Microfossils in metasediments from Prins Karls Forland, western Svalbard

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The stratigraphic importance of fossils is never more apparent than in attempts to unravel the complexities of metamorphic terrains. The age and stratigraphic relationships of the thick metasedimentary and metavolcanic succession of Prins Karls Forland, western Svalbard, have been the subject of investigation and debate since the early part of this century (Hoel 1914; Craig 1916; Tyrrel 1924), and sharply different interpretations have been proposed (e.g. Harland et al. 1979; Hjelle et al. 1979). Until now, such interpretations have been unconstrained by palaeontological data, an understandable consequence of the metamorphic alteration undergone by these rocks. In this paper, we report the discovery of stratigraphically useful microfossils preserved in chert nodules from carbonaceous, dolomitic shales on northern Prins Karls Forland. These fossils have significant implications for the stratigraphic and structural interpretation of Forland metasediments, as well as for the more general problem of palaeontological prospecting in severely deformed and metamorphosed terrains, including those characteristic of the Archean Eon.

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Geological setting

Stratigraphy

In broad terms, six different lithological successions can be recognized on Prins Karls Forland (e.g. Manby 1986): a conglomeratic unit (the Sutor Conglomerate of Hjelle et al. 1979), a succession of tilloids interstratified with metamorphosed greywackes, a black carbonate-pelite unit, a sequence containing quartzites and other metamorphosed sandstones and pelites, a series of sandstones and pelites interbedded with metavolcanics and a sequence of high grade metavolcanics and associated pelites including iron formation (Harland et al. 1979; Hjelle et al. 1979; Manby 1983a) (Table 1). In the absence of fossils and the poor preservation of orienting sedimentary structures, stratigraphic interpretation has been tied closely to structural interpretations and assumptions about the relationship between stratigraphic position and metamorphic grade. Concerned research groups agree on several important points:

1. The conglomerate unit contains clasts of other lithologies and thus sits at or near the top of the succession. According to Hjelle et al. (1979), this unit overlies the quartzite-pelite beds, from which it is separated by a low angle fault contact; its stratigraphic position is regarded as uncertain. On the other hand, Harland et al. (1979) regard this conglomerate as a member within their Grampian Group and, therefore, interstratified with the quartzite-pelite beds.

2. The high grade metavolcanic/pelitic/iron-ore-bearing succession is the oldest unit in the succession.

3. The tilloids correlate in a general way with Vendian glaciogenic rocks that occur throughout the peri-North Atlantic region.

4. The entire sequence was weakly metamorphosed and deformed during the Caledonian orogeny and is therefore pre-Devonian.

Concerning other relationships within the Forland complex, however, there is significant disagreement. On the basis of his reconnaissance of the entire island, Atkinson (1954, 1956, 1960) proposed an interpretation of the metamorphic and structural features of Prins Karls Forland. Among other things, he interpreted the structure of the island in terms of a large southwest verging nappe system. Continuing work by members of the Cambridge Spitsbergen Expedition led to the proposal of a formal stratigraphic framework by Morris (1982) and Manby (1983a, 1983b, 1986). The stratigraphic and structural interpretations embodied in this classification have been incorporated with some modifications. In this scheme, the Vendian tilloids (the Ferrier Group of

Harland et al. 1979) are considered to lie above the high grade succession (Pinkie Group), with the carbonate-pelite, psammo-pelitic/volcanic (Geikie, Peachflya and Scotia groups) and psammo-pelitic (Grampian Group) successions overlying it in ascending stratigraphic order (Table 1). In the informal stratigraphy of Hjelle et al. (1979) the units were arranged in essentially the opposite stratigraphic order, with the tilloids near the top of the succession. The two stratigraphic schemes and possible tie-lines are shown in Table 1. In this discussion, we will use the informal lithological nomenclature indicated in Table 1 (last column) in order to avoid possible confusion that might stem from the use of differing stratigraphic names.

Prins Karls Forland is a NNW-SSE trending horst block bounded by grabens on both sides (Fig. 1). In the northern part of the island where the microfossils were found, one can observe moderately open, km-scale folds (Fig. 2). The lithostratigraphy adopted in Table 1 (last column) is based mainly on field work completed in this area by three geologists of Norsk Polarinstitutt. (In other regions of the island overfolding and thrust structures complicate stratigraphic interpretation.) Even though the northern region of the island is *relatively* simple in structure, small scale features, including isoclinal folds, make the estimation of original stratigraphic thicknesses problematic. (The structural interpretations depicted in Fig. 2 are those of Norsk Polarinstitutt geologists; for an alternative interpretation, see Manby (1986).)

A critical relationship in this region is that between the black carbonate/pelite (BCP) and psammo-pelitic (PP) units (Fig. 2; Table 1). Within these units, competent lithologies such as quartzites and carbonates occur as brittly deformed beds within strongly cleaved slates. Rarely, sandy beds show cross-bedding and/or convolute textures that can be used to determine top and bottom. In Fig. 2 the locations and senses of six unequivocal bed orientations are illustrated by arrows – five are normal (right side up), and one, from a fault zone, is inverted. These observations occur in the PP near the boundary with

Table 1. Comparative summary of published lithostratigraphic shales of Prins Karls Forland (thickness, km, in parentheses). The third column indicating the informal terminology used in this paper is based on the current structural and stratigraphic interpretations of Y. Ohta.

Hjelle et al., 1979		Harland et al., 1979, Morris, 1983 Manby, 1986	This paper, only northern part
Sutor Conglomerate	Grampian Gr	Geddesflya Fm (1.8)	Sutor Conglomerate
Tilloid fm (1.0)	Grampian Gr	Fuglehuken Fm (0.4)	Black carbonate -pelite unit (BCP)
Calc-argillo -volcanic fm (1.0)	Grampian Gr	Barents Fm (0.5) * Includes Sutor Conglomerate	Psammo-pelitic unit (PP)
Quartzite-sand -stone fm (0.9)	Grampian Gr	Conqueror Fm (0.85)	Psammo-pelitic -volcanic unit (PPV)
	Grampian Gr	Utnes Fm (0.08)	
Black shale fm (0.55)	Scotia Gr	Omondryggen Fm (0.4)	
	Scotia Gr	Kaggen Fm (0.3)	
high-grade succession (0.3)	Scotia Gr	Bakila Fm (0.3)	
		Peachflya Gr (1.3)	
		Geikie Gr (0.77)	
		Ferrier Gr (0.73)	
		Pinkie Gr (0.2)	

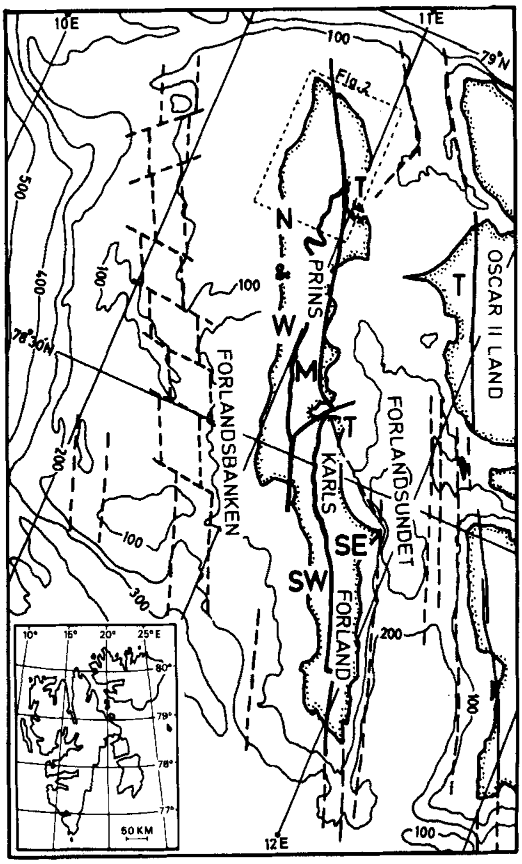

Fig. 1. Tectonic outline map of Prins Karls Forland. Bold letters indicate major structural divisions of the island. The area labelled T consists of Tertiary rocks. Prins Karls Forland is a horst bounded by the Tertiary graben on east and west sides.

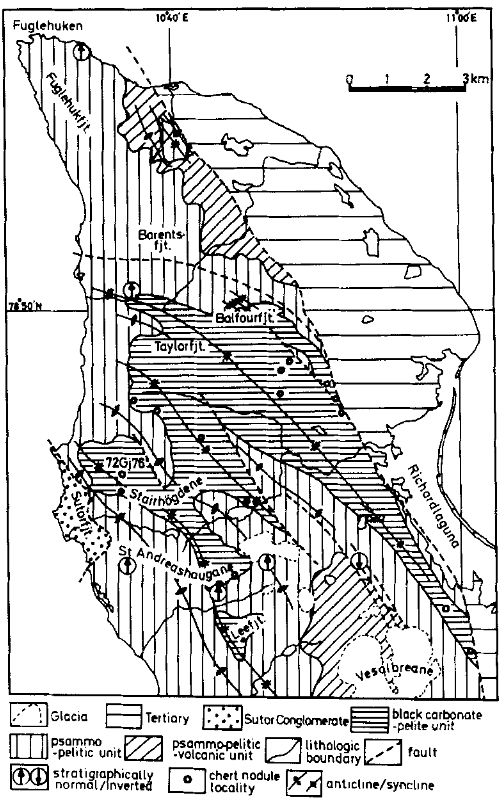

Fig. 2. Geological map of northern Prins Karls Forland. Data are from the field works of T. Gjelsvik 1968, 1970, 1971, 1972 and 1974, Y. Ohta 1972 and A. Hjelle 1985 and 1986. The fossiliferous chert locality is marked as 72Gj76.

the BCP. Boundary relationships are especially clear on the southern slope of St. Andreashaugane, where a basal conglomerate in the BCP shows normally oriented cross-bedding and contains clasts of underlying PP shaley and quartzitic rocks. On the basis of this evidence the BCP is placed stratigraphically above the PP. Manby (1986) interpreted this boundary as a thrust. Some displacement does exist along the steep western limb of syncline, but sedimentary contact has been preserved locally in the crestal part. Tilloids do not occur in northern Prins Karls Forland.

Metamorphism

The most highly metamorphosed rocks on Prins Karls Forland occur within a narrow fault block 3.5 km SSE of Vesalbreane (area M in Fig. 1). Here, within a mylonitized zone, rocks of the high grade succession occur as sillimanite-garnet-biotite gneisses and clinopyroxene-hornblende amphibolites having strongly cataclastic textures (Hjelle et al. 1979). Scapolite-calcite and scapolite-muscovite schists, chloritoid-bearing green phyllite, actinolite-chlorite-epidote ± garnet-schists (Manby 1983a) and stratiform quartz-magnetite schists have been described from adjacent fault blocks (Hjelle et al. 1979). These rocks have been brought up at least 4 km from beneath younger strata (Manby 1983a).

Younger metasediments record less severe metamorphic conditions. Green phyllites within the SW region of the island (Fig. 1) contain chloritoid with muscovite, chlorite and (±)actinolite. Manby (1983b) estimated that these rocks reached temperatures of 380–400°C and pressures of 4–5 kb. Morris (1982) examined various metasedimentary rocks that are structurally higher, but stratigraphically older than those in Manby (1983a), belonging to the Peachflya-Geikie-Ferrier Groups and recorded calcite-dolomite-(ankerite)-quartz-muscovite ± epidote mineral assemblages in calcareous lithologies, chlorite ± chloritoid-muscovite±green biotite ± epidote ± albite in psammitic and pelitic rocks and muscovite-biotite-chlorite ± tremolite-epidote-albite in green metavolcanics. The carbonate assemblages suggest metamorphic conditions of 300–500°C at P_{CO_2} of 0.5 to about 1.0 and a pressure of 1 to about 4 kb. The total-Al immiscibility between co-existing amphiboles gives a temperature range of 520–590°C, according to the immiscibility curve of Misch & Rice (1975). Morris (1982) concluded that younger metasediments in the SW region of Prins Karls Forland experienced maximum temperatures of 400–500°C at 4 kb pressure, for an inferred thermal gradient of about 18°C/km. That is, in the SW region metamorphic rocks are at lower to middle greenschist facies.

In the area where fossils were found, a chloritoid-bearing phyllite has been reported by Manby (1983a, 1986), but dominant muscovite ± chlorite ± calcite-dolomite-quartz assemblages with subordinate graphite, opaque metals and idiomorphic pyrite suggest a lower greenschist facies of metamorphism.

Fossil-bearing rocks

At the fossil localities noted in Fig. 2 the black carbonate-pelite (BCP) unit consists predominantly of slaty dolomite and dolomitic slates interbedded with black slates and carbonate units up to 20 m thick. The more competent carbonates are largely (90% or more) microcrystalline dolomite, with admixtures of fine-grained quartz clasts and opaque materials such as graphite, pyrite and oxidized sulfides. Cross-cutting calcite veins are common. Oolitic beds occur within these carbonate units. Slaty beds commonly contain 20–50% weakly recrystallized granular dolomite, along with up to 30% muscovite, graphite and opaque minerals. Local sandy layers contain 10–40% subangular quartz grains, as well as occasional detrital albite grains. Pyrite commonly occurs as idiomorphic grains up to 0.1 mm across with pressure shadows of ribbon-shaped quartz or calcite anhedra.

Chert nodules are found mainly near the base of the BCP unit, where they occur as 1–4 cm oblate spheroidal to irregularly shaped concretions within slaty dolomites. Unlike the beds in which they occur, these nodules are undeformed by cleavage. The nodules consist of microquartz anhedra with rare, later diagenetic, dolomite euhedra. In some cases, metamorphic calcitization has resulted in the replacement of all but the cores of nodules by coarse blocky calcite. Cherty areas contain abundant organic carbon, mostly graphitic or nearly so. Despite the history of these rocks, original bedding textures and, often, microfossils are clearly preserved. Locally within nodules, quartz recrystallization has obliterated original textures.

The microfossil assemblage

For the most part, the fossils contained in Forland chert nodules are not well preserved and would doubtfully survive conventional palynological preparation. They do, however, show up well in petrographic thin sections cut perpendicular to bedding. Within these rocks, microfossils are surprisingly abundant and well preserved. The following taxa have been identified in sample 76Gj76 (Fig. 2):

Eomycetopsis robusta Schopf emend. Knoll & Golubic (1979)

Nonseptate filaments, 2–3 μm in diameter, interpreted as the extracellular sheaths of oscillatorian cyanobacteria (Fig. 3E). Common as isolated and often fragmentary individuals and as densely interwoven populations oriented more or less parallel to bedding. The latter are interpreted as microbial mat building populations. *Eomycetopsis robusta* populations are common constituents of Proterozoic microfossil assemblages, including those from eastern Spitsbergen and Nordaustlandet (Knoll 1982; Knoll & Calder 1983). As morphologically identical cyanobacteria occur today, little of stratigraphic significance can be concluded from this observation.

Eomycetopsis sp.

3–4 μm nonseptate tubes that characteristically occur in groups of 20 or more individuals tightly wound together (Fig. 4C). Comparable to the modern cyanobacterium *Microcoleus*. Uncommon components of the microbenthos in the BCP cherts. Comparable microfossils are known from the c.680–790 Ma old Min'yar Formation of the southern Urals (Nyberg & Schopf 1984) and the c.700–800 Ma old Draken Conglomerate Formation of northeastern Spitsbergen (Knoll unpublished observations). Again, no stratigraphic relationships are implied by this distribution.

Siphonophycus inornatum Zhang

3–8 μm nonseptate sheaths interpreted as cyanobacterial sheaths (Figs. 4A, B). They commonly occur as mat building populations (Fig. 4B) and as short, probably allochthonous filaments. These filaments probably have little biostratigraphic significance, although they occur widely in Middle and Upper Proterozoic rocks of Spitsbergen and elsewhere.

Siphonophycus sp.

20–50 μm in diameter nonseptate tubes interpreted as cyanobacterial sheaths. Locally common as subordinate builders in mat clasts. Large sheaths of comparable aspect are widely distributed in Middle and Late Proterozoic mat assemblages.

Myxococcoides spp.

Coccoidal cells, isolated or in aggregates, 4–15 μm in diameter (Fig. 3E). The generally poor preservation of these cells makes attribution to species (or higher taxa) problematic.

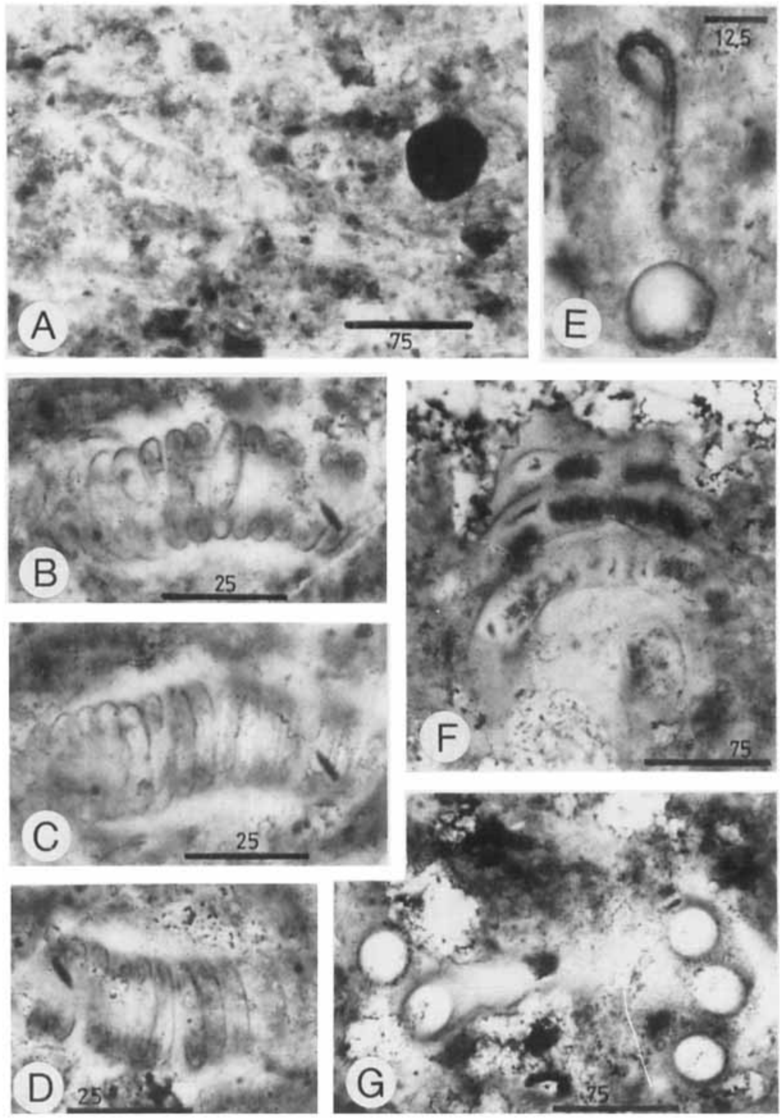

Fig. 3. Microfossils in BCP chert nodules. (Harvard University Paleobotanical Collection number, thin section number and England Finder coordinates are given for each specimen illustrated.) A: Lower power view showing *Obruchevella parva* Reitlinger and a nearly opaque spheroidal acritarch. B-D: *Obruchevella parva*, same specimen as in A, seen at different focal depths (HUPC # 62296, 72Gj76-2, 049/0). E: *Eomycetopsis robusta* Schopf emend. Knoll & Golubic and *Myxococcoides* sp. (HUPC # 62296, 76Gj76-2, S54/2). F: ?*Obruchevella* sp. (HUPC # 62301, 72Gj76-3c, R56/4. G: ?*Obruchevella* sp. (HUPC # 62298, 72Gj76-3g, G54/2). Scales are in µm.

Obruchevella parva Reitlinger (1959)

Nonseptate cylindrical filaments wound into a tight helical spiral with a cylindrical cavity; filament diameter = 4–5 µm; diameter of spiral = 25–30 µm; coiled individuals about 80 µm long (Fig. 3A-D). This species is a rare component of the BCP assemblage. It has generally been interpreted as cyanobacterial in origin, but might better be considered problematical. This species helps constrain age estimates, see discussion below.

?*Obruchevella* sp.

Large spirally wound tubes; tube diameter 28–33 µm and spiral diameter up to 230 µm; only two to four winds in spiral (Figs. 3E, F). This fossil is a conspicuous but uncommon constituent of the BCP assemblage. It is organized generally like *Obruchevella*, but is larger and shorter than most described species and is clearly septate. Only large specimens from the uppermost Proterozoic or lowermost Cambrian Tindir group of Alaska, discussed but not figured by Cloud et al. (1979),

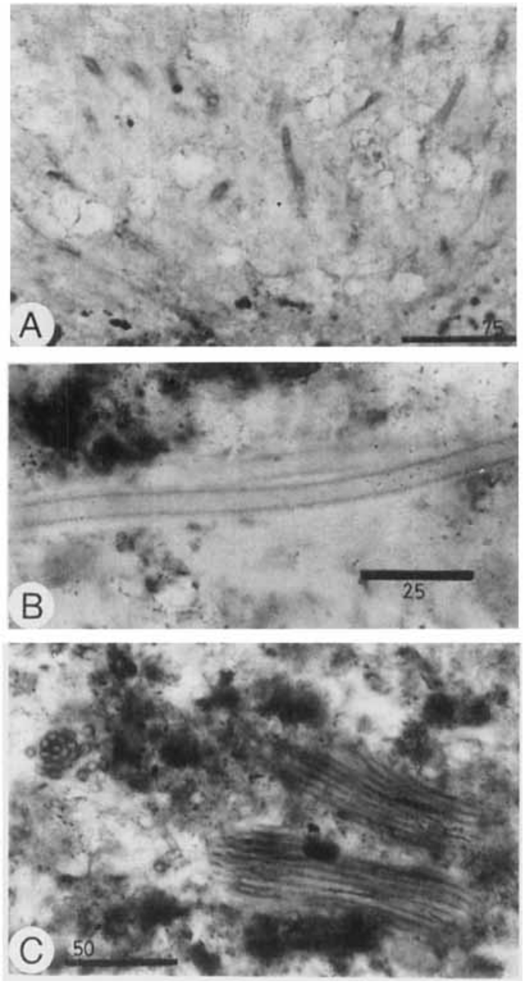

Fig. 4. Microfossils in BCP chert nodules. (Harvard University Paleobotanical Collection number, thin section number and England Finder coordinated are given for each specimen illustrated.) A: Microbial mat population of *Siphonophycus inornatum* Zhang, showing predominantly vertical orientation of filaments (HUPC # 62296, 72Gj76–2, T51/2). B: *Siphonophycus inornatum* (HUPC # 62297, 72Gj76–3f, N62/4). C: *Eomycetopsis* sp. (HUPC # 62298, 72Gj76–3g, L59/4). Scales are in µm.

reach the dimensions of this Forland population. Although members of this population are distinct from previously described species of *Obruchevella*, they are most similar to *O. meishucunensis* Song (1984) from the basal Cambrian of the Yunnan Province, China. Dimensions of the Forland Fossils are approximately 50% greater than those of the Chinese population. Fossils described as *Circulinema jinningense* Wang et al. (1983), also from the Yunnan Lower Cambrian, resemble the Forland fossils as well.

Acritarchs

Large (>30 µm diameter) spheroidal vesicles are scattered throughout the BCP cherts. Most are poorly preserved and essentially featureless; these are probably comparable to leiosphaerid acritarchs that are widely distributed in Upper Proterozoic and Paleozoic marine rocks. More interesting are rare specimens of large, process-bearing acritarchs (Fig. 5). Three measured speci-

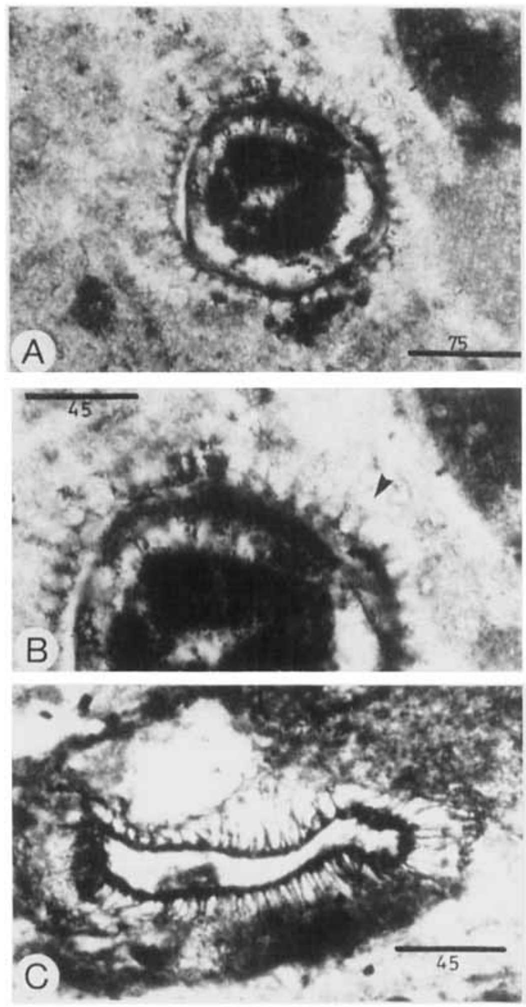

Fig. 5. Large, process-bearing acritarchs in BCP chert nodules. A: Undeformed specimen (62299, 72Gj76–3a, J47/0). B: Enlarged view of A. C: Compressed specimen – long axis parallels bedding (HUPC # 62300, M-4, H56/4). Scales are in µm.

mens of this taxon have vesicles 123, 132 and 143 µm in diameter and are densely covered with hollow processes about 1 µm in diameter and averaging 8, 12 and 14 µm in length, respectively. The processes appear to flare slightly at their distal ends. Although there is no clearly preserved outer membrane supported by the processes, the absence of pigmenting organic matter in the chert between adjacent processes suggests that such a feature may originally have been present. Several genera of comparably large and complex acritarchs have been described from Upper Riphean and Vendian rocks (e.g. Timofeev et al. 1976; Knoll 1984; Zhang 1984; Vidal & Ford 1985; Yin 1985; Awramik et al. 1985; Zang & Walter in press; Butterfield et al. unpublished). Among these, a specimen described as *Vandalosphaeridium* sp. from the latest Proterozoic Doushantuo Formation of the Yangzte Gorge District, China (Yin 1985), and fossils reported as *Cymatiosphaeroides* n. sp. from the latest Proterozoic Pertetateka Formation, central Australia, (Zang & Walter in press) are most similar to the Forland process-bearing acritarchs. The biostratigraphic significance of this population is discussed below.

Paleontological interpretations

Paleoenvironmental constraints

The BCP cherts contain in situ microbial mats and photoautotrophic microbenthos, as well as discrete clasts of ripped up and redeposited mat sediments. Therefore, the BCP sediments were deposited within the photic zone. Comparison of mat and clast populations to those of better known microfossil assemblages further suggests deposition in shallow water, consistent with the presence of oolites in associated dolomites.

Stratigraphic constraints

Obruchevella parva has been described from Vendian to basal Cambrian deposits of the Soviet Union, China and Saudi Arabia (Cloud et al. 1979; Golovenok & Belova 1983; Wang et al. 1983; Song 1984). More generally, the genus *Obruchevella* has a known range extending from the Upper Riphean to the Adtabanian (Golovenok & Belova 1983; Riding & Voronova 1984), with possible extension to the Ordovician. Large specimens such as ?*Obruchevella* are known only from near the Proterozoic-Cambrian boundary. Large spiny acritarchs of the type found here are also best known from late Vendian (i.e. stratigraphically above tilloids and below lowermost Cambrian beds) deposits of China and Australia, although generally similar large and complex acritarchs do occur in latest Riphean deposits from Spitsbergen, Nordaustlandet and the Soviet Union. Process-bearing acritarchs are common in Paleozoic assemblages, but they are almost invariably smaller than the specimens observed in the BCP cherts, averaging 30–50 µm in vesicle diameter or less.

Based on these fossils, the most likely age for the BCP beds is late Vendian – i.e. post-tilloid but pre-Cambrian in age. Two observations support this determination. First, acritarch and prasinophyte algal fossils that characterize Cambrian and younger rocks have not been observed in these beds. Granted, the total number of observed acritarchs is small. However, the likelihood of encountering only leiosphaerid and large process-bearing acritarchs in a random sampling of a typical Paleozoic assemblage is low. Second, the BCP cherts contain no textural evidence for the presence of skeletons. While this observation does not unequivocally rule out a Paleozoic age for the rocks, the lack of shell fragments coupled with the preservation of microbial mat microfossil populations in shallow marine sediments is most reminiscent of known Proterozoic rocks.

The uncertainties of this age estimate need to be underscored. The published records of both *Obruchevella* and large, process-bearing acritarchs are scattered and likely to be incomplete. Thus, it is entirely possible that *O. parva* will eventually be described from Upper Riphean rocks along with acritarchs of the type figured in this paper. It is less likely that comparable assemblages will be found to characterize some Cambrian or younger environments.

If a late Vendian age can be confirmed by continued research, then stratigraphic schemes placing the BCP above the tilloids will be favored. An earlier age would, of course, favor the opposite arrangement. At present, the former option appears to be favored, but we reiterate the biostratigraphic uncertainties noted in the previous paragraph. It is worth noting that no *Obruchevella*-bearing assemblages have been found on eastern Spitsbergen or Nordaustlandet. In these areas, late Vendian rocks are either nonmarine or missing (Fairchild & Hambrey 1984; Knoll & Swett 1987).

Preservational significance

Metamorphic terrains of all ages present special problems of stratigraphic interpretation because fossils are rarely preserved. Chert nodules in moderately deformed areas appear to shield enclosed microfossils from the full effects of deformation and metamorphism; thus, they provide otherwise unavailable opportunities for biostratigraphic age determination. This circumstance has been recognized and exploited by micropaleontologists studying radiolaria preserved in Mesozoic cherts from the Alps, California and elsewhere. The potential application to regions containing deformed Paleozoic and Upper Proterozoic successions is high. While not answering unequivocally the major questions of Forland stratigraphy, our preliminary work shows the means by which these questions can be answered.

The preservation of fossils in greenschist facies metasediments from Prins Karls Forland also has implications for the preservation of microfossils in Archean terrains, virtually all of which have suffered regional greenschist facies metamorphism. Our work suggests that even though most Archean sediment-bearing terrains have undergone at least weak metamorphism, there is a significant probability that delicate microfossil remains will be preserved in locally lower grade rocks, and within these, in lithologies protected by early diagenetic silicification.

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