Coniacian–Santonian Radiolaria from the Upper Cretaceous of Bornholm, Denmark: *A preliminary investigation*

STEPHEN R. PACKER & MALCOLM B. HART

A moderately diverse fauna of Late Cretaceous Radiolaria are described for the first time from the Arnager Limestone and Bavnodde Greensand formations exposed on the island of Bornholm (Den-mark). Our preliminary investigation suggests that the fauna from the Arnager Limestone Forma-tion is relatively abundant and is assigned to the *Orbiculiforma vacaensis* Subzone (*Alievium praegallowayi* Zone) of Coniacian age. Relatively poor recovery from the Bavnodde Greensand For-mation precludes assignment to the zonation scheme of Pessagno, although, the radiolarian taxa present indicate that the formation can be no younger than Santonian. The ages given for both formations by the radiolarian faunas compare favourably with published macrofossil and microfossil data. The radiolarian faunas described are of moderate abundance and diversity when compared to contemporaneous faunas described elsewhere, particularly the Tethyan area. Maximum radiolar-ian abundance and diversity is reached in the middle of the Arnager Limestone Formation equating to a level of maximum water depth from the foraminiferal data. A decline in radiolarian recovery is recognised into the Bavnodde Greensand Formation and is associated with a reduction in relative water depth to inner and (?)middle shelf conditions, as indicated by foraminiferal data.

Key words: Radiolaria, Upper Cretaceous, Coniacian, Santonian, Bornholm, Denmark.

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The Danish island of Bornholm lies in the southern Baltic Sea (Fig. 1). The island sits within the structurally complex Fennoscandian Border Zone which trends NW-SE through Scania and across the Baltic Sea. The greater part of the island is formed of Precambrian granites, migmatites and gneisses. Palaeozoic and Mesozoic sediments occur as block-faulted areas within the southern and western parts of the island. Running northwest-southeast through the island are a series of major faults which are associated with the Fennoscandian Border Zone (Christensen 1985). On the west coast of the island between Rønne and Hasle, is the edge of a north-south trending graben. The intersection of the two trends (northwest-southeast and north-south) provides the main geological structure, as well as the overall shape of the island. During the Mesozoic the Fennoscandian Bor-der Zone acted as a boundary between the stable Fennoscandian Shield to the north and east and the subsiding Danish Basin to the south and west. Upper Cretaceous sediments deposited over the horst and graben topography in the Bornholm area formed a uniform sheet, tapering in a northeast direction (Vejbæk 1985). This study is concentrated on part of the Upper Cretaceous marine succession of the island, comprising sediments of Coniacian to Santonian age, and examines the radiolarian faunas from the succession, assessing their biostratigraphic potential and significance. This follows on from detailed biostratigraphic and palaeoecological work by Packer (1991) and subsequent work on sea-level change (Packer & Hart 1994).
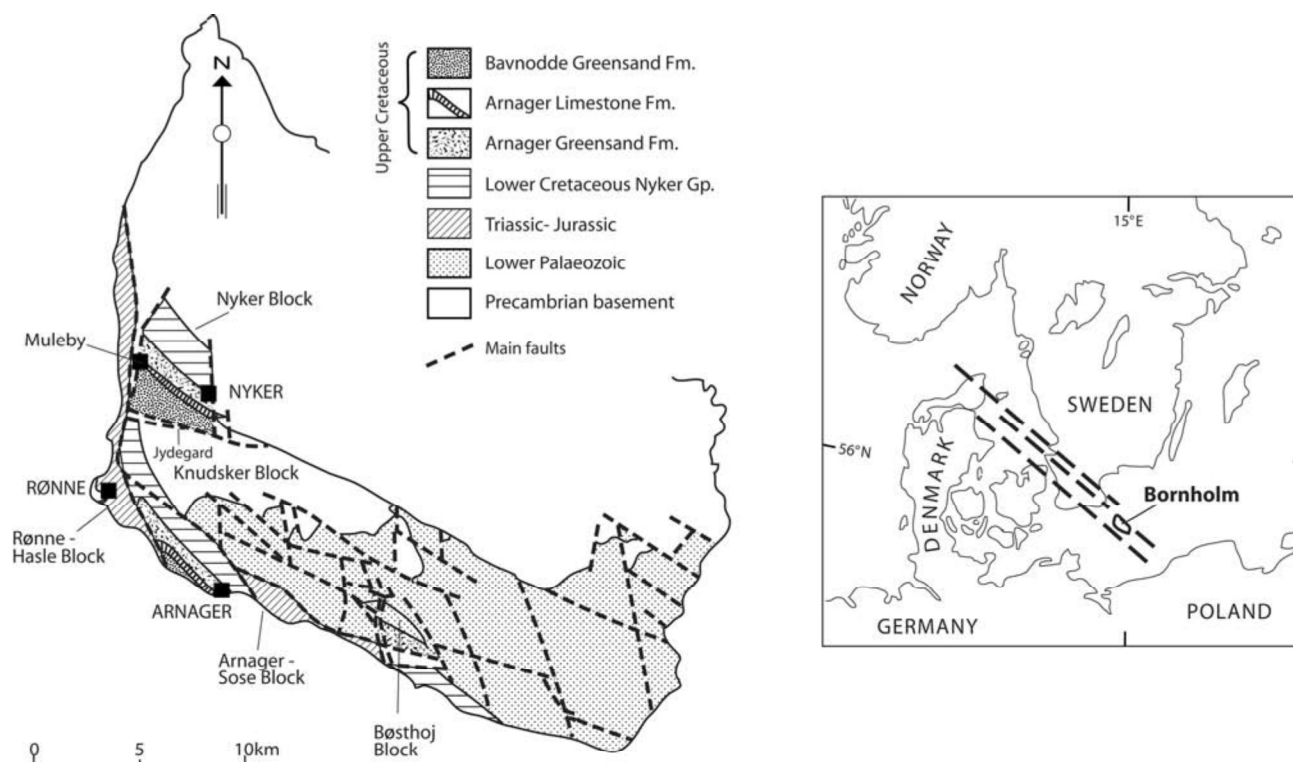
Fig. 1. Outline geological map of the Island of Bornholm (after Gravesen *et al.* 1982) and the location of Bornholm within the Fennoscandian Border Zone.

The Cenomanian to Santonian succession of Bornholm

The Cenomanian to Santonian succession consists of, from bottom to top: the Arnager Greensand, the Arnager Limestone, and the Bavnodde Greensand formations (Christensen 1985). The best exposures of the succession are found on the south coast of the island in the Arnager-Rønne area (Fig. 2). More detailed outcrop locations and details are beyond the scope of this paper, but may be found in Packer (1991), Tröger & Christensen (1991) and Christensen & Schultz (1997). The general succession is shown in Figure 3. Radiolaria are present in the Arnager Limestone and Bavnodde Greensand formations but have not been found in samples of the Arnager Greensand.

The Arnager Limestone is a silica-rich chalk which is approximately 12–20 m thick (Ravn 1918; Christensen 1985: Noe-Nygaard & Surlyk 1985). The contact between the Arnager Greensand and overlying Arnager Limestone is complex, consisting of several generations of phosphatised and glauconitised pebbles (Fig. 4). The boundary is best exposed on the south-west coast of the island, and has been illustrated by Bromley (1979). The presence of compound phosphatised intraclasts at the boundary indicates

repeated periods of sedimentation, cementation, erosion and phosphatisation.

The main part of the Arnager Limestone is lithologically uniform, although low mud mounds formed by sponge baffling have been described by Noe-Nygaard & Surlyk (1985). The macrofauna of the formation comprises inoceramids (Tröger & Christensen 1991), belemnites (Christensen & Schultz 1997), brachiopods, ammonites (Kennedy & Christensen 1991) and sponges (Noe-Nygaard & Surlyk 1985). In their investigation of the sponges (and in particular the spicule 'mats'), the latter make no mention of radiolarians within the sediments.

The ammonite faunas recovered from the formation have recently been reviewed by Kennedy & Christensen (1991), who suggest that the formation is, in part, at least middle Coniacian, based principally on the occurrence of *Peroniceras tridorsatum* (Schlüter). Work on the inoceramid fauna by Tröger & Christensen (1991), indicates that the formation is of early Coniacian age at its type locality (on the coast), although variations in the age of the formation at different localities have been noted (Tröger & Christensen 1991, fig. 2).

Packer (1991) reviewed the foraminiferal age data for the formation, and concluded that the formation is of mid-Coniacian age. Schiøler (1992) examined
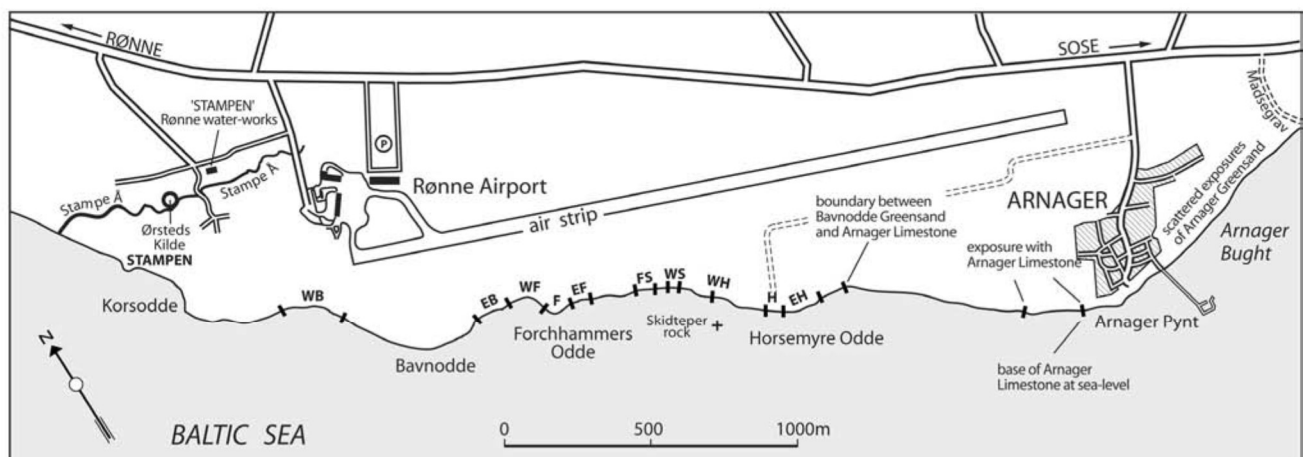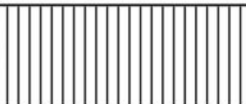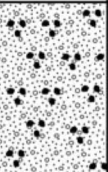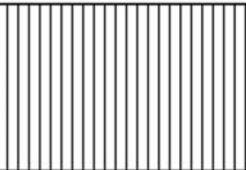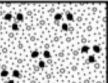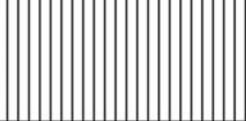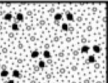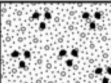
Fig. 2. Location of the outcrop of the Arnager Limestone and the Bavnodde Greensand formations on the south coast of Bornholm. The sections in the valley of the Stampe Å are also indicated. WB-West Bavnodde; EB-East Bavnodde; WF-West Forchhammers Odde; F-Forchhammers Odde; EF-East Forchhammers Odde; FS-between Forchhammers Odde and Skidteper rock; WS-West of Skidteper rock; WH-West Horsemyre Odde; H-Horsemyre Odde; EH-East Horsemyre Odde.

the dinoflagellate cysts from the formation and concluded that it is of early to mid-Coniacian age. Of the dinocyst species described by Schiøler (1992) several species have particular stratigraphical significance. An age no older than early Coniacian is suggested for the base of the Arnager Limestone from the combined presence of *Florentina tenera* (Davey & Verdier, 1976) Duxbury, 1980, and *Oligosphaeridium pulcherrimum* (Deflandre & Cookson, 1955) Davey & Williams, 1966, and from the succeeding first occur-

Fig. 3. Lithostratigraphy and chronostratigraphy of the mid-Cretaceous succession of the Arnager-Sose Block, Bornholm.

West Bavnodde locality (WB)

BO12
BO11
BO10
BO1/BO5
BO2/BO6
BO3/BO7   nodular glauconitic sand
BO4/BO8
BO9   quartzose glauconitic sand

BO21
BO20
BO19
BO16   East Bavnodde
BO17   locality (EB)
BO13
BO14
BO15

BO16   AK32   locality (FS)
            AK31
            AK30

BO29   locality (WS)
BO28

BO25   locality (EF)
BO24
BO23
BO22
BO26

BO27

—10m

—0m

AK22
AK20   upper part of section dug from
            undergrowth just E. of Horsemyre Odde
AK19   - bad exposure - thickness estimated
            - based on WKC locality EH
AK18
AK16   lower part of the Greensand is nodular,
            calcareous and sits on planar surface
AK17   of Arnager Lst. Limestone is slightly
            muddy, but otherwise shows no
            unusual features for this section
AK21
            dark grey marl seam
AK15
            gap in section
AK8
AK9   —2m
AK10   —0m
AK11
AK12   lower part of the Arnager Lst. section
            based on eastern bluff of main cliff
AK13   with sample AK15 being found in the
            centre of the West cliff
AK14

AK7

AK22
AK20
AK19
AK18
AK16   top Arnager Limestone Formation
AK17
AK21

C S F M C

lower part of the Arnager Lst. section
based on eastern bluff of main cliff
with sample AK15 being found in the
centre of the West cliff

site 4

AK7
AK6
AK5   complex 'pebble bed'

Thalassinoides   limestone with glauconite
burrow systems   and phosphates
at this level

AK4   1.20m
           1.00m
           0.80m
AK3   0.60m

expanded section   deep 'burrow' systems
of boundary   in uppermost Arnager
AK2   Greensand Formation
AK1   0.40m
           0.20m
           0.00m

0.80m 0.60m 0.40m 0.20m

rence of *Spinidium echinoideum* (Cookson & Eisenack, 1960; emended Sverdlove & Habib, 1974) Lentin & Williams, 1976. Evidence for an age of no younger than late Coniacian for the Arnager Limestone is provided by the highest occurrence of *Florentina deanei* (Davey & Williams, 1966) Davey & Verdier, 1973, within the mid-Stampe Å stream locality. In addition, *Spinidinium echinoideum* was found (Schiøler 1992) to be common to abundant at the base of the Stampe Å stream succession, and may be correlated with the first common occurrence event of the taxon recorded by Pearce (2000) from eastern England in the upper Coniacian. Finally, it must be noted that the intense bioturbation of the lower part of the Arnager Limestone may complicate the interpretation of the maximum age of the formation. Overall, the available biostratigraphic evidence suggests an age of early to late middle Coniacian for the entire formation.

Hart (*in* Bromley 1979) and Packer *et al.* (1989) recognised a major hiatus between the Arnager Greensand (of middle Cenomanian age) and the Arnager Limestone, based on the foraminiferal data. There is no evidence from the boundary between the two formations to suggest that deposition may have continued at a reduced rate through the Cenomanian to Turonian interval (Packer *et al.* 1989; Packer 1991; Packer & Hart 1994). This interpretation of sea-level fluctuations has been further tested and supported by later work (Vadja-Santivanez & Solakius 1999). Mixed dinocyst assemblages from this level indicate a late (?)Cenomanian to late Coniacian age. There is very little macrofaunal evidence for the age of the boundary, though Christensen (1985) reports the occurrence of *Echinocorys* ex. gr. *gravesi* Desor, which ranges from the middle Turonian to early Coniacian, *Inoceramus lamarcki* Zone – *Inoceramus deformis* Zone.

The Bavnodde Greensand is a poorly sorted, glauconitic, fine grained, silty, quartz sand, approximately 180 m thick (Christensen 1985). There is very little published sedimentological information available on the formation as a major investigation of the succession remains unpublished (Brüsch 1984). Packer *et al.* (1989) suggested that coarse levels within the formation may represent storm events, while Schmidt (1982) has suggested that the graded sandstone units within the Bavnodde Greensand could be accounted for by shallow-water turbidite events. The Bavnodde Greensand rests on the eroded upper surface of the Arnager Limestone. Clasts of reworked lime- stone are present in the basal Bavnodde Greensand (Packer 1991).

Tröger & Christensen (1991) and Christensen & Schultz (1997) have recently reviewed the macrofossil evidence for the age of the Bavnodde Greensand. Ravn (1921) assigned the formation to the lower and lower middle Santonian on the basis of ammonites and belemnites. Importantly, all outcrops of the Bavnodde Greensand on the coast were considered to be of the same age. Birkelund (1957) assigned the formation to the lower middle Santonian. Subsequent work on the belemnite fauna by Christensen (1971) indicated that the Bavnodde Greensand west of Bavnodde should be assigned to the lower and lower middle Santonian. Studies of the inoceramid fauna by Tröger & Christensen (1991) suggest that an early Santonian age is appropriate for the Bavnodde Greensand at its type locality on the coast, whilst at Jydegaard and Risenholm it is older and may, at least in part, be of late Coniacian age at Jydegaard.

Packer (1991) reviewed the foraminiferal data and concluded that the formation is of (?)early – middle Santonian age. Solakius (1989) and Packer (1991) also suggest the presence of a hiatus between the Arnager Limestone and Bavnodde Greensand, with some of the upper Coniacian and possibly lower Santonian missing. This is based on the presence of the foraminiferids *Cibicides* ex. gr. *beaumontianus* and *Loxostomum eleyi* at the base of the Bavnodde Greensand, suggesting a level within the *Cibicides* ex. gr. *beaumontianus* Assemblage Zone of Bailey *et al.* (1983), which is of middle Santonian age. Closer sampling and analysis at the base of the formation (Packer 1991) confirmed a greater intraformational range for the latter species, than had been previously suggested by Packer *et al.* (1989), based on earlier analyses. The underlying Arnager Limestone falls within the *Lingulogavelinella* sp. cf. *vombensis* Assemblage Zone of Bailey *et al.* (1983), of mid-Coniacian age. The lack of the intervening *Loxostomum eleyi* Zone of Bailey *et al.* (1983), indicates the presence of a hiatus. It is possible, however, that the benthic foraminiferids are showing an earlier, facies-controlled, appearance related to the development of a greensand facies, as the Bailey *et al.* (1983) scheme derives foraminiferal data from the relatively lithologically uniform U.K. chalk succession. There remain, then, minor discrepancies for the age of the Bavnodde Greensand between the macrofaunal and microfaunal data.

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Fig. 4. Lithological successions and sampling horizons for the coastal succession west of Arnager.

Sample collection and preparation

Samples from the Arnager Limestone and Bavnodde Greensand formations were collected in 1975 by one of us (MBH) at approximately one metre intervals through the succession (Fig. 3). Samples were prepared for routine foraminiferal study by gentle crushing, followed by soaking in white spirit, the application of boiling deionised water and subsequent wet sieving, using a 63 µm sieve. Residues were dried, sieved (into the >250 µm, 250–125 µm and 125–63 µm size fractions) and picked for microfossils. Subsequently selected residues from the Arnager Limestone have been soaked in 10% hydrochloric acid to concentrate and clean the radiolarian fauna. The resulting residue has been found to consist of radiolaria, internal siliceous casts of planktonic foraminifera and free quartz grains. In certain samples the radiolaria comprise, we estimate, at least 95% of this residue. This simple method appears, therefore, to be highly effective. The acid digestion method is unnecessary for samples from the Bavnodde Greensand as this is a fairly unconsolidated lithology which can be broken down by simple water washing, though the non-siliceous content can be reduced by addition of hydrochloric acid, thereby concentrating (and cleaning) the radiolarian fauna.

The use of the acid digestion method on the Arnager Limestone samples in particular, has clearly shown that enhanced recovery of siliceous microfossils may be achieved. The use of this technique may also assist in obtaining more concentrated recovery of radiolaria in the Bavnodde Greensand. At present we have only been able to run the acid digestion technique on a limited number of samples through the Arnager Limestone, where we have retained bulk material from previous foraminiferal studies. The results of our initial studies presented herein are, therefore, considered to be only a preliminary study of the radiolarian faunas. At present we are not in a position to show detailed and consistent distribution data throughout the studied sections as radiolarian recovery is significantly increased by the application of the acid digestion method, whilst samples subjected to standard microfaunal processing techniques yield significantly lower numbers of radiolaria. In August 2004 a further 100+ samples were collected from the Cretaceous succession between Madsegrav and Korsodde, particularly from parts of the section better exposed at the present time. All of these samples are now being processed, many by acid digestion, in the anticipation of improving our recovery of radiolarians.

Specimens to be photographed were mounted on copper stubs with double-sided tape and coated with approximately 13 Å of gold. A Jeol (JSM-5600) Scanning Electron Microscope was utilised for photography, whilst elemental analysis of test material was carried out using a Jeol (JSM-6400) Scanning Electron Microscope.

Previous studies

Published studies on Cretaceous radiolarian faunas have increased significantly in number during the last two decades, with many new taxonomic and biostratigraphical studies being produced. These studies cover a wide variety of geographical locations across the globe, including Asia-Pacific, North and South America, Atlantic, Mediterranean, Arctic and Antarctic regions.

Much of the published work on Late Cretaceous Radiolaria in north-west Europe has come from the Tethyan region: Spain, Gibraltar and Italy (Thurow & Kuhnt 1986; Thurow 1988; Marcucci et al. 1994; Pignotti 1994; O'Dogherty 1994; Erbacher & Thurow 1996; Khan et al. 1999); Montenegro (Gorican 1994); and Romania (Dumitrica 1970, 1975). Further to the south and east there are also a large number of detailed studies from Greece, Turkey and the Russian Platform (Popova-Goll et al. 2005 and references therein).

In the north–west European Boreal province there are still relatively few published data on Late Cretaceous radiolarian faunas from more northerly areas. A wealth of radiolarian data has been generated in the Polish-Danish Trough, mainly from Poland. Radiolarian assemblages have been described from the Campanian (Górka 1989), Aptian? to Turonian (Bak 1995, 1999a; Bak & Bak 1999), the late Albian to Cenomanian (Bak 1993a, b; Bak & Oszcypko 2000), the Cenomanian–Turonian (Górka 1991; Bak 1994, 1996a, 2000; Górka 1995, 1996; Bak & Salowicz 2000; Bak et al. 2001), the Turonian–(?)Coniacian (Bak et al. 2000), the Cenomanian–Santonian (Bak 1996b), and the Maastrichtian (Bak 1999b). Radiolarian assemblages are also described from the Campanian of northern Germany (Zittel 1876), the Campanian of Belgium (Cayeux 1897) and the 'Senonian' of Czechoslovakia (Perner 1891). Recent work on the Russian Platform (Popova-Goll et al. 2005) has provided information on the radiolarian fauna of the Santonian-Campanian and also provided a useful insight into other work in that, and adjacent, areas (e.g. Vishnevskaya 1993; Bragina 1994; Vishnevskaya & De Wever 1998). There are, as far as we are aware, no published radiolaria data from the Upper Cretaceous of Scania and no

Table 1. Radiolarian occurrence data (Arnager Limestone and Bavnodde Greensand)

Lithostratigraphy	Chronostratigraphy	Radiolarian Zone (Pessagno 1976)	Sample	Preparation method*	Orbiculiforma sp. 1	Orbiculiforma quadrata	Crucella spp.	Spumellaria (undifferentiated)	Praeconocaryomma spp.	Pseudoaulophacus spp.	Orbiculiforma monticelloensis	Orbiculiforma vacensis	Dictyomitra spp.	Archaeospongoprunum spp.	Pseudoaulophacus lenticulatus	Xitus ex. gr. asymbatos	Praeconocaryomma universa	Crucella latum	Pseudoaulophacus praefloresensis	Orbiculiforma spp.	Praeconocaryomma californiaensis	Cryptamphorella corana?	Stichomita spp.	Orbiculiforma (?) regis	Orbiculiforma presenex	Crucella cachensis	Crucella espartoensis	Orbiculiforma multa	Archaeospongoprunum bipartitum	Dictyomitra multicostata	Microsciadiocapsa berryessensis	Archaeospongoprunum rumseyensis	Orbiculiforma aff. impressa	?Patulibracchium spp.	Crucella sp. cf. aster	Tesserastrum quadratum	Stichomitra cp. cf. Amphipyndax stocki	Cavaspongia antelopensis	Allievium praegalloway	Cavaspongia spp.	Paronaella venadoensis	Patulibracchium ungulae	Patulibracchium spp.	Allievium spp.	"Cenosphaera" sp. 1	Diversity radiolaria (species count)	Total count radiolaria	Selected Biostratigraphic events
Bavnodde Greensand	Santonian to Middle ?Late Coniacian	Unassigned	BO12	RM	2	1	1	23	4	1	3	7	1	1	2																															6	32	O. quadrata (LAD)
			BO5	RM	1	1		9																																				9	28	O. vacensis (LAD); P. lenticulatus (LAD)
			BO21	RM	1	2					2	2			1																													4	7	
			BO20	RM	3	1		16	1		2	6		1		2	2	3	1																											7	36	Crucella latum (LAD)
			BO17	RM	2			8	1		7	3		1	1	2	5	2	2																											7	21	
			BO15	RM				3									4																													7	18	
			AK30	RM	1					1	2	1	1	1	1		1		1	1																										5	6	P. californiaensis (LAD)
			BO25	RM																2																										5	9	
			BO23	RM				3			2	2																																		3	5	
			BO22	RM		1		22	2		2	2				1				1																										8	32	
			AK22	RM				2																																						1	2	
			BO26	RM	1	1		9			4				1		1			2																										5	13	
			BO27	RM	2						2																																			3	12	
			AK19	RM		1		2			1			1				1		1																										4	7	
			AK18	RM	1			3			2																																			3	5	
Arnager Limestone	Coniacian Middle - Early	Orbiculiforma vacensis Subzone	AK16	RM		1		24		3	3		1	1	4		2		1		5			1	1	4		1			3			1		1											10	42	O. presenex (LAD)
			AK17	RM	2	2		56	14		17	17		1	5	13									4	15	2	1	5	3	1					2			1	1	2	4	1		1		14	127	A. bipartitum (LAD); S. multa (LAD)
			AK21	RM				23			4	3		1				3						1	7	2		1	2				3	1													5	30	
			AK15	RM	1			1																																							2	5	A. rumseyensis (LAD)
			AK8	AP		5	2	47	4	14	38			5	1		5	3		8		2	3		5	15	2	2	1	3	9	2	3	1	2	1	1	1	1	1	2	4	1		1	10	19	146	A. rumseyensis (LAD)
			AK9	RM				28			17						13			4				1	4	25		1	1				7	1													9	103	
			AK10	AP	3	1	1	118	1	1	21			5	10	5	5	6	2	4			1	7	15	2	2		8		2	7	1	2			1	1	1		2	1	1	1	37	33	285	A. praegalloway (single occurrence); O. regis (FAD); A. bipartitum (FAD)
			AK12	RM							14			1	4						3				5	7	1	1																		10	57	
			AK13	RM							4				7											5	1													5			1	1	5	7	27	
			AK14	RM	1			10			3				3				2																							4	6		22	
			AK7	RM				21			6									3					2	2			2		1											8	60	O. vacensis (FAD); O. presenex (FAD); P. lenticulatus (FAD); S. multa (FAD)
			AK1	RM																																									0	0	

*RM = Routine micropalaeontological preparation
*AP = Hydrochloric acid preparation
FAD = First Appearance Datum (inception)
LAD = First Appearance Datum (extinction)

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data have been published on the faunas from Bornholm, although the occurrence of radiolaria in the Arnager Limestone was first noted by Hill (1912). Hill based his comments on information in Ravn (1903), although the latter author did not specifically describe the Bornholm fauna.

The U.K. onshore succession has yet to yield significant radiolarian faunas although there are rare records in the 19th and early 20th Century literature. Holmes (1900) described, and illustrated with exceptional line drawings, radiolaria from the *H. planus* Zone while Hill & Jukes-Browne (1895) reviewed the occurrence of radiolarians in the chalk succession. Many of the forms illustrated by these authors can be identified using modern taxonomy. Rare radiolaria are described from the Upper Greensand by Grimes (1895), whilst Braley (1990) has indicated the presence of radiolaria in the Santonian(?) chalk of Scotland. Recent work on the Campanian of the Trunch borehole by the senior author has identified the presence of a silicified level at the base of the lower Campanian where, although radiolaria have not yet been found, microfaunal recovery comprises only the siliceous moulds of foraminifera. The occurrence of this level equates to an excursion in the silica values from geochemical data and may represent an expression of the so-called global earliest Campanian biosiliceous event, in a relatively proximal depositional setting.

In off-shore areas of the North Sea basin, West of Shetlands, West of Ireland and mid-Norway, radiolarian and diatom acme events occur in both the Chalk Group and the Shetland Group. Major acme events are recorded in the early Turonian and earliest Campanian, together with a number of other consistently identifiable events within the Late Cretaceous (Gradstein *et al.* 1999). Preservation is often poor and taxonomic 'lumping' an inevitable outcome. The application of enhanced processing methods may, in due course, improve our understanding of these events. Unfortunately almost all of these data remain unpublished in oil company files.

Distribution and preservation of radiolaria

The distribution and abundance data collected from initial studies of the Bornholm succession based on routine foraminiferal preparations and the selected acid digestions described above are presented in Table 1 and are illustrated, where appropriate in Figures 5–7. The radiolarians are moderately well preserved as opaline silica. Delicate spines and spine bases can be consistently recognised in the Spumellaria, though in a large number of the specimens the spines are broken or completely absent. Nassellarians occur in low numbers, with some primary structures visible despite the generally poor preservation. In many cases smaller structures, such as pore frames, are often difficult to differentiate.

Radiolarians first occur within the Bornholm succession immediately above the base of the Arnager Limestone and become more abundant in the middle and upper parts of the formation. Radiolarian diversity appears to be highest in the middle part of the formation, although this may be a function of the different preparation techniques employed in this initial study. The radiolarian assemblages are dominated by Spumellaria whilst Nassellaria are present only in relatively low numbers. The Spumellarian fauna is characterised by a high proportion of *Orbiculiforma* spp., together with lesser numbers of *Pseudoaulophacus* spp., *Praeconocaryomma* spp., *Crucella* spp., *Paronaella* spp., *Cavaspongia* spp., *Patulibracchium* spp., *Alievium* spp. and *Archaeospongoprunum* spp. The nassellarian fauna is represented by the genera *Dictyomitra* spp., *Stichomitra* spp., *Microsciadiocapsa* spp. and ?*Cryptamphorella* spp. Nassellarians appear to be most abundant in the middle and upper parts of the formation, where overall radiolarian diversity appears to be highest.

A notable decline in radiolarian abundance and diversity occurs in the Bavnodde Greensand, relative to the underlying Arnager Limestone. Preservation is generally poor in the Bavnodde Greensand with many specimens incomplete or partially corroded. Our initial data for the Bavnodde Greensand, outlined in Table 1 suggest that radiolarian abundance and diversity fluctuates throughout the formation, although a general increase in abundance may be inferred up-section. Spumellaria are predominant with only rare Nassellaria recorded. The Spumellaria fauna is characterised by a high number of poorly preserved indeterminate taxa, consistent occurrences of *Orbiculiforma* spp., together with low numbers of *Pseudoaulophacus* spp., *Crucella* spp. and *Praeconocaryomma* spp. The Nassellaria elements are represented by rare occurrences of *Dictyomitra* spp., *Stichomitra* spp. and *Xitus* spp.

Radiolarian biostratigraphy

Radiolarian zonations for the Upper Cretaceous have been erected for various geographical locations and for a variety of timeslices within selected intervals
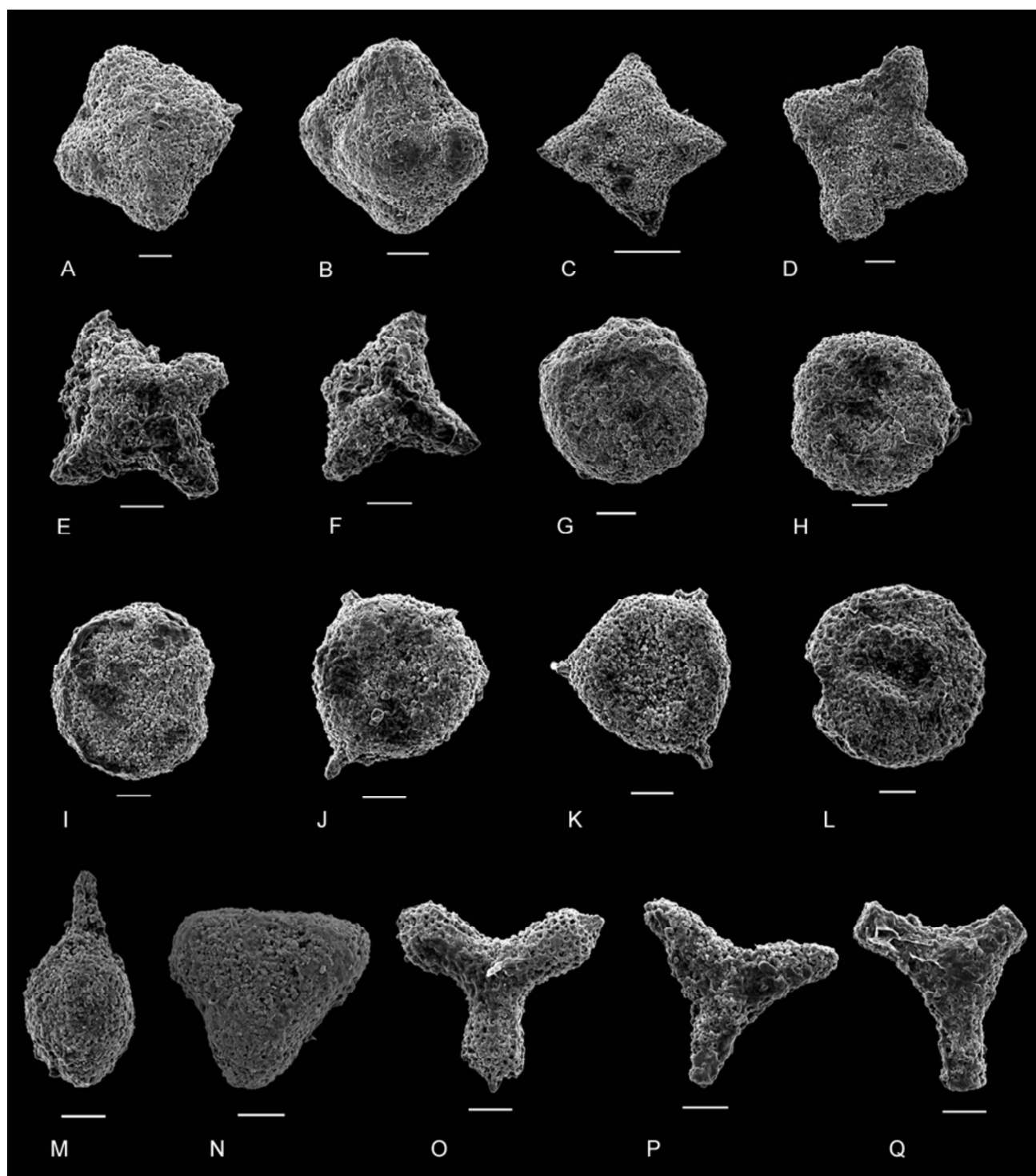
Fig. 5. Radiolaria from the Upper Cretaceous of Bornholm. All scale bars are 50 μm apart from C, which is 100 μm. All specimens are from Sample AK10 of the Arnager Limestone except A-D which are from Sample AK8 of the Arnager Limestone. A, *Crucella latum*: B, *Tesserastrum quadratum*: C, D, *Crucella* sp. cf. *Crucella aster*: E, F, *Crucella espartoensis*: **G - I**, *Orbiculiforma persenex*: **J, K**, *Orbiculiforma*(?) *regis*: **L**, *Orbiculiforma* sp.1: **M**, *Archaeospongoprunum rumseyensis*: **N**, *Cavaspongia antelopensis*: **O**, *Patulibracchium ungalae*: **P, Q**, *Paronaella venadoensis*.
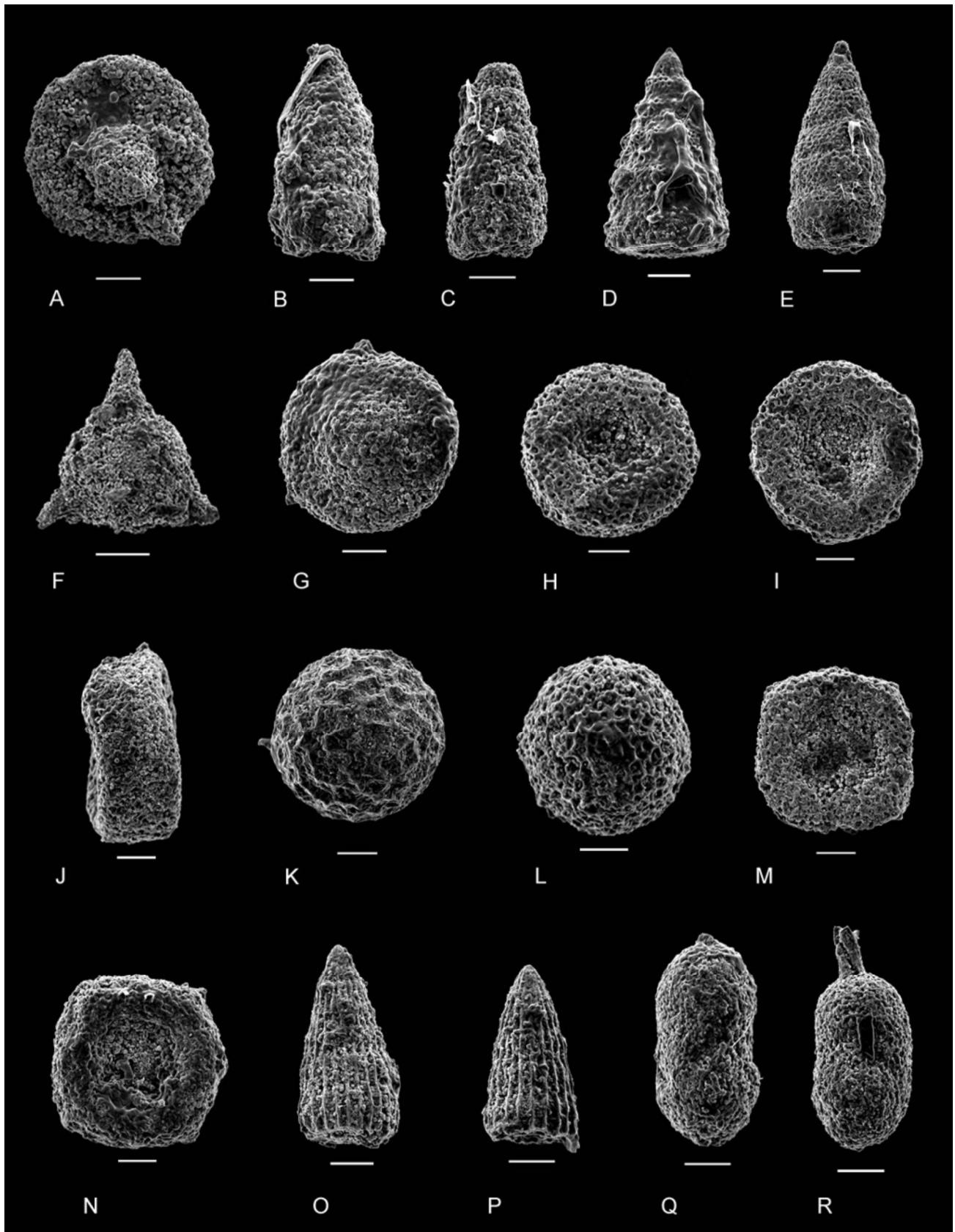
or covering the whole of the interval. (e.g. Dumitrica 1975; Pessagno 1976; Sanfilippo & Riedel 1985; Thurow 1988; Tumanada 1989; Vishnevskaya 1993; O'Dogherty 1994; Khan *et al*. 1999). There is, however, still no single widely accepted zonation scheme for the Upper Cretaceous that encompasses both Boreal and Tethyan provinces. Khan *et al*. (1999) suggest that the lack of consistency and refinement between the various zonations is due to the lack of calcareous plankton in many of the sections that have been studied to date, and this limits calibration. Other factors included the inconsistency in recorded radiolarian taxon ranges and taxonomic nomenclature usage between different areas due to variable preservation and the relatively small number of radiolarian workers.

The majority of the published zonations are restricted to the Tethyan province, with the exception of Pessagno (1976), which is based on data from the 'Boreal Faunal Province, Pacific Subprovince'. The succession he was describing, from Central and Northern California, contains a fauna of 'Boreal' aspect and clearly belongs to what he termed the Pacific Subprovince. The molluscan faunas found in these successions are more closely allied to those of Japan rather than the Western Interior Seaway or the Gulf Coast (Pessagno 1976, p. 21). The planktonic foraminifera (Douglas 1972, p. 25) are likewise 'Boreal' in aspect, with many taxa being limited to the Pacific region. Comparisons to Pessagno's fauna must, therefore, be made with caution although a great many of the Bornholm species do appear to be co-specific with his fauna.

Pessagno (1976) defined two radiolarian zones encompassing the Coniacian (*Alievium praegallowayi* Zone) and Santonian (*Alievium gallowayi* Zone). The Coniacian *Alievium praegallowayi* Zone was further subdivided into a lower *Archaeospongoprunum triplum* Subzone and an upper *Orbiculiforma vacaensis* Subzone. O'Dogherty (1994) noted that the zonations proposed by Pessagno (1976) for the California Coast Ranges were difficult to compare with the Mediter-

ranean region due to range discrepancies (inceptions), although faunal similarities are evident.

There appears to be few published Late Cretaceous radiolarian data from the Boreal north-west European province. The published work from Poland (much of which is based in the Carpathian Mountains and, as such, well away from the Baltic area) has attempted to place the radiolarian faunas recovered into a variety of schemes with varying degrees of success. At the current time it is, therefore, relatively difficult to place the Bornholm fauna directly into a global radiolarian zonation. Our initial studies suggest that the documented fauna most closely match the Pessagno (1976) scheme, although there are significant differences. The Bornholm succession is also relatively unusual for the Upper Cretaceous in that the radiolarian fauna can be calibrated with well-documented macrofossil and microfossil data.

Taxa recorded from the Arnager Limestone are generally consistent with Coniacian-aged faunas described elsewhere. A number of important taxa are present in the formation, which allow for limited chronostratigraphic correlation with other areas. *Orbiculiforma presenex* is present just above the base of the Arnager Limestone and occurs in abundance to the top the formation. This taxon appears to be restricted to the Coniacian and the *Alievium praegallowayi* Zone (*Orbiculiforma vacaensis* Subzone) of Pessagno (1976). This is supported by the occurrence *of Archaeospongoprunum rumseyensis* which, according to Pessagno (1976), has a first occurrence at the base of the *Orbiculiforma vacaensis* Subzone. Other taxa present in the Arnager Limestone are apparently restricted to the Coniacian including *Patulibracchium ungulae* (range; Coniacian, Pessagno 1976), *Patulibracchium venadoensis* (range; Coniacian, Pessagno 1976), and *Praeconocaryomma californiaensis* (range; Coniacian, Pessagno 1976). Rare occurrences of *Microsciadiocapsa*(?) *berryessaensis* (range: early Coniacian, Pessagno 1976), which is present in the middle of the formation, are at variance with the placement of the limestone within the *Orbiculiforma vacaensis* Subzone. According to Pessagno (1976) this taxon is restricted to the *Archaeospongoprunum triplum* Subzone. As has been noted above, however, the general understanding of the ranges of Late Cretaceous radiolarian taxa is relatively poor when compared to other groups of plankton and range inconsistencies are likely to be encountered. The interim conclusion herein is that the radiolarian fauna recovered from the Arnager Limestone appears to show similarities to the *Alievium praegallowayi* Zone (*Orbiculiforma vacaensis* Subzone) of Pessagno (1976).

As has been outlined above, radiolarian recovery and preservation is relatively poor in the Bavnodde
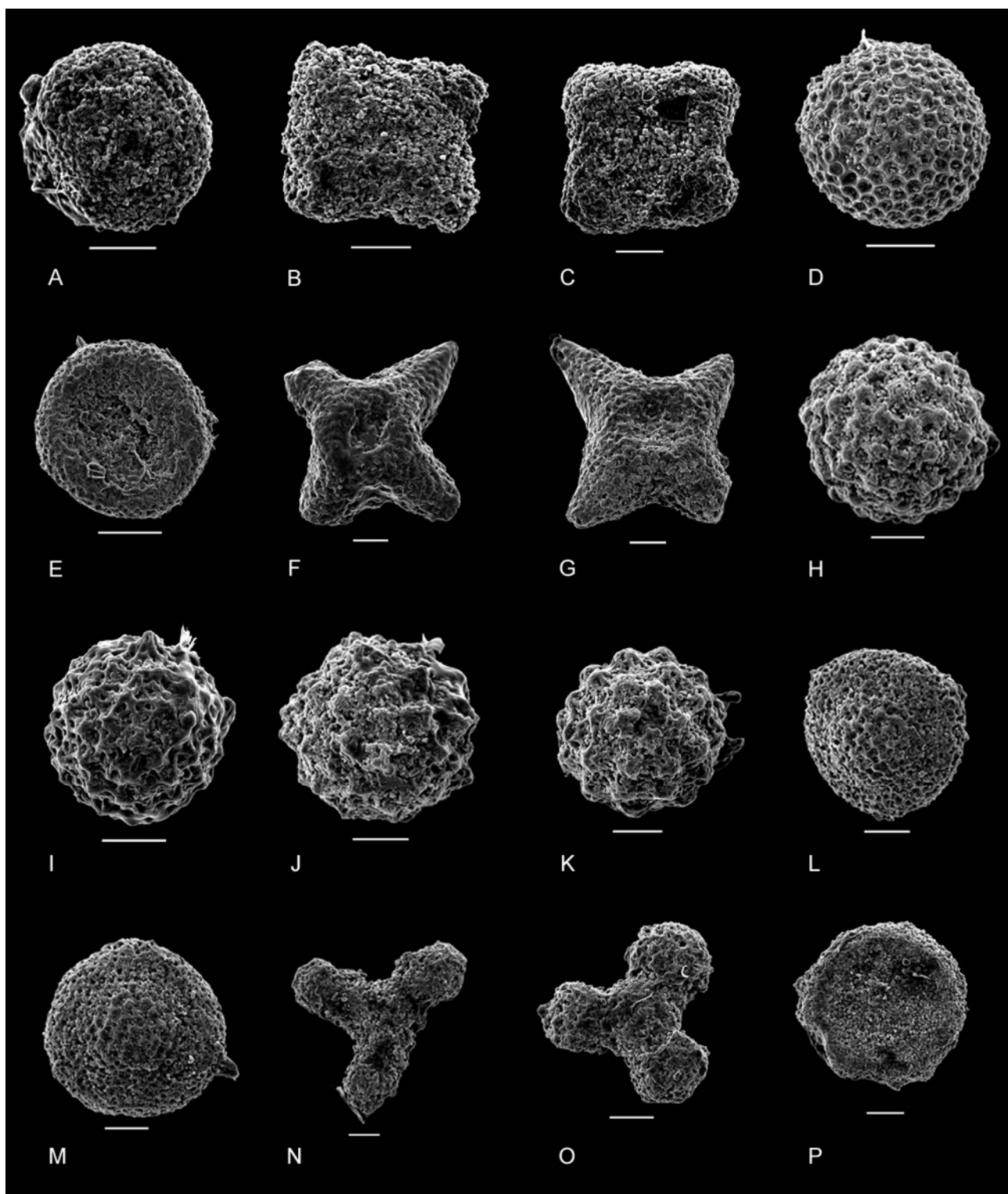
Facing page:
Fig. 6. Radiolaria from the Upper Cretaceous of Bornholm. All scale bars are 50 μm apart from **F**, which is 100 μm. All specimens are from Sample AK10 of the Arnager Limestone except **E**, which is from Sample BO23 of the Bavnodde Greensand. **A**, *Microsciadiocapsa*(?) *berryessaensis*: **B, C**, *Stichomitra* sp.1: **D**, *Xitus* ex gr. *asymbatos*: **E**, *Stichomitra* sp. cf. *Amphipyndax stocki*: **F**, *Alievium praegallowayi*: **G**, *Pseudoaulophacus lenticulatus*: **H - J**, *Orbiculiforma vacaensis*: **K, L**, *"Cenosphaera"* sp.1: **M, N**, *Orbiculiforma quadrata*: **O, P**, *Dictyomitra multicostata*: **Q, R**, *Archaeospongoprunum bipartitum*.

Fig. 7. Radiolaria from the Upper Cretaceous of Bornholm. All scale bars are 50 µm apart from **E**, which is 100 µm. All specimens are from Sample AK10 of the Arnager Limestone except **D** (Sample AK17 Arnager Limestone), **E** (AK18 Arnager Limestone) and **L, M** (Sample AK8 of the Arnager Limestone). **A**, *Orbiculiforma multa*: **B, C**, *Crucella* sp. cf. *Crucella aster*: **D**, *Cryptamphorella corona*: **E**, *Orbiculiforma* sp. aff. *impressa*: **F, G**, *Crucella cachensis*: **H, I**, *Praeconocaryomma universa*: **J, K**, *Praeconocaryomma californiaensis*: **L, M**, *Pseudoaulophacus praeflorenensis*: **N**, *Patulibracchium* sp.1: **O**, *Patulibracchium* sp.2: **P**, *Orbiculiforma monticelloensis*.

Greensand. The taxa recorded are generally all long-ranging Late Cretaceous species. The presence of *Orbiculiforma monticelloensis* (range; Turonian–Santonian, Pessagno 1973) and *Orbiculiforma quadrata* (range; Coniacian – Santonian, Pessagno 1973), suggest that the formation can be no younger than Santonian. Other taxa recorded are also long-ranging; for example, *Pseudoaulophacus praefloresensis* and *Pseudoaulophacus lenticulatus* both range into the Campanian. At present we are unable be assign the Bavnodde Greensand to a radiolarian zonation defined elsewhere, although further work may lead to improved resolution.

Palaeoecology of the Bornholm radiolarian faunas

The data from our initial studies indicate that the radiolarian faunas present in the Arnager Limestone and Bavnodde Greensand formations are of moderate diversity and abundance. The fauna is dominated by Spumellaria with low numbers of Nassellaria. The faunas also appear to be of lower diversity in comparison to coeval mid-Cretaceous assemblages from the Tethyan area. The radiolarian fauna does, however, appear to show some compositional similarities to the faunas described from the California Coast Ranges (Pessagno 1976), though they are clearly not as diverse. Pessagno (1976) suggests that no marked diversity gradient existed among radiolarian assemblages of the Tethys, Boreal and Austral faunal provinces during the Late Cretaceous. O'Dogherty (1994) also suggests that there is little evidence for Boreal provincialism in the Late Cretaceous. Our initial data on the Bornholm fauna is suggestive of a lower radiolarian abundance and diversity. This may indicate that radiolarian provincialism was indeed prevalent during the Late Cretaceous, although other factors, such a relative water-depth, may influence faunal composition. Preservational factors may, however, be the primary influence controlling apparent abundance and diversity. Clearly more data are needed from further north, particularly the North Sea Chalk and Shetland Groups, before a firm conclusion can be reached. The idea that radiolarian assemblage composition variation may be related to provinciality is supported by the occurrence of distinct forms such as *Orbiculiforma multa* that appear to be present only in the Danish-Polish Trough and Russian Platform. What is not in question, however, and appears to be agreed between the majority of radiolarian workers, is that our picture of the Late Cretaceous is still fragmentary and comparisons between different, widely spaced localities are limited by problems of preservation and taxonomy.

In modern oceans radiolarians are a ubiquitous part of the microzooplankton, being present in all oceans, water masses and levels within the water column, although abundances and diversity of different components of the populations vary according to local ecological conditions (Empson-Morin 1984). Their absence, or relatively poor record of occurrence, within the Upper Cretaceous of N.W. Europe, particularly the onshore UK Chalk succession is, therefore, probably due to issues relating to preservation within the dominantly carbonate-rich sediments. The UK onshore chalk succession has clearly been subject to silica re-mobilisation as shown by flints and the sporadic recovery of radiolarian faunas in flint 'meal' (Hill & Jukes-Browne 1895; Holmes 1900). Coeval successions in the central North Sea Basin and the Danish-Polish Trough (including Bornholm) clearly have not been subjected to the same intensity of silica re-mobilisation as the UK onshore successions, and yield moderately diverse assemblages. This may be a function of the relatively shallow burial of the Cretaceous succession on Bornholm.

In the Bornholm succession the first occurrence of radiolaria occurs just above the base of the Arnager Limestone, associated with the onset of carbonate deposition in an outer shelf to upper bathyal setting (Packer & Hart 1994). Our initial distribution data (Table 1) suggest that radiolarian abundance and diversity are at a maximum in the middle of the formation, equating to the level of maximum water depth within the Arnager Limestone as indicated by Packer & Hart (1994). Microfaunal data (Packer 1991) suggest outer shelf to upper slope water depths for the formation, as shown by relatively high foraminiferal planktonic/benthic ratios and calcareous benthic assemblages composed of relatively deeper-water taxa. The decline in radiolarian recovery associated with the transition to Bavnodde Greensand is associated with a reduction in water depth from outer neritic/bathyal to inner – (?)mid shelf conditions (Packer & Hart 1994). This change in the radiolarian fauna is also reflected in the foraminiferal populations. The microfauna recovered from the Bavnodde Greensand is characterised by relatively low numbers of keeled planktonic foraminifera and a change to more typically calcareous benthic shelf assemblages. The radiolarian faunas in both formations, therefore, appear to show compositional abundance and diversity changes that mirror changes in relative water depth as indicated by the other microfauna.

Summary

The radiolarian fauna of the Arnager Limestone and Bavnodde Greensand formations is described for the first time. Samples have been prepared using standard microfaunal preparation methods together with the application of acid digestion on selected samples using hydrochloric acid. Recovery has been shown to improve using the later technique.

Our initial studies suggest that radiolarians are present just above the base of the Arnager Limestone, becoming abundant within the middle of the succession and declining towards the top of the formation. Radiolarian recovery is relatively poor in the Bavnodde Greensand, with abundance and diversity fluctuating throughout the formation, though a general increase in abundance up-section may be inferred.

The assemblages recovered show compositional similarities to those described by Pessagno (1976) and similar-aged sections from elsewhere in the Danish-Polish Trough. The fauna from the Arnager Limestone appears comparable to the *Orbiculiforma vacaensis* Subzone (*Alievium praegallowayi* Zone) of Coniacian age. Relatively poor recovery from the Bavnodde Greensand precludes assignment to the zonation scheme of Pessagno (1976). The taxa present indicate that the formation can be no younger than Santonian.

A number of the taxa recorded from the Bornholm succession are also recorded from the Russian Platform and Moscow Basin (see Popova-Goll *et al.* 2005, table 2) and used in a number of zonal schemes. While Vishnevskaya (1993) uses the top of a zone based on *Archaeospongoprunum bipartitum* to define the Coniacian-Santonian boundary, this cannot immediately be applied to the Bornholm succession (see Table 1) without a clearer understanding of the Moscow Basin succession and the ranges of the individual taxa.

The radiolarian faunas described are of moderate abundance and diversity when compared to contemporaneous faunas described elsewhere, particularly the Tethyan area. Radiolarian abundance and diversity is at a maximum in the middle of the Arnager Limestone equating to a level of maximum water depth suggested by the foraminiferal data. The decline in radiolarian recovery associated with the transition to the Bavnodde Greensand is associated with a reduction in relative water depth to inner to (?)middle shelf conditions and is reflected in the foraminiferal data. As further information is published from N.W. Europe and more data are generated from the Bornholm succession following re-sampling, it is hoped that this fauna can more accurately be placed in context.

Acknowledgements

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Appendix: List of species

The radiolarian taxa identified to date are given in the listing below (alphabetic). A number of distinctive species have been left in open nomenclature. To date these have not been matched to published taxa and may be new species, although further work is required to clarify their status.

Alievium praegallowayi Pessagno, 1972 [*Alievium praegallowayi* Pessagno, 1972, p. 301, pl. 25, figs 2, 3.]

Alievium spp.

Amphipyndax stocki (Campbell & Clark, 1944) [*Stichocapsa*(?) *stocki* Campbell & Clark, 1944, p. 44, pl. 18, figs 31–33].

Archaeospongoprunum bipartitum Pessagno, 1973 [*Archaeospongoprunum bipartitum* Pessagno, 1973, pp. 59–60, pl. 11, figs 4–6].

Archaeospongoprunum rumseyensis Pessagno, 1973 [*Archaeospongoprunum rumseyensis* Pessagno, pp. 62–63, pl. 12, figs 3–6]

Archaeospongoprunum spp.

Cavaspongia antelopensis Pessagno, 1973. [*Cavaspongia antelopensis* Pessagno, 1973, pp. 76-77, pl. 18, figs 4-6, pl. 19, fig.1]

Cavaspongia spp.

'*Cenosphaera*' sp.1

Crucella aster (Lipman, 1952). [*Histiastrum aster* Lipman, 1952, p. 35, pl. 11, figs 6, 7]

Crucella cachensis Pessagno, 1971. [*Crucella cachensis* Pessagno, 1971, pp. 53–54, pl. 9, figs 1-3]

Crucella espartoensis Pessagno, 1971. [*Crucella espartoensis* Pessagno, 1971, pp. 54–55, pl. 18, figs 1–4]

Crucella latum (Lipman, 1960). [*Histiastrum latum* Lipman, 1960, p. 130, pl. 29, figs 7, 8]

Crucella spp.

Cryptamphorella corona (Foreman, 1968). [*Hemicryptocapsa corona* Foreman, 1968, p. 35, pl. 4, fig. 11a, b]

Dictyomitra multicostata Zittel, 1876, emend, Pessagno, 1976, p. 50. [*Dictyomitra multicostata* Zittel, 1876, p. 81, pl. 2, figs 2, 4]

Dictyomitra spp.

Microsciadiocapsa berryessaensis Pessagno, 1969. [*Microsciadiocapsa berryessaensis* Pessagno, 1969, p. 404, pl. 31, figs 8-12]

Orbiculiforma impressa (Lipman, 1952). [*Spongodiscus impressus* Lipman, 1952, p. 38, pl. 2, fig. 14]

Orbiculiforma monticelloensis Pessagno, 1973. [*Orbiculiforma monticelloensis* Pessagno, 1973, pp. 72–73, pl. 16, figs 5–6, pl. 18, figs 1–2]

Orbiculiforma multa (Koslova, 1966). [*Spongodiscus*(?) *multus* Koslova in Koslova & Gorbovets, 1966, pp. 87-88, pl. 4, fig. 10]

Orbiculiforma persenex Pessagno, 1976. [*Orbiculiforma persenex* Pessagno, 1976, p. 35, pl. 6, figs 12–13]

Orbiculiforma quadrata Pessagno, 1973. [*Orbiculiforma quadrata* Pessagno, 1976, pp. 73–75, pl. 16, figs 1–4, pl. 18, fig.3].

Orbiculiforma regis Pessagno, 1976. [*Orbiculiforma regis* Pessagno, 1976, p. 35, pl. 11, figs 9–10]

Orbiculiforma vacaensis Pessagno, 1973. [*Orbiculiforma vacaensis* Pessagno, 1973, pp. 74-75, pl. 17, figs 1–6]

Orbiculiforma sp. 1

Orbiculiforma spp.

Patulibracchium ungulae Pessagno, 1971. [*Patulibracchium ungulae* Pessagno, 1971, pp. 44–45, pl. 7, figs 3–5]

Patulibracchium spp.

(?)*Patulibracchium* spp.

Paronaella venadoensis Pessagno, 1971. [*Paronaella venadoensis* Pessagno, 1971, pp. 49–50, pl. 10, figs 4–6, pl. 11, fig. 1]

Praeconocaryomma californiaensis Pessagno, 1976. [*Praeconocaryomma californiaensis* Pessagno, 1976, p. 41, pl. 7, figs 1–8].

Praeconocaryomma universa Pessagno, 1976. [*Praeconocaryomma universa* Pessagno, 1976, p. 42, pl. 6, figs 14–16]

Praeconocaryomma spp.

Pseudoaulophacus praefloresensis Pessagno, 1972. [*Pseudoaulophacus praefloresensis* Pessagno, 1972, pp. 309–310, pl. 27, figs 2–6]

Pseudoaulophacus lenticulatus (White, 1928). [*Baculogypsina*(?) *lenticulatus* White, 1928, p. 306, pl. 41, figs 9, 11]

Pseudoaulophacus spp.

Spumellaria (undifferentiated)

Stichomitra sp.1

Tesserastrum quadratum Lipman, 1952. [*Tesserastrum quadratum* Lipman, 1952, p. 38, pl. 2, fig. 10]

Xitus ex gr. *asymbatos* (Foreman, 1968). [*Stichomitra asymbatos* Foreman, 1968, p. 73, pl. 8, fig. 10a–c]