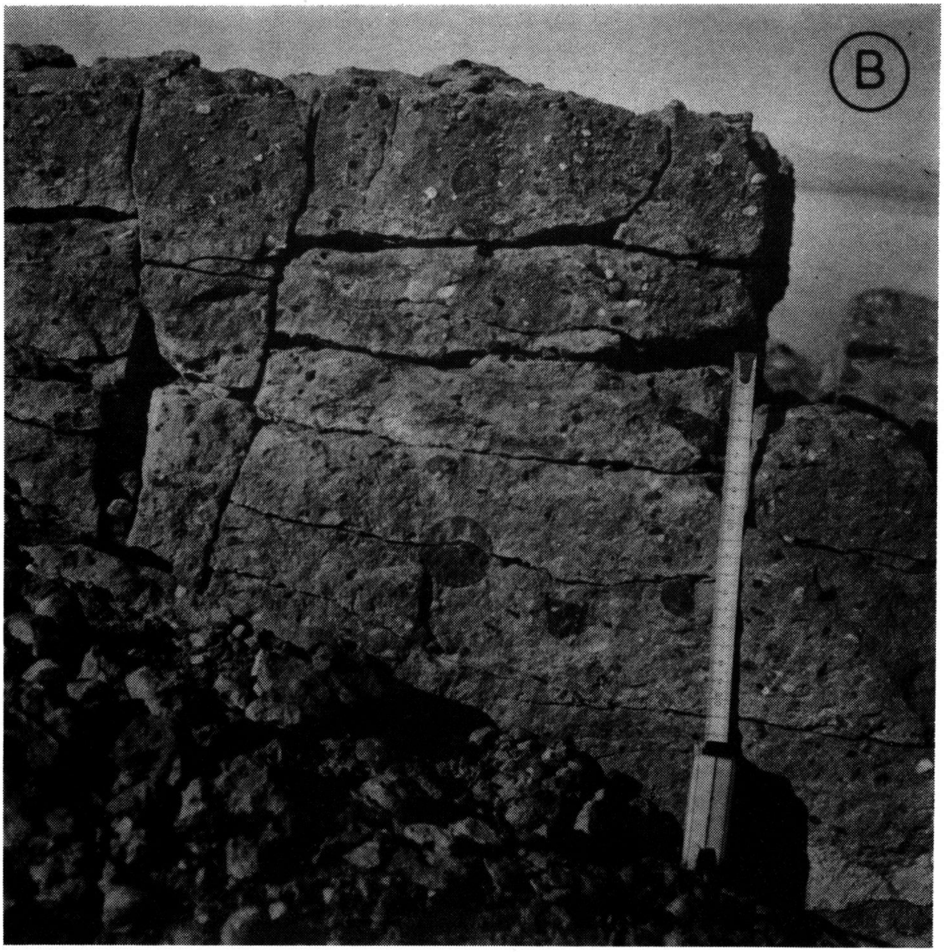
PLATE 5

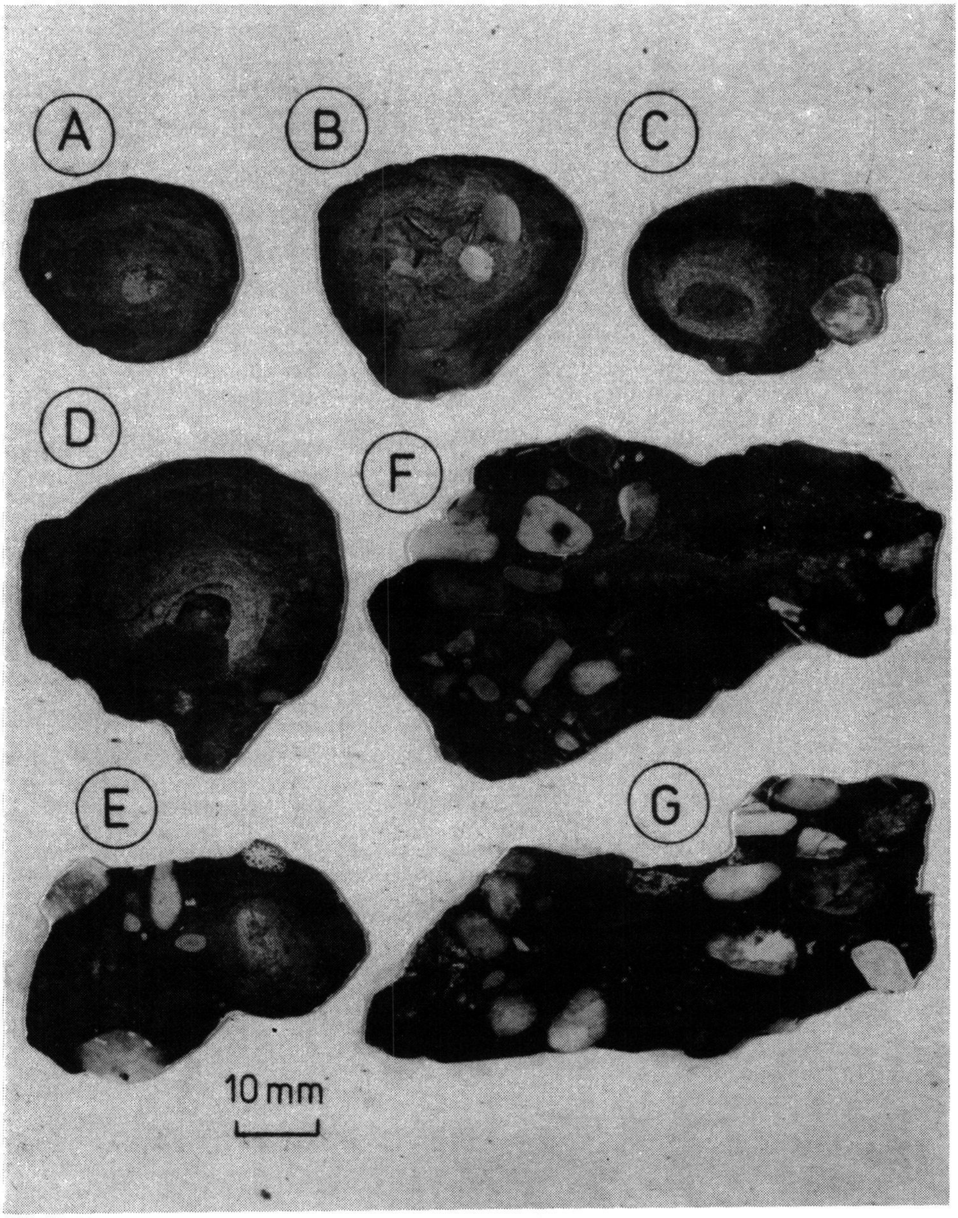
Relic sediments that commonly occur within residual phosphate nodules in the Brentskardhaugen Bed. A – Botneheia, crinoidal sandstone. B – Knorringfjellet, *Pleuromya* sandstone; note the ultimately replaced biogenic material (black); thin section photographs.

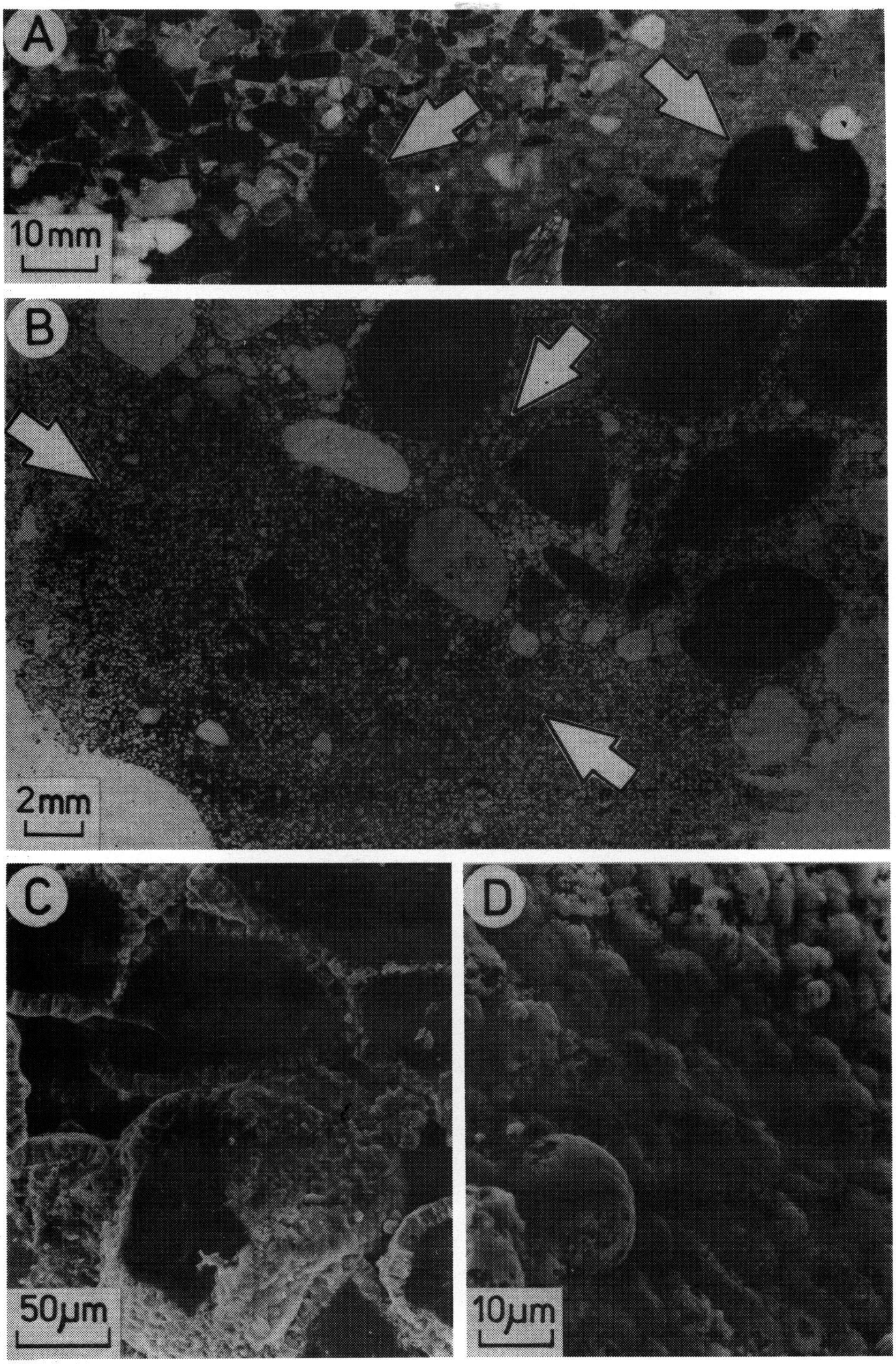
PLATE 6

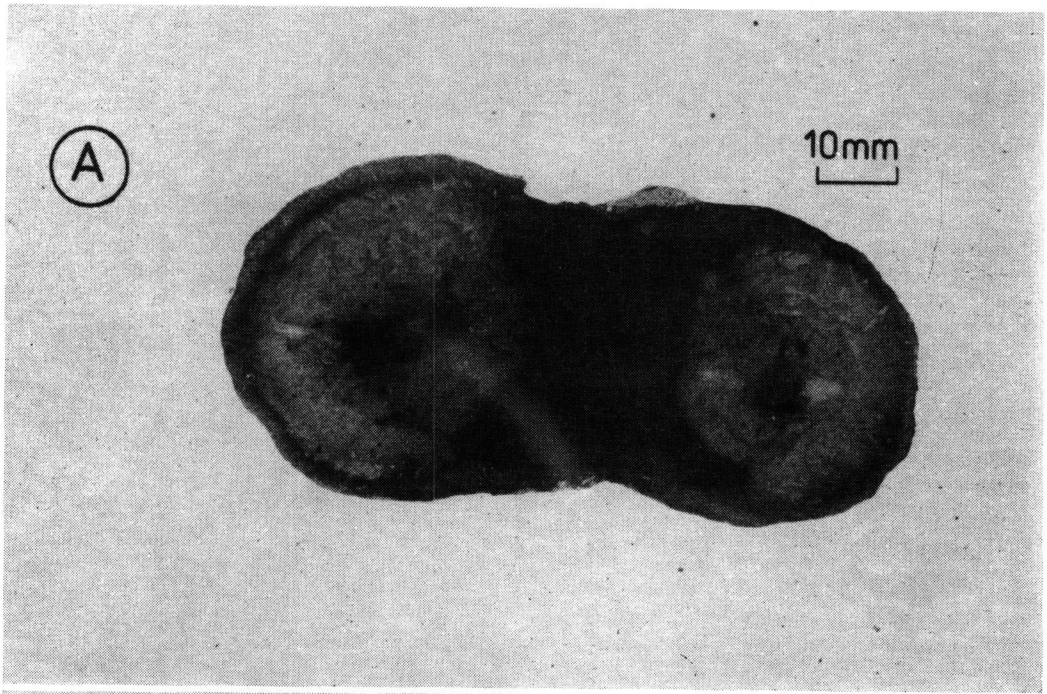
Phosphate nodules showing two growth stages. A – Wimanfjellet, finely laminated sand with vertical burrow (arrowed) is cemented by the first CFA cement generation (p1); the second cement generation (p2) is developed within conglomeratic sediment; the two stages of nodule growth are separated by clear-cut erosional boundary. B – Marhögda, the first nodule generation (p1) is developed within homogeneous sand and serves as a centre for the second generation development (p2); arrowed is erosional boundary between the two generations; polished section photographs.


A
10mm


B


A
B
C
D
F
E
G
10 mm


A
10mm
B
2mm
C
50µm
D
10µm


Ⓐ
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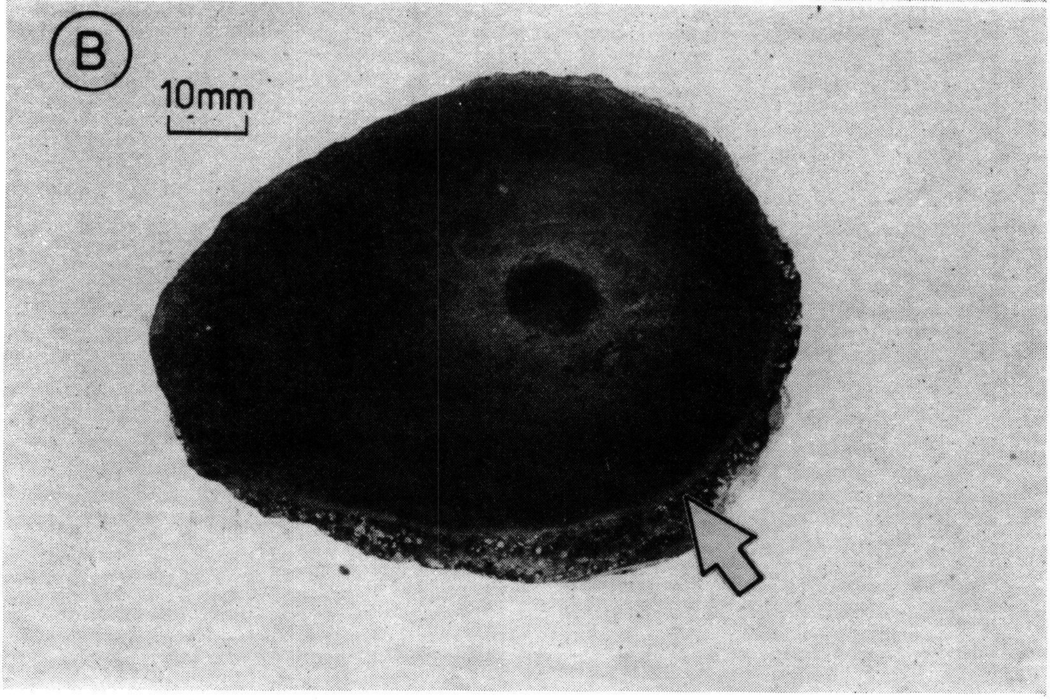
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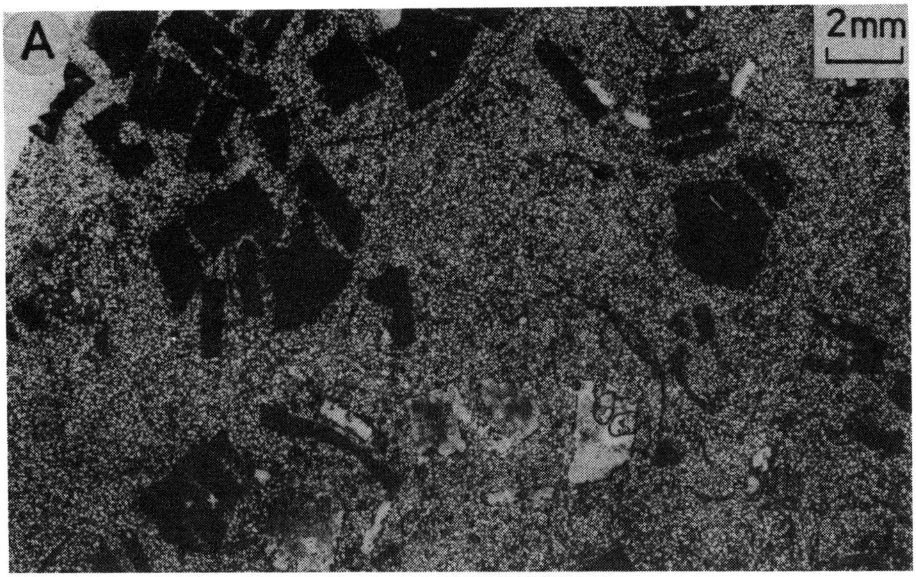
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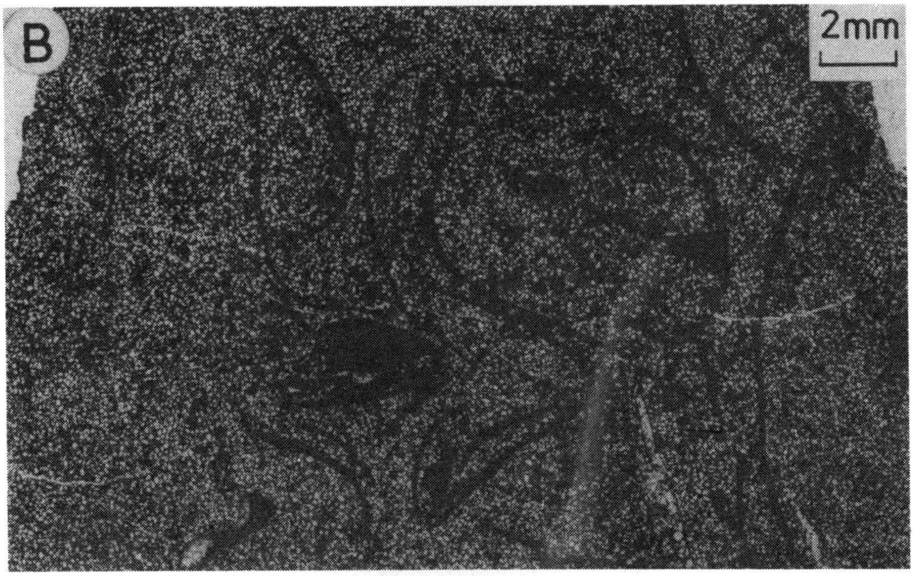
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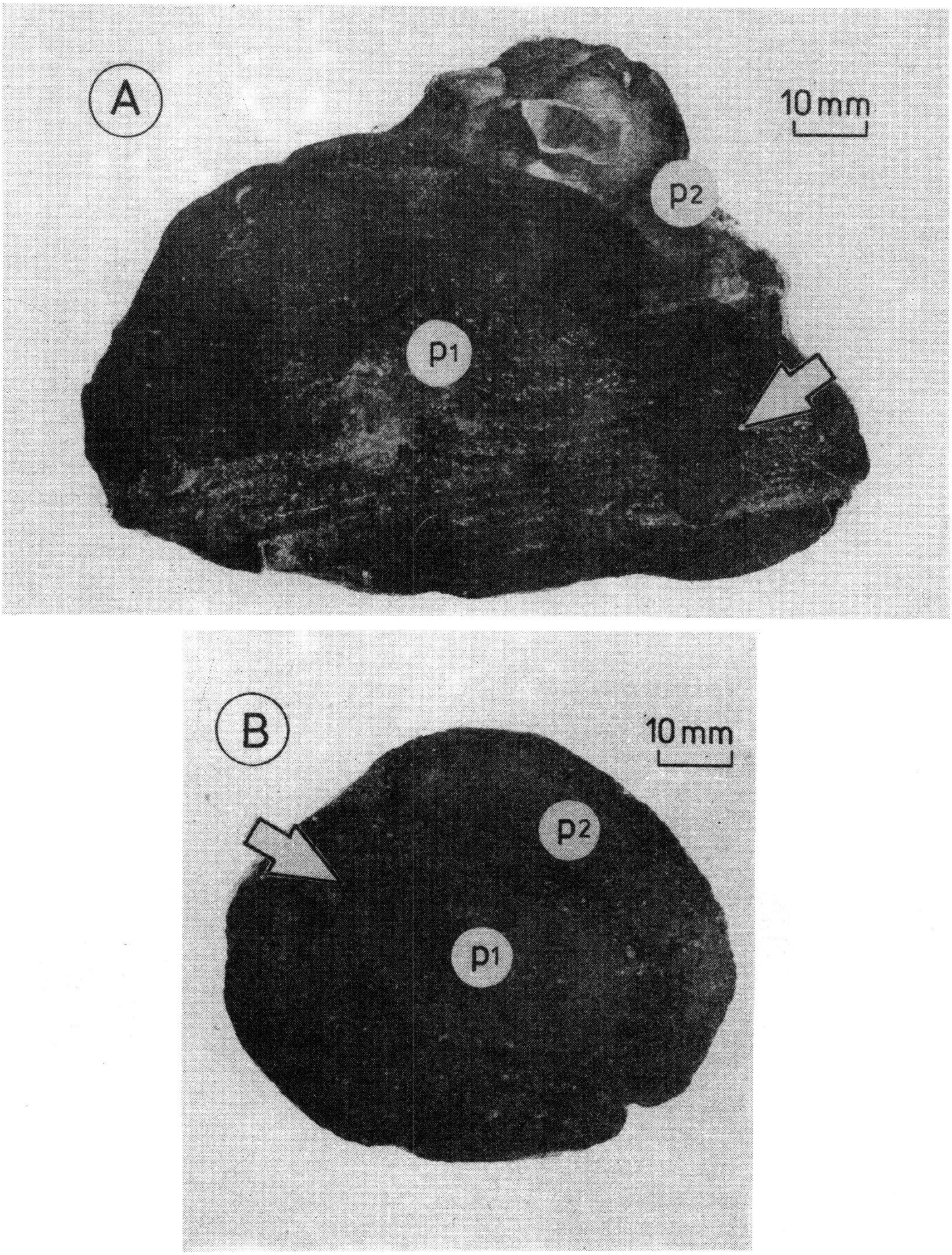
A
10 mm
p2
p1
B
10 mm
p2
p1