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Acritarch assemblages from the Silurian Pomeranian Caledonides and their foreland

Monika JACHOWICZ

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Comprehensive palynological studies of the Silurian rocks of the Pomeranian Caledonides are described, the first since Eisenack's (1972) work. 250 clastic rock samples were analysed, all from deep boreholes. Three of these boreholes (Lębork IG 1, Gdańsk IG 1 and Kościerzyna IG 1) are located NE of the Teisseyre-Tornquist Zone (TTZ) and contain horizontal successions of the western, marginal part of the East European Craton. Other boreholes studied (Bydgoszcz IG 1, Klosnowo IG 1 and Stobno 1) penetrated folded Lower Palaeozoic sediments, and lie SE of the TTZ. The investigations included a complete Silurian profile from the Llandovery to the Přidoli, which is documented in detail by graptolites. Associations of microflora (*Acritarcha, Prasinophyceae, Sporites*) and microfauna (*Chitinozoa, Scolecodonta*) varied in quality and quantity. There was considerable variability in the preservation and thermal maturity of the organic-walled microfossils. Detailed investigations of the acritarchs are described. 7 characteristic acritarch assemblages have been distinguished, and these are correlated with the graptolite biozones. Llandovery rocks contain assemblages with *Domasia*, *Ammonidium* and *Tylotopalla* genera. Wenlock deposits include *Tylotopalla*, *Leptobrachion* and *Cymbosphaeridium*. The Upper Ludlow deposits contain well preserved assemblages with *Visbysphaera*, *Veryhachium*, *Onondagella* and *Leoniella*, accompanied by *Neoveryhachium carminae*, *Geron gracilis*, and some *Deflandrastrum* and *Visbysphaera* species generally considered characteristic of Gondwana. Throughout the Silurian profile, individual specimens of typical Ordovician genera such as *Acanthodiacrodium*, *Frankea*, *Striatotheca* and *Coryphidium* occur. The acritarch assemblages overall show mixed characters, typical of both Baltica and Gondwana.

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INTRODUCTION

Microscopic fossils called acritarchs have been known since the 19th century, but their nature and systematic position remain controversial (Downie, 1984; Martin, 1993).

It is generally accepted that these were unicellular organisms, probably planktonic, with an extremely resistant organic wall. Some of the researchers consider that this group is polyphyletic, embracing algae, cysts and probably also some plant spores (Downie, 1984; Martin, 1993). Taxonomically, acritarchs have been associated with different groups of algae. Many acritarchs also resemble, in terms of their general structure dinoflagellate cysts. Some acritarchs also seem related to the Prasinophyceae.

The distinctive morphologies of acritarchs and their abundance in marine deposits has led to their widespread application in biostratigraphical and palaeogeographical studies. They were most widespread, abundant and diverse in the Cambrian and Ordovician periods. After the Upper Devonian, they declined considerably decreased and younger deposits contain only scarce representatives of this group (Downie, 1984; Martin, 1993).

Acritarchs are abundant and diverse in Silurian marine deposits. They were first described by White (1862) from limestone in the New York State, USA. In 1931, A. Eisenack discovered them in the Baltic area. Since then, they have been found in many parts of Europe, Africa and North and South America (Martin, 1989).

In 1969, F. Martin correlated acritarch associations from Silurian deposits in Belgium with the 16 graptolite biozones distinguished in that area. In 1963–1977, F. H. Cramer with his co-workers studied acritarch assemblages in Wenlock to Lower Devonian deposits in northern Spain, and successfully applied the results to effect correlations across Algeria, Tunisia, Florida, Turkey and the southern part of Arabia. In Great Britain, in the period 1959–1963, C. Downie studied Silurian acritarchs from the Wenlock shales. Using these, he proposed a

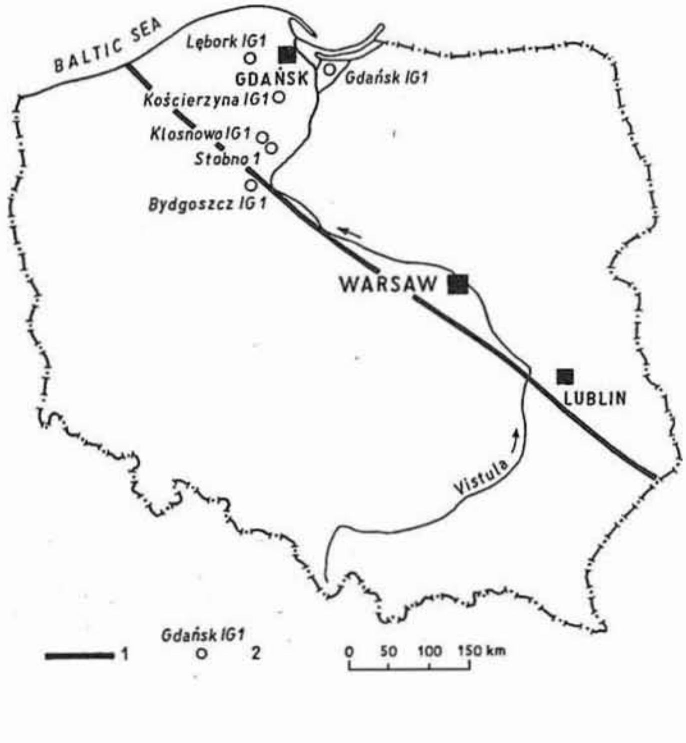


Fig. 1. Location map of the boreholes

1 — Trans-European Suture Zone (TESZ) (supposed cross), 2 — investigated boreholes

threefold division of the Wenlock shales and determined typical ranges for Silurian genera such as *Domasia* and *Deunffia*. Lister (1970), in his work on the Acanthomorphitae from Ludlow deposits, created typical Silurian genera such as *Ammonidium*, *Dilatisphaera* and *Visbysphaera*. Hill (1974) described Lower Silurian acritarchs from the Llandovery area and the Welsh Borderlands, distinguishing acritarch biozones in the Llandovery to Lower Wenlock interval. Dorning (1981*b*) established 7 acritarch biozones in British Wenlock and Ludlow deposits then, together with P. J. Hill (Hill and Dorning, 1984), he distinguished 4 zones in the Llandovery. Le Hérissé (1989), in his work on acritarchs and prasinophytes from Sweden, established 11 acritarch zones. Local Silurian zonations have been proposed for Africa (Jardiné *et al*., 1974). So far, these microfossils have not been systematically investigated in Australia, China, Antarctica and South America (Molyneux *et al*., 1996).

There has been little detailed study of Silurian acritarchs in Poland. In the 30s and 70s, acritarchs from the Baltic area were investigated by A. Eisenack, part of his material coming from boreholes in Poland. Recently, preliminary results of investigations on the Silurian acritarch associations of the Małopolska Block (Jachowicz *et al*., 1987; Jachowicz, 1993, 1994) and Holy Cross Mountains (Stempień, 1990; Masiak, 1996, 1999) have been published.

For the last two years, the Polish Geological Institute has carried out detailed palynological investigations of Silurian rocks from deep boreholes in Western Pomerania (Fig. 1). This paper represents the first general account of these investigations. In all, 250 samples from 6 boreholes were analysed. Three of the boreholes studied (Lębork IG 1, Gdańsk IG 1 and Kościerzyna IG 1) are located NE of the TTZ and contain horizontal strata of the western, marginal part of the East European Craton. Other samples came from the boreholes (Bydgoszcz IG 1, Klosnowo IG 1 and Stobno 1) which penetrated folded Lower Palaeozoic sediments, SE of the TTZ.

All the samples were macerated using standard methods (Wood *et al*., 1996). The samples were crushed into 5–10 mm diameter particles and then were macerated using 36% hydrochloric acid and 40% hydrofluoric acid. The material obtained was passed through a nylon sieve with a mesh 10 μm in diameter, and used to prepare standard microscopic slides. The preparations were subjected to planimetric microscope analysis in transmitted light.

PALYNOLOGICAL RESULTS FROM SILURIAN BOREHOLE CORES FROM THE MARGINAL ZONE OF THE EAST EUROPEAN CRATON

Most of the material studied came from the Lębork IG 1, Gdańsk IG 1 and Kościerzyna IG 1 boreholes. Silurian strata reach considerable thicknesses in the profiles studied, from 1400 m in the Gdańsk IG 1 borehole to 2300 m in the Kościerzyna IG 1 borehole. These rocks mainly comprise mudstones with graptolites of Llandovery to Přidoli age (Tomczyk, 1982; Tomczykowa, 1989). Sedimentation was continuous, and the thickness of individual Silurian stages increases upwards. Llandovery rocks are thin, from 23 m in the Lębork profile to 65.2 m in the Kościerzyna profile. The thickness of Wenlock deposits ranges from 131.3 m (Lębork IG 1) to 323.5 m (Kościerzyna IG 1). In the Upper Silurian, the sedimentation rate increased and Ludlow and Přidoli strata reach thicknesses from 1271.5 m (Gdańsk IG 1) to 2053 m (Lębork IG 1). This distinctive thickness pattern is seen in the three profiles investigated (Tomczyk, 1982, 1989). The stratigraphy is based on graptolites, and follows Tomczyk (1963, 1982), Tomczykowa (1989), Urbanek and Teller (1997) as interpreted by Jaworowski (1999 — unpublished data). All the samples analysed are calibrated by graptolite biostratigraphy.

The analyses revealed the presence of rich organic-walled microfloras, belonging to two groups:

1. Acritarchs an autochthonous component of these deposits.

2. Microspores of terrestrial plants (*Sporites*), transported into the basin and representing allochthonous component.

There were also numerous *Chitinozoa* and scolecodonts, both autochthonous to this basin.

The analyses show that similar associations and identical successions of microflora occur in the Lębork IG 1, Gdańsk IG 1 and Kościerzyna IG 1 boreholes.

Acritarchs have been found in most of the samples studied. The only exception is in Lower Ludlow (Gorstian) strata, in which, despite detailed investigation, no specimens of this group have been found (Table 1). The samples here contained only numerous amorphous organic fragments, fragmentary chitinozoans and graptolites. 7 acritarch assemblages have been distinguished.

ASSEMBLAGE I; LLANDOVERY — RHUDDANIAN, AERONIAN

Gdańsk IG 1 (depth in metre: 3087.5, 3085.0) — *acuminatus, atavus*.

Kościerzyna IG 1 (depth in metre: 4390.2, 4380.1, 4378.7) — *acuminatus, convolutus*.

Lębork IG 1 (depth in metre: 3270.5, 3267.5, 3267.5) — *cyphus, triangulatus*.

These rocks contain very restricted associations of organic-walled microfossils. Simple spherical forms (*Leiosphaeridia*) are typical. The material contains only fragments of typical Silurian genera such as *Diexallophasis* and *Oppilatala*. Despite detailed investigations, no index acritarch genera known elsewhere have been determined. This conforms to a general pattern. Acritarch associations obtained from Silurian strata elsewhere show the poorest generic and specific differentiation at this level (Kaljo *et al.*, 1995).

The material is poorly preserved, the specimens showing much damage to the walls in the form of perforations and cracks. The specimens are dark or very dark in colour. There usually only a few specimens per slide.

ASSEMBLAGE II; LLANDOVERY — TELYCHIAN

Gdańsk IG 1 (depth in metre: 3080.4, 3075.5, 3072.1, 3068.6, 3066.5, 3063.3, 3060.2) — *crispus, griestonensis, crenulata, spiralis*.

Kościerzyna IG 1 (depth in metre: 4365.5, 4360.4, 4355.1, 4349.7, 4340.3, 4344.8, 4329.3, 4329.3) — *turriculatus, griestonensis, crenulata, spiralis*.

Lębork IG 1 (depth in metre: 3263.5, 3261.0, 3255.0, 3253.0) — *crispus, griestonensis, spiralis*.

Telychian rocks contain acritarch assemblages differentiated in terms of both quality and quantity. These are quite different from the associations identified in Rhuddanian and Aeronian strata and also from associations determined in Wenlock, Ludlow and Přidoli sediments. The samples studied contained many acritarchs — more than 100 specimens per slide.

The more important species and genera identified here include: *Domasia trispinosa, D. limaciforme, D. amphora, Salopidium granuliferum, Evittia sanpetrensis, Tylotopalla caelamenicutis, Ammonidium listeri, A. microcladum, Visbysphaera meson* and *V. oligofurcata*. The material also contained numerous representatives of genera characteristic of long expansion, namely *Leiosphaeridia, Diexallophasis, Veryhachium, Leiofusa, Micrhystridium, Multiplicisphaeridium, Onondagella* and *Oppilatala*. Scarce specimens of *Geron, Lophodiacrodium pepino* and *Moyeria* were identified, as well as individual specimens of *Neoveryhachium carminae*.

Acritarch associations of similar generic and specific composition are known from the Lower Silurian of other areas. The Telychian was marked by many short-ranged species occurred. This was the time of the largest generic and specific differentiation of Silurian acritarchs. Acritarch assemblages obtained from Telychian sediments of Pomerania are very similar to those described from Great Britain (Hill, 1974), Norway (Smelror, 1987), Baltic area (Eisenack, 1965, 1968; Cramer *et al.*, 1979; Le Hérissé, 1989), Russia (Sheshegova, 1971, 1975, 1984; Kirjanov, 1978), Belgium (Martin, 1969, 1974), Czech Republic (Dufka and Pacltová, 1988; Dufka, 1990) and North America (Cramer and Diez, 1972). Most of the forms documented in the profiles studied are also known from North Africa (Le Hérissé, 1992; Keegan *et al.*, 1990) and South America (Rubinstein, 1996).

The preservation of the specimens is not very good. There are many damaged forms, which makes taxonomic identification difficult. The damage consists of irregular perforations, cracks and damage to sculpture elements. Microflora in the *crispus* Biozone is especially badly preserved. Microfossils here are dark brown or sometimes even black in colour. Microfossils in the *griestonensis* and *spiralis* Biozones are better preserved, though showing brown and dark brown thermal alteration colours (Pl. I).

ASSEMBLAGE III; WENLOCK — SHEINWOODIAN

Gdańsk IG 1 (depth in metre: 3035.7, 3032.6) — *flexilis*.

Kościerzyna IG 1 (depth in metre: 4312.0, 4308.8, 4305.6, 4295.3, 4275.2) — *antenularius, flexilis, ellesae*.

Lębork IG 1 (depth in metre: 3247.0, 3245.0, 3240.5, 3238.0, 3228.0, 3221.0, 3215.0, 3209.0, 3205.0, 3201.5, 3195.0, 3190.0, 3185.0, 3180.0, 3175.0) — *centrifugus, murchisoni, riccartonensis, antenularius, flexilis, rigidus, ellesae*.

Despite detailed investigations, only poorly differentiated microfossil associations were encountered. The specimens are poorly preserved and there were only several specimens per slide. Most genera are long-ranging, such as *Leiosphaeridia, Diexallophasis, Micrhystridium, Veryhachium* and *Leiofusa*. The preservation of the specimens was not good enough to carry out specific determination.

The genus *Leiosphaeridia* is dominant comprising 90% of the identified specimens. Specimens range from 10–200 μm in diameter. Other genera are rare. The microfossils are dark brown in colour.

ASSEMBLAGE IV; WENLOCK — HOMERIAN

Gdańsk IG 1 (depth in metre: 2979.2, 2924.3) — *lundgreni, spinosus*.

Kościerzyna IG 1 (depth in metre: 4254.7, 4236.9, 4163.5, 4140.7, 4060.5) — *lundgreni, nassa, ludensis, spinosus*.

Lębork IG 1 (depth in metre: 3170.0, 3165.0, 3160.0, 3155.0, 3150.0, 3138.5, 3115.0, 3110.0, 3085.0, 3080.0, 3075.0, 3070.0, 3065.0) — *lundgreni, ludensis, spinosus*.

Acritarchs are numerous at this level, with 100–150 specimens per slide. *Leiosphaeridia* is common, and accompanied by *Moyeria*, which locally comprises 50% of the assemblage. These are accompanied by *Diexallophasis, Tylotopalla* and ?*Cymbosphaeridium*.

Despite its low generic and specific diversity the Homerian assemblage is distinctive, especially as regards the abundance of *Moyeria*. This genus, generally classified as an acritarch

Table 1

Stratigraphical range of the investigated taxons

Acritarcha	Silurian							
	Llandovery			Wenlock		Ludlow		Přidoli
	Rhuddanian	Aeronian	Telychian	Sheinwoodian	Homerian	Gorstian	Ludfordian	
1	2	3	4	5	6	7	8	9
Leiosphaeridia sp.	—	—	—	—	—		—	—
Diexallophasis denticulata	—	—	—	—	—		—	—
Diexallophasis sp.	—	—	—	—	—		—	—
Moyeria cabotti			—		—		—	
Micrhystridium stellatum			—	—	—		—	
Veryhachium lairdii			—		—		—	
Veryhachium trispinosum			—		—		—	
Dictyotidium sp.			—		—		—	
Oppilatala sp.	—	—	—		—		—	
Domasia trispinosa			—					
Domasia limaciforme			—					
Domasia amphora			—					
Salopidium granuliferum			—					
Salopidium sp. 1			—					
Salopidium sp. 2			—					
Ammonidium listeri			—					
Ammonidium microcladum			—					
Domasia elongata			—					
Lophodiacrodium pepino			—					
Evittia sanpetrensis			—					
Visbysphaera meson			—					
Visbysphaera oligofurcata			—					
Tylotopalla celloniensis			—					
Tylotopalla caelamenicutis			—					
Geron sp. 1			—					
Onondagella asymmetrica			—					
Tunisphaeridium minutum			—				—	—
Multiplicisphaeridium sp.			—				—	—
Tylotopalla sp.					—		—	—
Moyeria sp.					—			
Neoveryhachium carminae			—				—	

Continuation of Table 1

1	2	3	4	5	6	7	8	9
Cymbosphaeridium sp. 1							—	
Dilatisphaera sp.							—	
Tylotopalla wenlockia							—	
Eupoikilofusa striatifera							—	
Elektoriskos aurora							—	
Leoniella carminae							—	
Visbysphaera gotlandica							—	—
Visbysphaera microspinosa							—	—
Visbysphaera dilatispinosa							—	
Visbysphaera erratica							—	
Visbysphaera brevifurcata							—	
Visbysphaera jardinae							—	—
Visbysphaera sp. 1							—	
Deflandrastrum millepiedii							—	
Eupoikilofusa cantabrica							—	
Geron guerillerus							—	
Geron gracilis							—	—
Leptobrachion sp.							—	
Pterospermella sp.							—	
Visbysphaera sp. 2							—	
Dictyotidium sp. 2							—	
Hemibaltisphaeridium dedosmuertosi							—	

group, is considered by some authors to represent the oldest freshwater Protozoa, due to its similarity to modern euglenoids (Gray and Boucot, 1989).

The preservation of the microfossils is poor. Only fragments of *Diexallophasis* and *Cymbosphaeridium* are preserved, so their determination is approximate. The specimens are brown and dark brown (Pl. II).

ASSEMBLAGE V; LUDLOW — LOWER LUDFORDIAN

Gdańsk IG 1 (depth in metre: 2795.5, 2791.1, 2787.2, 2731.0, 2722.0, 2667.2, 2584.0) — *?leintwardinensis, praecornutus, cornutus*.

Kościerzyna IG 1 (depth in metre: 3214.9) — *leintwardinensis*.

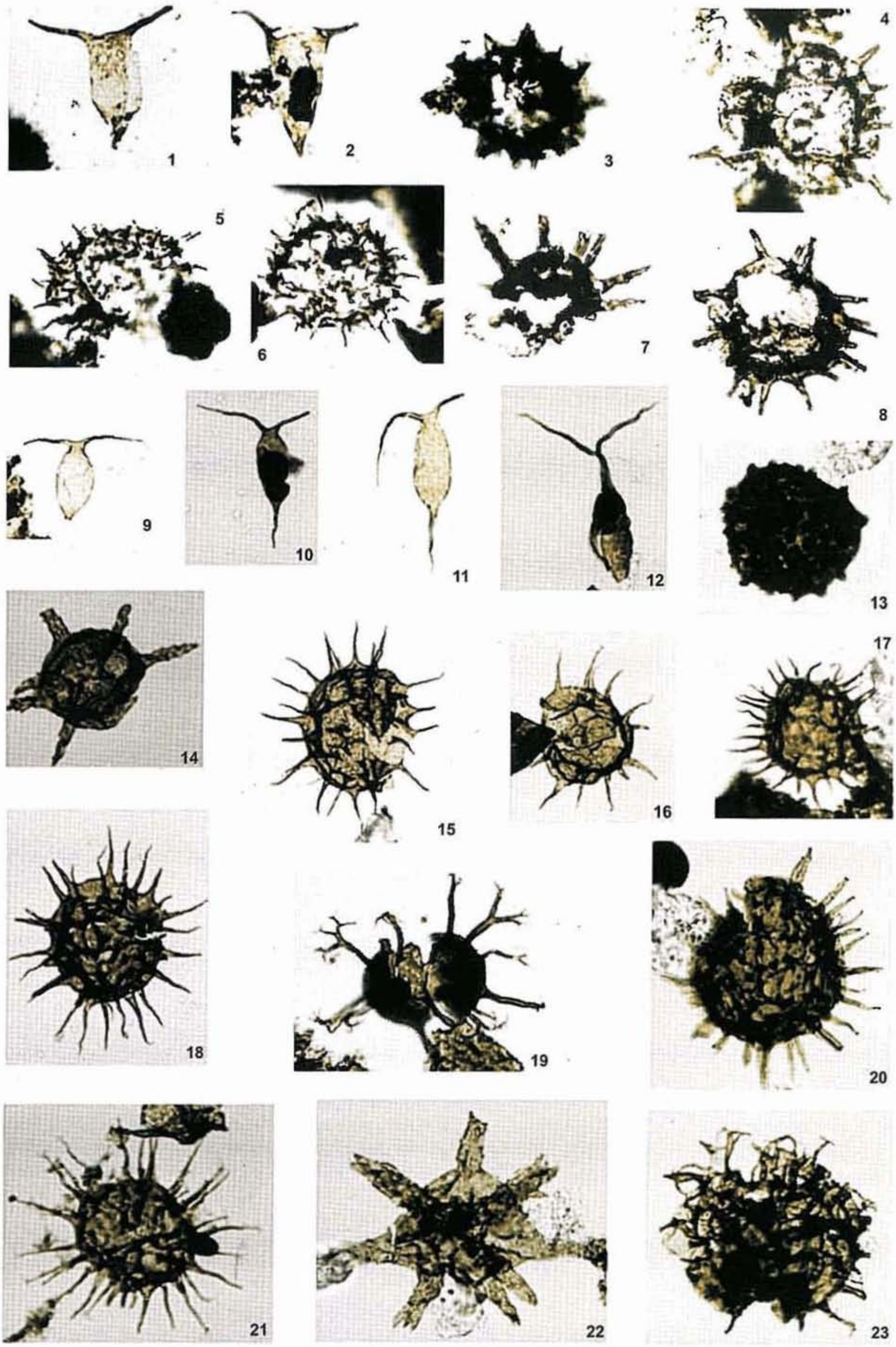
Lębork IG 1 (depth in metre: 2825.0, 2775.0, 2755.0, 2725.0, 2705.0, 2675.0, 2645.0, 2625.0, 2570.0, 2510.0, 2410.0, 2400.0, 2320.0, 2315.0, 2270.0, 2200.0, 2125.0, 2095.0, 2044.0, 1963.3, 1934.0, 1882.4) — *leintwardinensis, praecornutus, cornutus, auriculatus, inexpectatus, kozlowskii*.

Acritarchs are abundant in rocks of this age (300 specimens per slide). The most abundant forms include *Dilatisphaera, Cymbosphaeridium, Tylotopalla, Diexallophasis denticulata, Leiofusa, Eupoikilofusa, Elektoriskos* and *Leiosphaeridia*. Genera such as *Micrhystridium, Geron* and *Tunisphaeridium* were also determined. In terms of quantity, *Cymbosphaeridium* is the most numerous genus and may locally reach 60–70% of the total assemblage. The taxon *Cymbosphaeridium* sp. 1 is short-ranged.

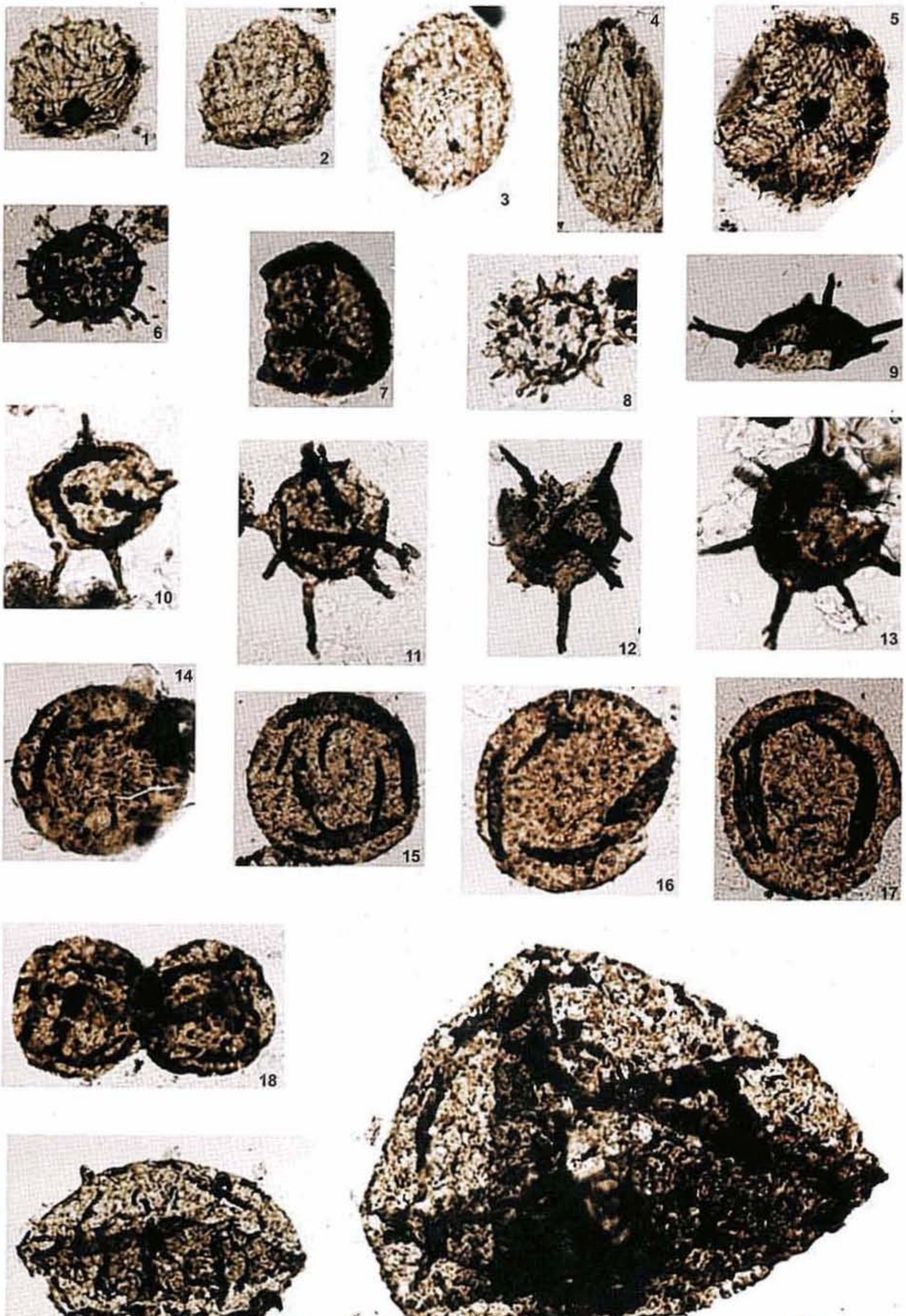
The acritarchs are quite well preserved and largely undamaged. The specimens are brown and dark brown (Pl. III).

ASSEMBLAGE VI; LUDLOW — UPPER LUDFORDIAN

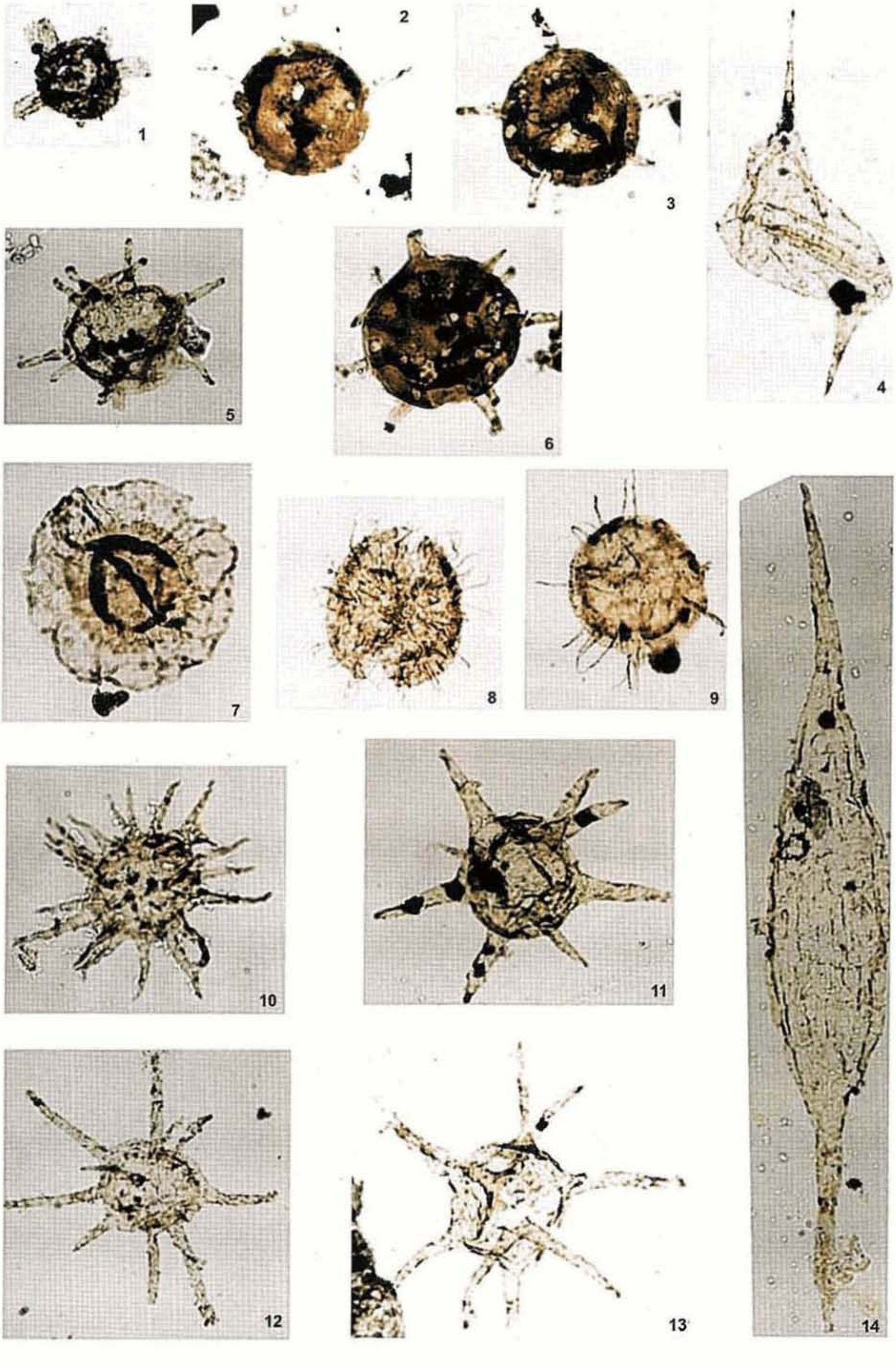
Gdańsk IG 1 (depth in metre: 1995.8) — *?spineus*.



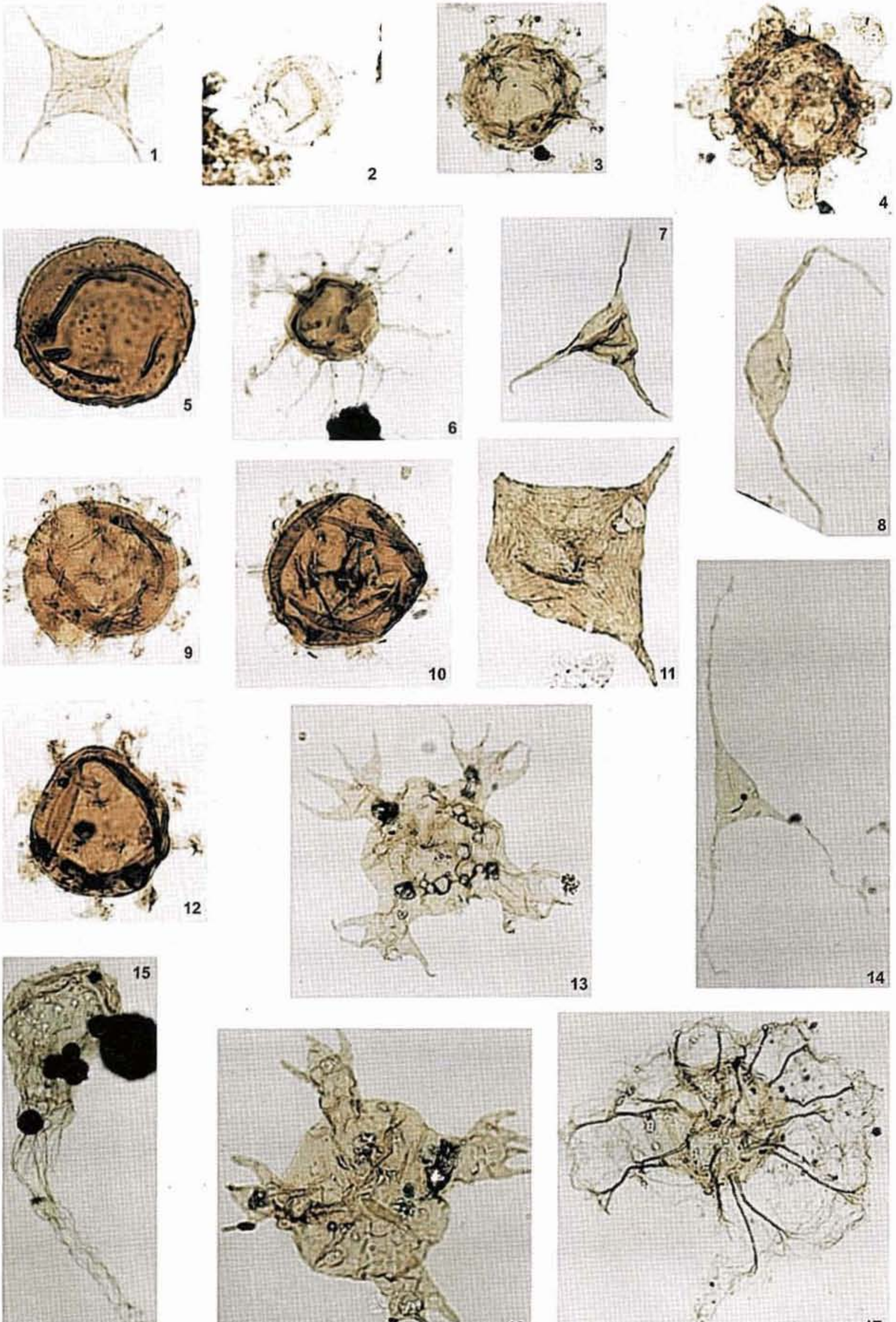
Llandovery (Telychian) acritarch assemblage, x 800; *1. Domasia trispinosa* Downie, 1960. *2. Domasia limaciforme* (Stockmans et Williere) Cramer, 1970. *3. Tylotopalla caelamenicutis* Loeblich Jr., 1970. *4, 8. Ammonidium listeri* Smelror, 1987. *5, 6. Ammonidium* sp. *7, 14. Evittia sanpetrensis* (Cramer) Lister, 1970. *9, 12. Domasia amphora* Martin, 1969. *10, 11. Domasia trispinosa* Downie, 1960. *13. Tylotopalla* cf. *deerlijkiana* (Martin) Martin, 1978. *15, 18. Salopidium granuliferum* (Downie) Dorning, 1981. *16, 17. Salopidium* sp. *19. Oppilatala frondis* (Cramer et Diez) Dorning, 1981. *20, 23. Visbysphaera oligofurcata* (Eisenack) Lister, 1970. *21. Ammonidium microcladum* (Downie) Lister, 1970. *22. Diexallophasis* sp. *1–8, 14* — depth 3263.5 m; *9–13, 15–23* — depth 3255.0 m; Lębork IG 1 borehole



Wenlock (Homerian) acritarch assemblage, x 800; *1, 2. Moyeria* sp. *3, 4, 5. Moyeria cabotti* (Cramer) Miller et Eames, 1982. *6, 10, 11, 12, 13. Micrhystridium* sp. *7. Ambitisporites* sp. *8. Tylotopalla* sp. *9. Cymbosphaeridium* sp. 1. *14, 15, 16, 17. Visbysphaera microspinosa* (Eisenack) Lister, 1970. *18, 19, 20. Leiosphaeridia* sp. Depth 4140.7 m, Kościerzyna IG 1 borehole

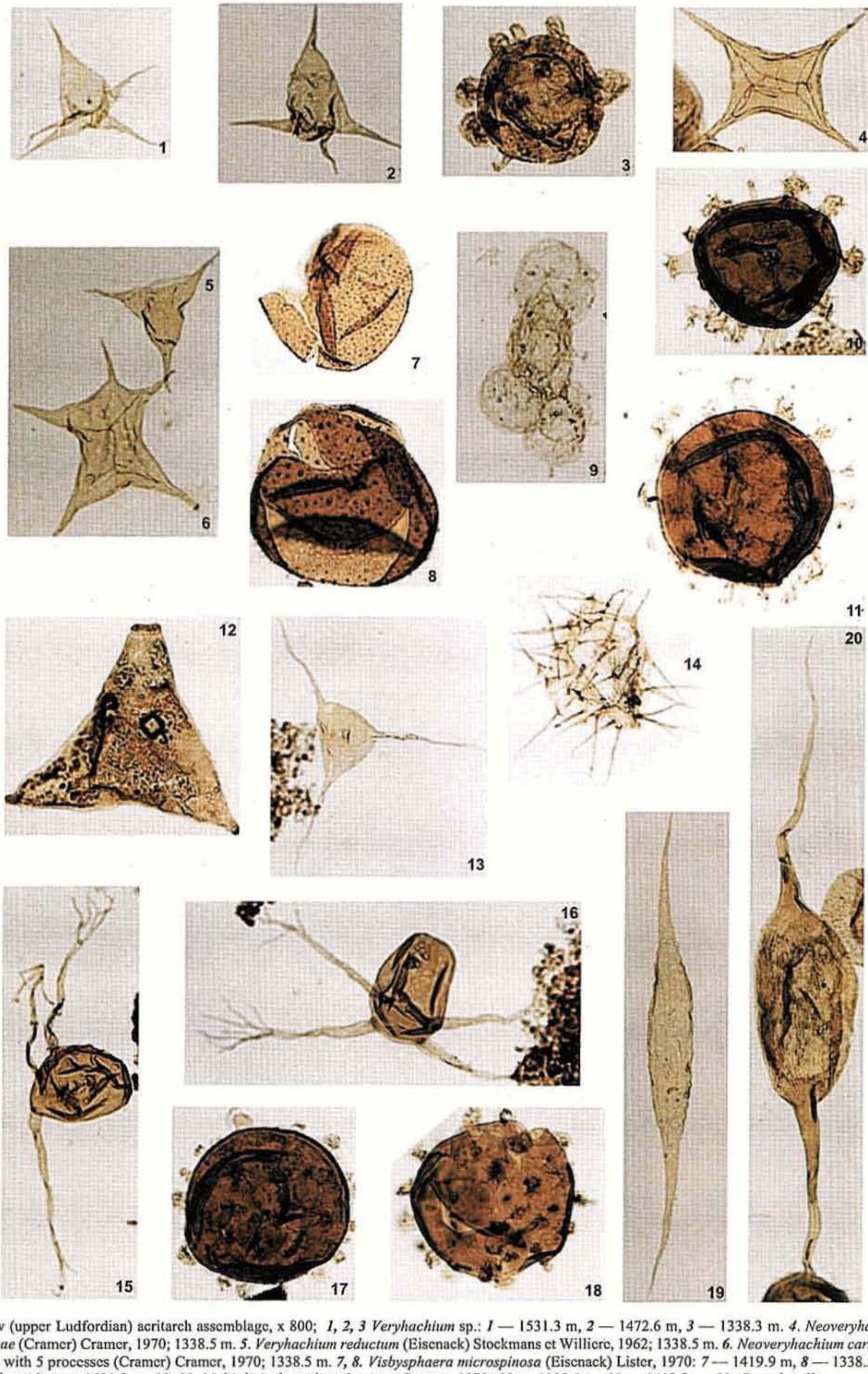


Ludlow (lower Ludfordian) acritarch assemblage, x 800; ***1***. *Dilatisphaera williereae* Martin, 1966; 2645.0 m. ***2, 3, 5, 6***. *Cymbosphaeridium* sp.; 2795.5 m. ***4***. *Leiofusa* sp.; 2795.5 m. ***7***. *Pterospermopsis* sp.; 2320.0 m. ***8***. *Percultisphaera stiphrospinata* Lister, 1970; 2270.0 m. ***9***. *Elektoriskos aurora* Loeblich Jr. 1970; 2270.0 m. ***10***. *Tylotopalla wenlockia* Dorning, 1981; 2320.0 m. ***11***. *Diexallophasis* sp.; 2320.0 m. ***12, 13***. *Diexallophasis denticulata* (Stockmans and Williere) Loeblich Jr., 1970; 2320.0 m. ***14***. *Eupoikilofusa striatifera* (Cramer) Cramer, 1970; 2795.5 m. ***1–6, 14*** — Gdańsk IG 1 borehole; ***7–13*** — Lębork IG 1 borehole



Ludlow (upper Ludfordian) acritarch assemblage, x 800; *1. Neoveryhachium carminae* (Cramer) Cramer, 1970; 1730.1 m. *2. Pterospermopsis* sp.; 1730.1 m. ***3, 9, 10, 12***. *Multiplicisphaeridium bonitum* Cramer, 1970: ***3*** — 1730.0 m, ***9, 10, 12*** — 1657.5–1659.7 m. *4. Visbysphaera jardinae* (Cramer, 1970) Le Hérissé, 1983; 1730.0 m. *5. Visbysphaera microspinosa* (Eisenack) Lister, 1970; 1618.3 m. *6. ?Leptobrachion* sp.; 1618.3 m. ***7, 14***. *Veryhachium trispinosum* (Eisenack) Stockmans et Williere, 1962: ***7*** — 1657.5–1659 m, ***14*** — 1576.1–1583.8 m. *8. Leiofusa banderillae* Cramer, 1964; 1612.3 m. *11. Striatotheca* sp., Ordovician taxon; 1657.5–1659.7 m. ***13, 16***. *Leoniella carminae* Cramer, 1964: ***13*** — 1612.3 m, ***16*** — 1652.5–1659.7 m. *15. Geron guerillerus* Cramer; 1576.1–1583.8 m. *17. Tunisphaeridium tentaculiferum* (Martin) Cramer, 1970; 1612.3 m. Lębork IG 1 borehole

PLATE V



Ludlow (upper Ludfordian) acritarch assemblage, x 800; ***1, 2, 3*** *Veryhachium* sp.: ***1*** — 1531.3 m, ***2*** — 1472.6 m, ***3*** — 1338.3 m. ***4***. *Neoveryhachium carminae* (Cramer) Cramer, 1970; 1338.5 m. ***5***. *Veryhachium reductum* (Eisenack) Stockmans et Williere, 1962; 1338.5 m. ***6***. *Neoveryhachium carminae*; variant with 5 processes (Cramer) Cramer, 1970; 1338.5 m. ***7, 8***. *Visbysphaera microspinosa* (Eisenack) Lister, 1970: ***7*** — 1419.9 m, ***8*** — 1338.5 m. ***9***. *Leiosphaeridia* sp.; 1531.9 m. ***10, 11***. *Multiplicisphaeridium bonitum* Cramer, 1970: ***10*** — 1338.5 m, ***11*** — 1419.9 m. ***12***. *Onondagella asymmetrica*; 1472.6 m. ***13***. *Veryhachium trispinosum* (Eisenack) Stockmans et Williere, 1962; 1531.3 m. ***14***. *Baltisphaeridium* sp.; 1338.5 m. ***15, 16***. *Hemibaltisphaerosum dedosmuertosi* (Cramer) Cramer, 1970; 1472.6 m. ***17, 18***. *Visbysphaera pirifera* (Eisenack) Le Hérissé, 1989; 1338.5 m. ***19***. *Leiofusa* sp.; 1531.3 m. ***20***. *Eupoikilofusa cantabrica* (Cramer) Cramer, 1970; 1338.5 m. Lębork IG 1 borehole

Kościerzyna IG 1 (depth in metre: 2432.8, 2358.0, 2301.7, 2373.3) — *?spineus* + *?protospineus* + *?lebanensis* + *?balticus*.

Lębork IG 1 (depth in metre: 1812.0, 1810.1, 1768.3, 1730.1, 1679.8, 1653.0, 1612.3, 1584.3, 1578.0, 1531.3, 1472.6, 1419.9, 1338.3, 1283.6, 1257.1, 1242.3, 1207.7, 1183.3, 1166.8, 1135.0, 1125.5, 1121.0, 1102.9) — *balticus, acer, ?protospineus, regnans* = *hemsiensis* = *?spineus*.

Very rich and well preserved acritarch associations occur (over 1000 specimens per slide). Apart from numerous long-lived genera and species such as *Leiosphaeridia, Veryhachium lairdii, V. trispinosum, V. reductum* and *Leiofusa*, many associations contain also taxa which occur for the first time in the profiles. These include *Leoniella carminae, Visbysphaera jardinae, Geron guerillerus, G. gracilis, Deflandrastrum millepiedii, Tunisphaeridium tentaculiferum* and *Leiofusa banderillae*. Associations dominated by *Neoveryhachium carminae* (over 200 specimens per slide) are characteristic. This is the first occurrence of this species in Poland. So far, assemblages containing it were considered characteristic of Silurian strata on Gondwana and in peri-Gondwana regions (western and central Africa, northern France and Iberian Peninsula; Cramer and Diez, 1972). Acritarch preservation and morphology is shown in Plates IV–V.

ASSEMBLAGE VII; PŘIDOLI

Gdańsk IG 1 (depth in metre: 1800.5, 1654.0) — *prima–incerta, ?paraultimus* + *?ultimus*.

Kościerzyna IG 1 (depth in metre: 2103.0) — *lochkovensis* + *ultimus* + *?paraultimus*.

Lębork IG 1 (depth in metre: 1046.3) — *prima–incerta, ?paraultimus* + *?ultimus*.

Abundant and very well preserved organic-walled microfossils occur in Přidolian strata (more than 1000 specimens per slide). *Tasmanites* and *Cymatiosphaera* are dominant, locally reaching 80% of the assemblages. These are associated with common *Leiosphaeridia* and also: *Veryhachium trispinosum, Leoniella carminae, Onondagella* sp., *Leiofusa, Visbysphaera microspinosa, Deflandrastrum, Micrhystridium* sp., *Geron gracilis, Tunisphaeridium parvum, Moyeria cabotti* and *Pterospermella* sp. Most acritarchs determined here occur also in Ludfordian sediments. The associations found in the Přidoli differ from these in the greater abundance of *Tasmanites* and *Cymatiosphaera* and also in fewer *Visbysphaera* and *Hemibaltisphaeridium*. As in the Ludfordian rocks, preservation is very good. The specimens do not show any damage, even on delicate elements of the sculpture. They show little thermal alteration, being light yellow or orange in colour.

PALYNOLOGICAL RESULTS FROM THE BOREHOLES OF THE TESZ

The Silurian rocks in the Bydgoszcz IG 1, Klosnowo IG 1 and Stobno 1 boreholes did not have a well-defined stratigraphy. Acritarchs were analysed to try to provide one.

22 samples were investigated, from the following boreholes:

— Bydgoszcz IG 1 (depth in metre: 5603.0, 5602.6, 5602.0, 5601.5, 5600.9, 5600.5, 5600.0);

— Klosnowo IG 1 (depth in metre: 2460.4, 2460.0, 2454.2, 2453.3, 2452.6, 2452.6);

— Stobno 1 (depth in metre: 2525.9, 2525.0, 2524.0, 2522.3, 2521.3, 2560.8, 2519.7, 2490.5).

Determinable acritarchs were found in the samples from the Klosnowo IG 1 and Stobno 1 boreholes. Despite detailed investigation, no stratigraphically useful acritarchs were recovered from the Bydgoszcz IG 1 borehole.

STOBNO 1

The most abundant organic-walled microfossils were determined from the Stobno 1 borehole, with over 300 specimens per slide. The association chiefly comprised: *Leoniella carminae, Visbysphaera microspinosa, Hemibaltisphaeridium dedosmuertosi, Veryhachium lairdii, Tunisphaeridium parvum* and *Geron gracilis*. The samples also contained numerous specimens of *Leiosphaeridia, Veryhachium, Onondagella, Diexallophasis* and *Leiofusa*. The specimens are well preserved and show little damage. Their orange and light brown colour indicates that the temperature did not exceed 100–120°C. The similar associations were found in the upper Ludfordian sediments of the Gdańsk IG 1, Kościerzyna IG 1 and Lębork IG 1 boreholes. These associations show comperable preservation and also a similar intensity of thermal metamorphism.

KLOSNOWO IG 1

Here, there were well preserved acritarchs with over 100 specimens per slide. The associations are dominated by *Leiosphaeridia*, which is accompanied by more diagnostic taxa such as *Tylotopalla, Leiofusa* and *Micrhystridium*. Similar associations are known from Wenlock strata in other areas (Dorning, 1981*b*; Le Hérissé, 1989). Acritarch associations of similar specific composition have not yet been determined in Silurian rocks from the Gdańsk IG 1, Kościerzyna IG 1 and Lębork IG 1 boreholes.

The acritarchs are well preserved, showing little damage or change in colour: light yellow and yellow colours indicate temperatures below 80°C. The lowest thermal maturity was encountered in the Klosnowo IG 1 borehole.

PALAEOECOLOGY

Acritarchs occur mostly in marine sediments, having been determined in shale, siltstone, claystone and in limestone. Their wide geographical expansion and size suggests a planktonic mode of life. Their morphology, chemical composition, and the occurrence of a distinctive opening in many taxa suggest that many forms belonging to this group represent cysts analogous to those of the dinoflagellates. Comparison with modern ecosystems suggests that they were phytoplankton in the photic zone of a basin, producing large amounts of organic matter and oxygen (Tappan, 1980). Acritarch morphology is commonly interpreted as an adaptation to open sea conditions and to maximise exploitation of the photic zone. Their processes helped the organisms to maintain their position in the water column.

The growth of phytoplankton in the basin depends on many factors, such as temperature, salinity, intensity of light penetration and turbulence.

Quantitative and qualitative studies have shown a relationship to sedimentary facies. Acritarchs, similarly to dinocysts, are most diverse in offshore shelf deposits, diversity decreasing in deep water (Wall *et al*., 1977). Staplin (1961) was the first to associate acritarch associations with depth, while Dorning (1981*a*) considered that it is possible to determine distance to the shore and depth using acritarchs. He distinguished three acritarch associations in the Silurian of southern Wales related to increasing depth and distance from shore. The offshore association is of low diversity (15–50 species) and is dominated by small spherical forms with a smooth surface and short processes. The second acritarch association, associated with a deeper, open shelf, shows high diversity (10–90 species in a sample), without any dominant taxon. The third, deep water, association is of low diversity (2–5 species in a sample), and representatives of the Sphaeromorphitae subgroup are dominant. They have thick walls which, according to some authors, may suggest high energy conditions (Martin, 1993).

The Silurian profiles studied here show a distinctive temporal differentiation of the acritarch associations. The lowest Silurian (Rhuddanian and Aeronian) associations are poorly diversified with a predominance of simple spherical *Leiosphaeridia* with thick walls, accompanied by scarce spinose acritarchs. This composition suggests a deep-water setting.

The rich and diverse associations of the Telychian, Ludfordian and Přidoli rocks are typical for an offshore shelf setting.

PALAEOGEOGRAPHY

The Proterozoic to Devonian interval is optimal for acritarchs. Acritarch associations show a mostly cosmopolitan nature, facilitating long-range correlation. But, the limited spatial range of some taxa has led to them being used in Lower Palaeozoic palaeogeographic reconstructions (Vavrdová, 1974; Cramer and Diez, 1972).

M. Vavrdová was the first to observe in 1974 distinctive geographical differentiation of acritarch associations in the Lower Ordovician strata of Europe. She suggested, using differences at a generic level, the existence of two provinces: Mediterranean and Baltic.

Cramer (1970) and Cramer and Diez (1972) revealed further distinctive geographical differentiation of acritarch associations in Silurian sediments. They assumed that each organism had its own maximal, optimal and minimal "living temperature". They used acritarch distribution data to identify subequatorial zones, assuming control mainly by the climate.

The palaeogeographic implications of Lower Palaeozoic acritarchs has been further discussed (Nautiyal, 1976, 1977; Hill and Molyneux, 1988; Colbath, 1990) and earlier models have been revised (Le Hérissé, 1989; Le Hérissé and Gourvennec, 1995). Lateral variations in acritarch associations of the same age are increasingly being interpreted as facies preferences of individual taxa.

These studies of Pomeranian acritarchs have revealed new distributional data. Most of the forms determined here have a cosmopolitan nature, ranging from the Baltic area to northern Africa and South America. These are accompanied by taxa so far considered to have a more limited occurrence. For example, the species as *Domasia amphora*, *Tylotopalla pyramidalis* and *Dilatisphaera williereae,* identified in this study, were earlier known only from low palaeolatitudes. Numerous specimens of *Geron gracilis*, *Deflandrastrum millepiedii*, *Neoveryhachium carminae*, *Hemibaltisphaeridium*, some *Visbysphaera* species have also been documented, and these were previously known only from high palaeolatitudes. Surprisingly, no specimens of typical Baltic genera such as *Hoegklintia* or *Pulvinosphaeridium* have been determined in the samples studied. This may be due to gaps in sampling of these thick Silurian successions.

The Silurian deposits of Pomerania also contain typical Lower Ordovician taxa such as *Acanthodiacrodium*, *Frankea*, *Striatotheca*, *Baltisphaerosum* and *Coryphidium* on secondary deposit. These are characteristic of the Mediterranean Province as defined by Vavrdová (1974). They are well preserved, suggesting short transport.

PATTERNS OF THERMAL ALTERATION

The Pomeranian acritarch assemblages show clear differences in preservation and thermal alteration. It is well established that organic substances change their colour with progressive thermal transformation from light yellow to orange, brown and black.

Acritarchs recovered from the *crispus* Biozone of the Llandovery show the greatest thermal alteration. Their dark brown to black colour suggests the temperatures of about 200°C. Acritarchs from Llandovery, Wenlock and lower Ludfordian deposits show brown to dark brown colours suggesting temperatures of about 150–180°C.

A distinctive change in microfossil preservation occurs in upper Ludfordian strata, appearing at the level of the *balticus* Biozone. Acritarchs here are light brown and orange in colour, suggesting temperatures of about 100–150°C. This intensity of thermal alteration continues to the top of the Silurian profiles studied.

These changes of thermal alteration intensity, observed in the Gdańsk IG 1, Kościerzyna IG 1 and Lębork IG 1 boreholes, are probably associated with changes of subsidence rate during sedimentation, or with the multi-stage heating.

OTHER MICROFOSSILS

Most of the samples studied contained numerous organic-walled microfossils other than acritarchs. These include *Chitinozoa*, scolecodonts and terrestrial plant-spores. Prasinophytes are common, especially in Upper Silurian deposits. Occasional samples from the Telychian contain also large muellerisphaerid fragments.

Among these, chitinozoans are the most numerous and have been found in most of the graptolite horizons investigated. The associations show considerable generic diversity, and specimens occur separately or joined in chains. Chitinozoans occurred also in those samples which otherwise contained only scattered organic matter and graptolite fragments, indicating a lower sensitivity to facies control than the acritarchs.

Terrestrial miospores are represented mainly by *Ambitisporites*, found in Llandovery, Wenlock and Ludfordian deposits. This genus represents simple forms of the Triletes-Azonales group, stratigraphically the earliest miospore group. Single specimens of *Zonotriletes* have been determined in the Ludfordian. The miospores comprise only about 5% of most samples studied. The terrestrial plant miospores, transported into the basin by aeolian or fluvial action, represent an allochthonous element in these marine rocks. The miospore exines are usually well preserved and do not show the kind of mechanical damage caused by long transport. Thus, the shoreline was probably not far away.

In occasional samples of Telychian rock, distinctive spiny forms with dimensions from 100 to 600 μm diameter have been determined. These represent muellerisphaerid fragments. These microfossils were first described from Silurian strata in Germany by Sannemann (1955), included them in the acritarch genus *Hystrichosphaeridium*, despite their large size. The group Muellerisphaeridia was defined by Kozur in 1984. Similar microfossils are also referred to the mazuelloids, a term proposed by Aldridge and Armstrong in 1981. These latter marine fossils usually occur as isolated spines which represent sculptural elements of much larger specimens; complete spheres are found only very rarely. Muellerisphaerids (= mazuelloids) have been recorded from Ordovician to Devonian pelagic deposits in Europe, Asia, North America and Australia (Priewalder, 1987; Hüsken and Eiserhardt, 1996).

CONCLUSIONS

Palynological investigations of Silurian deposits from Pomerania indicate the following:

1. In most of the samples studied from the Gdańsk IG 1, Kościerzyna IG 1, Klosnowo IG 1, Lębork IG 1 and Stobno 1 boreholes, there are determinable associations of organic-walled microfossils which represent both a microflora (acritarchs, prasinophites and microspores) and a microfauna (*Chitinozoa* and *Scolecodonta*).

2. Lower Silurian (Llandovery and Wenlock) associations are typical of deep water palaeoenvironments showing low taxonomic diversity. Telychian and Upper Silurian (Ludfordian, Přidoli) assemblages are rich and diverse at both generic and specific levels, and so typical of offshore shelf palaeoenvironments.

3. Assemblages from Llandovery, Wenlock and Lower Ludlow strata show poor preservation and high levels of thermal alteration. Assemblages from upper Ludfordian deposits are very well preserved and show much lower levels of thermal alteration.

4. 7 stratigraphically controlled acritarch assemblages have been recognised and these have been correlated with the graptolite biostratigraphy.

5. Associations characterised by *Domasia*, *Ammonidium* and *Tylotopalla* have been recognised in Llandovery strata; and by *Tylotopalla*, *Leptobrachion* and *Cymbosphaeridium* in Wenlock deposits is Upper Ludlow rocks contain rich and very well preserved associations characterised by *Visbysphaera*, *Veryhachium*, *Onondagella* and *Leoniella*; these are accompanied by *Neoveryhachium carminae*, *Geron gracilis* and *Deflandrastrum*, previously only described from the Baltic area.

6. Occasional specimens of typical Lower Ordovician genera such as *Acanthodiacrodium*, *Frankea*, *Striatotheca* and *Coryphidium* occur throughout, as reworked fossils. These are of Mediterranean Province affinity (Vavrdová, 1974).

7. Acritarch associations from the Silurian deposits of western Pomerania show genera and species known both from Baltica and Gondwana. The information to date is not sufficient to give an unambiguous determination of palaeogeographical position.

Palynological material obtained from Silurian strata of the East European Craton and TESZ is cosmopolitan in nature.

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