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by Leif Bergman, Risto Tynni and Boris Winterhalter

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PALEOZOIC SEDIMENTS IN THE RAPAKIVI AREA OF THE ÅLAND ISLANDS

by

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and 4 appendices

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Bergman, Leif, 1982. Clastic dykes in the Åland Islands, SW Finland and their origin. *Geological Survey of Finland, Bulletin 317,* 33 pages 15 figures, one table, one appendix, and one plate.

Clastic dykes occur in the rapakivi area of the Åland Islands, southwestern Finland, either as single dykes or as swarms forming complex fissure patterns. The dykes, ranging in width from a few mm to 60 cm, have mostly northern to east-northeastern trends and show great variation in grain-size distribution, even within a single dyke. They are cemented mainly by silica mixed with various amounts of iron compounds, rarely by calcite and fluorite. The median grain size varies from silt to coarse sand.

The rapakivi is of Middle Proterozoic age and the clastic dykes are according to microfossil determinations, of both Lower Cambrian and Lower Ordovician ages. It is proposed that the dykes were formed by the injection of unconsolidated sediments into fissures opened by tectonic activity. As the sedimentation proceeded, the underlying sediments were subsequently consolidated. New tectonic activity opened fissures in the basement again and also in the more consolidated parts of the sedimentary column, causing the injection of detritus from the upper loose parts of the sequence into the fissures.

Key words: clastic dykes, sandstone, siltstone, injection, tectonics, Cambrian, Ordovician, Åland, Finland

Tynni, Risto, 1982. On paleozoic microfossils in clastic dykes on the Åland Islands and in the core samples of Lumparn. *Geological Survey of Finland, Bulletin 317,* 81 pages, 23 figures, and 20 plates.

Of the sandstone dykes over 2 cm thick investigated in the rapakivi area of Åland Islands, some ten contain acritarch communities. Most of the communities met with are of same type as the ones known from, for example, Lower Cambrian deposits in Estonia. Some of the sandstone dykes contain acritarch species dating from the Lower Ordovician period.

The drillcore south of Tranvik, Lumparn Bay includes siltstone and limestone strata overlying a weathered bedrock of rapakivi granite. The siltstone was deposited during the Lower Cambrian. The c. 60-m thick limestone is greenish gray in its lower and middle parts and it contains a fair abundance of acritarch species. The majority consist of *Baltisphaeridium* and *Leiosphaera* species belonging to subgroups of Acanthomorphitae and Sphaeromorphitae. In part, they are newly discovered species; in addition, there occurs a form designated as a new genus and given the name of the place where the discovery was made: *Tranvikium polygonale.*

The lower part of the limestone bed in the Lumparn basin was probably deposited at the final stage of the Lower Ordovician, and the middle part during the Middle Ordovician. The uppermost part, consisting of fine-grained calcilutite, does not contain acritarchs.

Key words: acritarch, Cambrian, Ordovician, Lumparn, Åland, Finland

Winterhalter, B. 1982. The bedrock geology of Lumparn Bay, Åland. Geological Survey of Finland, *Bulletin 317*, 15 pages and 9 figures.

Lumparn Bay, on the main island of the Åland Islands, southwest of the Finnish mainland, occupies a depression within a large massif of postorogenic rapakivi-granite. Proterozoic and Lower Paleozoic sediments including Ordovician limestone, occur in the submarine parts of the basin, as deduced from seismic reflection profiles. The deposits have been protected from denudation by downfaulting. A meteoritic origin has also been proposed for the bay.

Key words: Lumparn Bay, tectonics, Precambrian, weathering, Proterozoic, sediment, Paleozoic, seismic profiling, bathymetry

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CLASTIC DYKES IN THE ÅLAND ISLANDS, SW FINLAND AND THEIR ORIGIN

by

Leif Bergman

CONTENTS

INTRODUCTION

The existence of clastic dykes in the rapakivi area of the Åland islands has been known since the end of the 19th century (Frosterus & Sederholm 1890). Up to 1972, some twenty or thirty dykes had been described by several authors, among them Tanner (1911), Simonen & Kouvo (1955), Mattson (1960), Hausen (1964) and Edelman (1964). During remapping of the rapakivi area 1972—78, over 250 new clastic dykes were found (Bergman 1976, Suominen 1978 and Ehlers & Ehlers 1981).

The rapakivi massif (5 000—5 500 sq. km, taking the submarine parts into account) is a composite pluton consisting of several texturally and petrographically different varieties of granite. The rapakivi granites are reddish, homogeneous and have no parallel structures. This homogeneity makes the rapakivi area suitable for the detection of clastic dykes.

The observations of the clastic dykes within the rapakivi area are compiled in a list (Appendix) and the sites are numbered. The

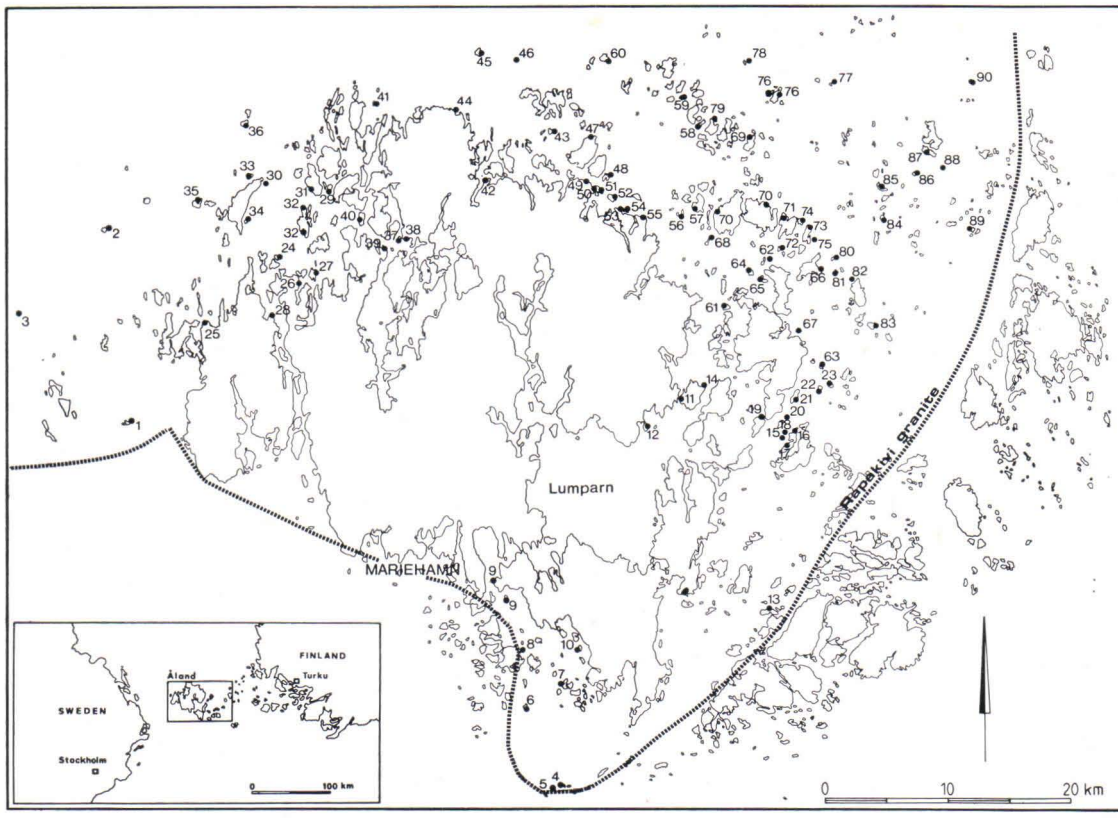

Fig. 1. The extent of the clastic dykes in the rapakivi area of the Åland Islands. The numbers refer to the list in the Appendix.

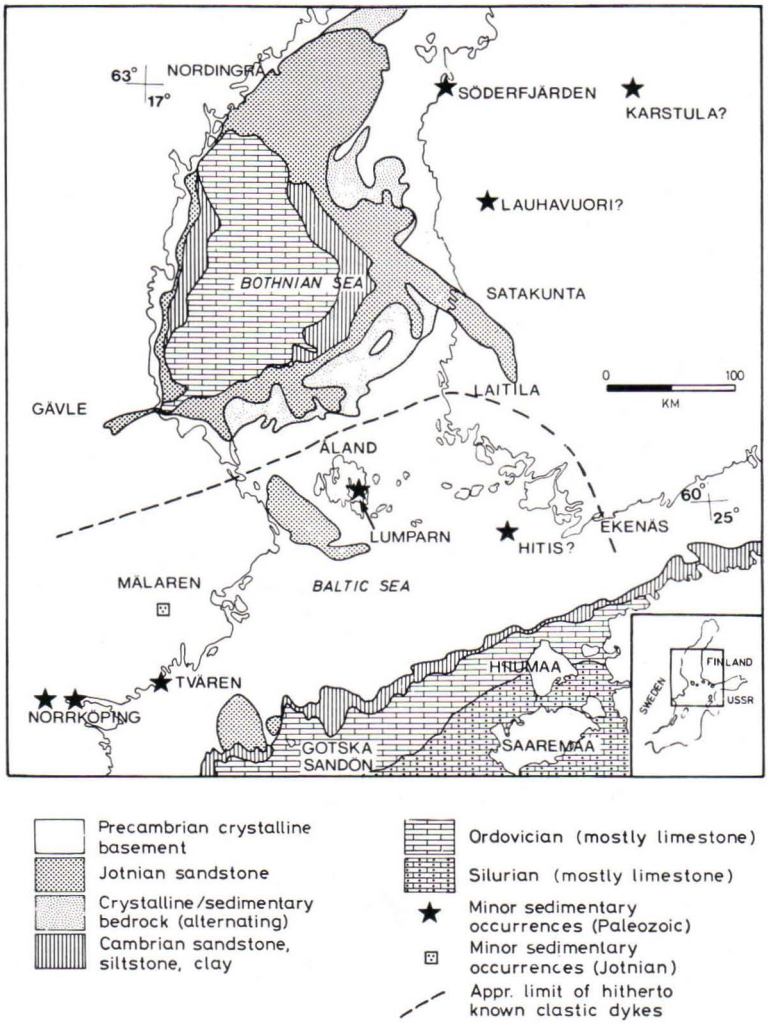

Fig. 2. The distribution of Jotnian and Paleozoic sedimentary rocks in southern Finland, east-central Sweden, the Bothnian Sea and the northern part of the Baltic Sea. The submarine distribution is simplified from Flodén and Winterhalter (1981). The landward continuation in the USSR is omitted. The supramarine Jotnian and minor occurrences are compiled from several authors.

sites are marked in Fig. 1. The list further contains the name of each locality, the Finnish map numbers and coordinates, the width and strike of the dykes and the notation of the dykes that were sampled for thin-section and microfossil investigations.

Outside the Åland rapakivi area, some twenty or thirty clastic dykes have been observed in the archipelago and the coastal area of southwestern Finland (e.g. Sederholm 1913, Martinsson 1955, Fig. 3, 1956, Edelman 1956, Lauren 1968 and Suominen 1973, 1978 and 1980). The approximate limit of the hitherto known clastic dykes in Finland is shown in Fig. 2. The northernmost dyke lies in the Laitila rapakivi area having been found in

1964 (Å. Mattson, personal comm.), and the most easterly dyke in the Ekenäs-Hangö archipelago (Sederholm 1913). The northern limit extends in Sweden through the Uppsala region (Wiman 1918).

The clastic dyke occurrences in the Precambrian basement seem to increase in frequency toward the west, judging by the fact that in central and southern Sweden, along the coastal region of the Baltic Sea and on the island of Bornholm in Denmark, a couple of hundred dykes have been observed (Ussing 1899, Nordenskjöld 1944, Rudberg 1954, Martinson 1958, Mattson 1962, Carlsson & Holmqvist 1968 and Samuelsson 1975).

OUTLINES OF THE SEDIMENTARY BEDROCK GEOLOGY IN SOUTHWESTERN AND WESTERN FINLAND

The Middle Proterozoic rapakivi massif in the Åland islands is postorogenic in relation to the Svecokarelian orogeny. After the rapakivi intrusion, denudation produced a peneplain upon which sediments were deposited, first in the Jotnian (Riphean) time and later in the early Paleozoic (Flodén and Winterhalter 1981). In the Lumparn Bay, weathered rapakivi is preserved below the Paleozoic sediments (Winterhalter 1981, p. 123), but the early Paleozoic clastic dykes have been found in »virtually unweathered bedrock» (Flodén and Winterhalter 1981, p. 31). Later erosion removed the sedimentary rocks, leaving the clastic dykes as evidence of the early Paleozoic sedimentary cover in the Åland area. Microfossil determinations show the dykes to be of both Lower Cambrian and Lower Ordovician ages (Tynni 1982, Fig. 22).

The locations of the unmetamorphosed Jotnian and Paleozoic sedimentary rocks within the area of the Precambrian basement are mainly confined to the submarine parts of the Bothnian Sea and the northern part of the Baltic Sea (Fig. 2). The Jotnian sediments continue landwards in tectonic depressions in the Satakunta area in Finland and the Gävle area in Sweden. A minor coastal extension occurs in the Nordingrå area, Sweden, as well as in a small, separate area in Mälaren.

Paleozoic sediments are known to occur in southern Finland in situ in three places: 1. The Lumparn Bay, 2. Söderfjärden and 3. Lauhavuori (?). The Lumparn occurrence consists of Lower and Middle Ordovician limestone underlain by poorly lithified Lower Cambrian siltstone (Tynni 1982, p. 85).

On a small islet, Röda kon, and in some places along the southern and eastern shores of Lumparn, there occurs in fracture zones and small cavities rapakivi gravel relatively loosely cemented by red iron oxides or hydroxides and reddish calcite. The deposits can be interpreted as weathering products or fault breccias. On the basis of analogies with Swedish occurrences, Asklund (1926) interpreted the breccia at Röda kon to be a basal breccia of Jotnian age. No microfossils were observed in the breccia (Tynni, personal comm.), but the loose consolidation indicates a younger age than Jotnian. The breccia is evidently of sub-Cambrian age formed prior to the deposition of the Cambrian sediments in Lumparn. The weathered Precambrian basement has also been met with in drillings through the Paleozoic in, e.g., Gotland and the southern Bothnian Sea (Thorslund 1938, p. 15 and Thorslund & Axberg 1979, p. 45).

In Söderfjärden, the sedimentary sequence is of the Lower Cambrian age (Tynni 1978). It consists mainly of sandstone and siltstone.

Both Söderfjärden and Lumparn are situated in depressions, which have been interpreted to be either structural basins or meteoritic impact structures. According to Laurén *et al.* (1978), the Söderfjärden structure was probably formed by either a meteoritic impact or forceful magmatic activity, judging by the tuffaceous basal breccia. Lumparn, which is very likely a tectonic depression (Winterhalter 1982, p. 129), has also lately been interpreted as an astroblem (Merril 1980).

The Lauhavuori occurrence differs from the two foregoing ones in that it forms a hill rising over the sub-Cambrian peneplain and not a depression where the sediments were preserved from later erosion. The sediments consist mostly of a hard quartz sandstone highly resistant to erosion (Simonen & Kouvo 1955). A drilling to a depth of 10 m at the flank of the Lauhavuori sandstone revealed that microfossils are quite scarce, no index fossils referable to the Cambrian were detected and thus a dating has not been possible (Tynni, personal comm.). A Cambrian age has, however, been proposed on the basis of petrographical similarities with the clastic dykes of southwestern Finland (Simonen & Kouvo 1955).

Sandstone erratics occur abundantly in the Karstula and Hitis areas (Sauramo 1916 and Edelman 1949). The boulders probably originated from two minor tectonic underwater depressions. Both localities resemble the clastic dykes petrographically in southwestern Finland, but the Karstula boulders contain no datable fossils suggesting a late Precambrian age (Tynni, 1974); the Hitis sandstone has not yet been investigated for fossils. As the Lauhavuori, Karstula and Hitis occurrences have not been definitely dated, their ages remain an open question, as marked in Fig. 2.

GENERAL DESCRIPTION OF THE CLASTIC DYKES

All the clastic dykes except one are situated along shores, where the bedrock is exposed due to sea action. The exception is a road cut on Prästö (No. 11) where a dyke occurs in the northern wall but not in the southern one. The dykes can usually be followed for a few dozen metres, until they disappear under the sea or the overburden and vegetation. The colour of the material forming the dykes is usually a different shade of brown, grey or greenish grey. Only five dykes are reddish or reddish brown. Dykes situated close to each other may differ in colour; e.g., there are on the islet of Skarven (No. 2) two dykes; one is rusty brown and the other greenish grey. The dykes vary from a few mm to 60 cm, but are mostly 1—4 cm, in width, 92 % of the dykes are thinner than 8 cm.

The clastic dykes are more susceptible to weathering than the adjacent rapakivi granites and therefore form furrows in the rock surface (Fig. 3). Another characteristic feature is that the contacts against the rapakivi are usually fractured (Fig. 4). Where the contacts have weathered away, the clastic dykes stand out like plates in the fissures. At Långholm (No. 51) and Långö (No. 73) there occur dykes with either both or one of the sides more eroded than the centre (Fig. 5). Further the more eroded parts differ in colour from the centre.

The clastic dykes are seldom straight, but curved and they form dyke systems irregular in pattern. Fig. 6 shows a dyke system with the main strike running N—S. The dyke system is cut by two minor fissure zones. The total width of the dyke system is approxi-

Fig. 3. Slightly eroded clastic dyke. Fåfängskär, (No. 74).

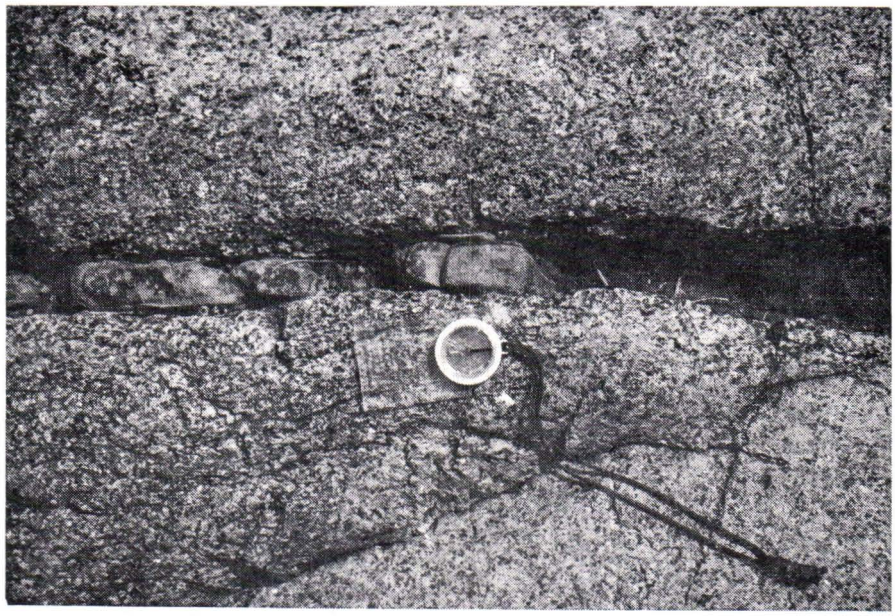

Fig. 4. Clastic dyke with factures along the rapakivi contact. Långholm, (No. 51).

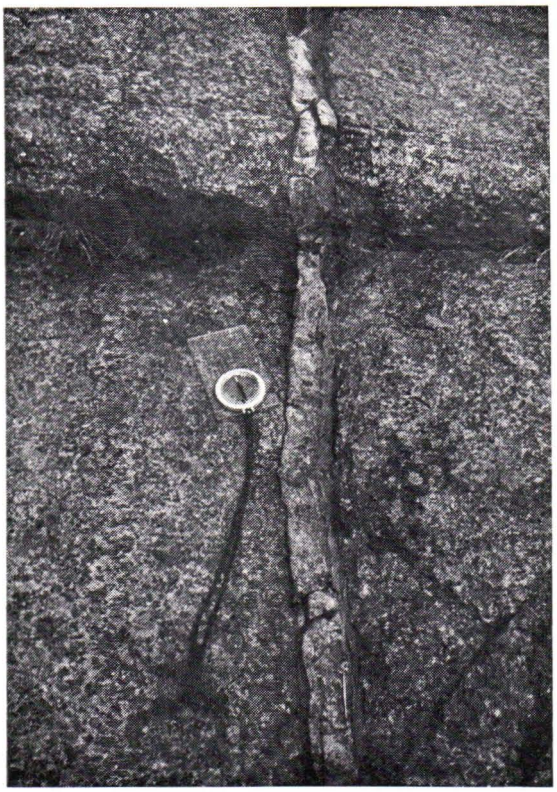

Fig. 5. Clastic dyke with one side deeper eroded. Långholm, (No. 51).

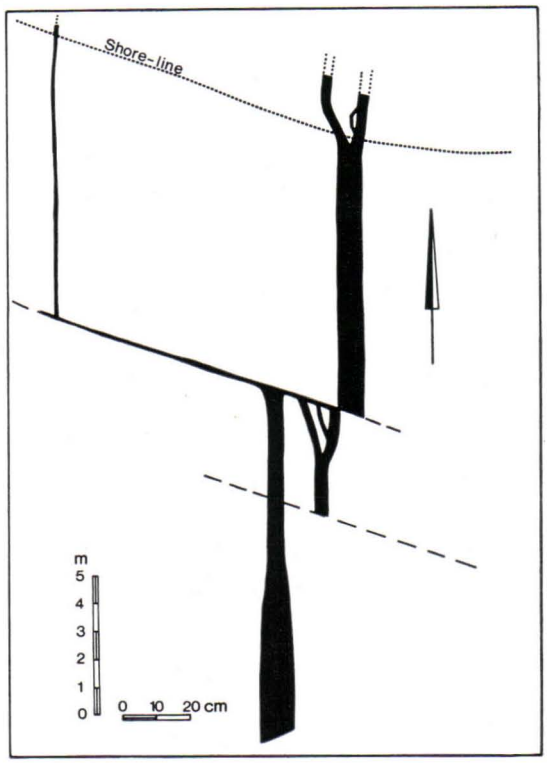

Fig. 6. Sketch of a clastic dyke system. Silverskär, (No. 53).

mately the same independent of whether it is a single dyke or several dykes occurring abreast and with equal dilation.

Examples of more irregular dyke systems are outlined in Fig. 7. The same feature also appears here; that is the total width of each dyke system is fairly constant. Sketch No. 1 (Fig. 7) seems to represent an exception, with a 12-cm wide dyke parting into two narnower, connected branches and a thin outlier. Sharp-edged rapakivi fragments lie within the dyke system; and where it crosses the aplite dyke, the fragments are displaced about 5 cm. It is therefore likely that the fragments have partly sunk down and the dilation is equal along the whole visible part. Fragments of rapakivi are common in the dykes as sketches Nos. 2 and 3 (Fig. 7) indicate. Also silt-clay inclusions are met with at, for example, Österholm (No. 21) and Långbergsöda-öjen (No. 53), and a few dykes are associated with galena (Bergman & Lindberg 1979). Field and microscopic observations indicate that the galena is younger than the clastic dykes.

The dominant strike direction of the dykes in the rapakivi area is 0—20° (Fig. 8). The dips are mainly vertical. As mentioned before the dykes often have a winding course, to either side of the main direction. Twenty-one of the dykes change their course and run in two main directions. In the diagrams (Fig. 8) therefore both of the main strikes are incorporated. Diagram No. 1 represents all

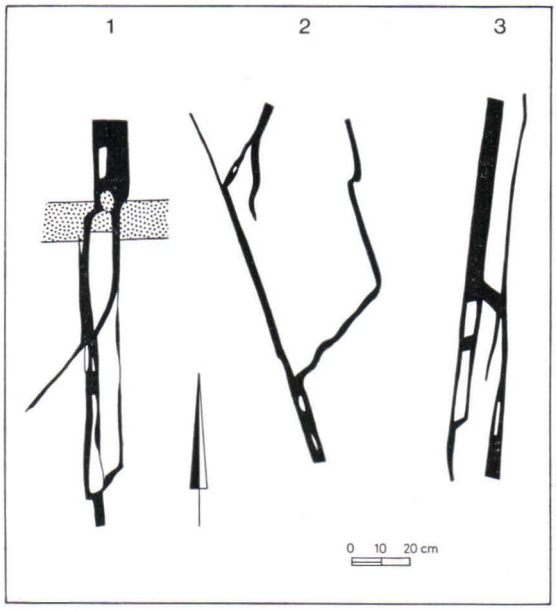

Fig. 7. Sketches of irregular clastic dykes. Note that only the widths of the dykes are to scale. 1. Hättskär, (No. 18). An aplite dyke is stippled; 2. and 3. Svartholmsöarna, (No. 20).

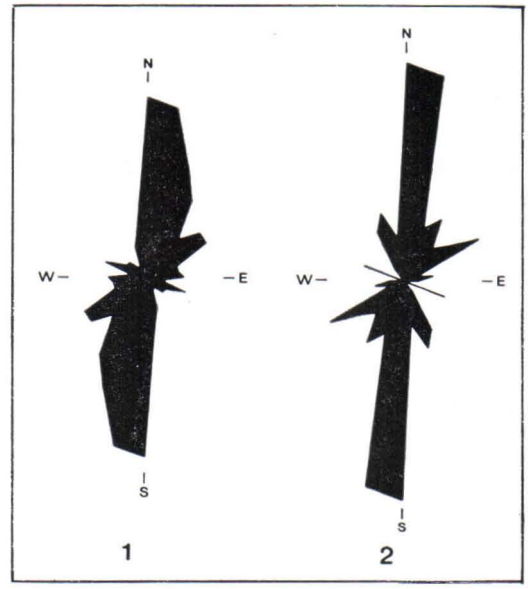

Fig. 8. The orientation of the clastic dykes in the Åland rapakivi area. The grouping interval in the rose diagrams is 10°. 1. All dykes, n = 317; 2. All dykes ≧ 5 cm, n = 75.

the clastic dykes in the rapakivi area. The northern trend is obvious, with a second frequency peak at 50—60°. Most of the dykes are in the 0—90° quadrant and only eighteen per cent exhibit a strike between 90° and 180°. In this quadrant, there is only a minor peak at 110°. This indicates that during the formation of the clastic dykes, fissures were opened principally in N—ENE directions.

Diagram No. 2 in Fig. 8 shows the direction frequency for dykes measuring 5 cm or more in width. The trend is the same as in diagram No. 1 but the maxima at 0—10° and 60° are more pronounced, in addition to which a new peak appears at 150—160°.

Comparing the regional strike directions in the Åland area with observations reported from Sweden (Fig. 9) it may be noted that the clastic dykes usually have certain preferential directions and do not strike randomly. The diagrams in Fig. 9 show that northeastern directions are dominant in the Småland and Trollhättan areas, while the WNW—ESE direction is very pronounced in the Bornholm and Göteborg areas. In Östergötland, Södermanland and the Vänern and Borås areas, the observations also point to a dominant trend of about NE—SW (e.g., Asklund 1921, Hjelmqvist 1939 and Mattson 1959).

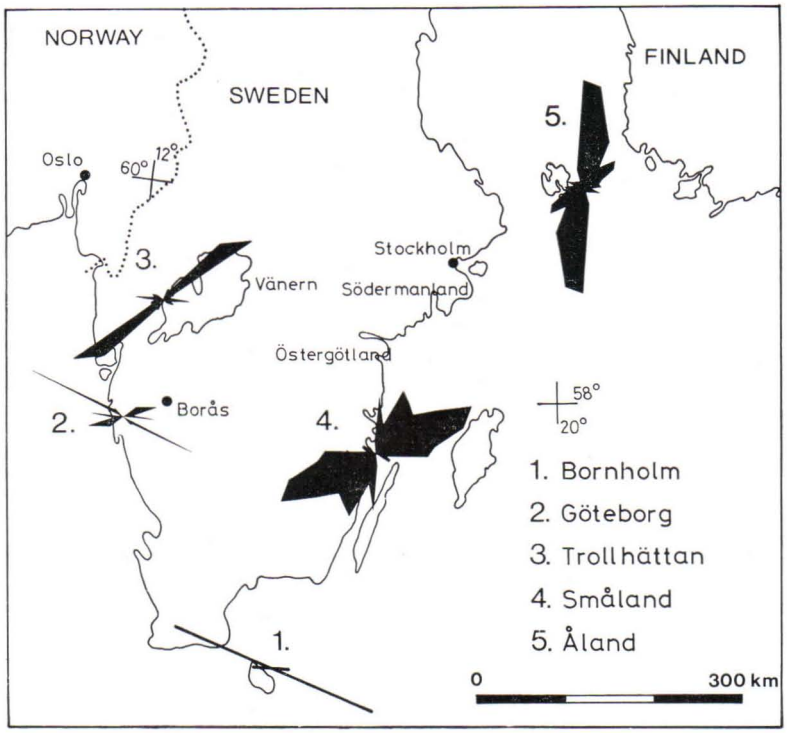

Fig. 9. The orientation of clastic dykes in the Precambrian basement in five different areas. 1. Bornholm, redrawn from Mattson (1962, Abb. 4, Nos. 3 and 5), n = ?; 2. Göteborg, Samuelsson (1975, Fig. 3), n = 131; 3. Trollhättan, redrawn from Mattson (1959, Fig. 7 c), n = 19; 4. Småland, redrawn from Nordenskjöld (1944, Fig. 57), n = 145; 5. Åland, n = 317.

LITHOLOGY

The microscopic investigations indicate that the clastic dykes can be divided into three main groups: 1. breccia, 2. siltstone and 3. sandstone dykes. This division is in accordance with the different types of sandstone dykes Hadding (1929, p. 135) distinguished on Bornholm.

Breccia dykes

Three of the clastic dykes, No. 9 Rödö, No. 19 Ballerö and No. 66 Högskär are breccia-like with sharp-edged grains of quartz, pigmented orthoclase and rapakivi. The cementing material is red pigmented quartz or cryptocrystalline silica. The grain size varies from < 0.1 to 5 mm with scattered larger fragments of rapakivi.

On Västra Sundskär (1011 09, x = 6645.2 y = 447.3), about 500 metres southwest of the rapakivi contact of locality No. 5 in Fig. 1, there occurs a combined sandstone and breccia dyke. The dyke is 4—12 cm in width and strikes 40—60°. On the shore, the dyke, 4 cm wide, is a normal sandstone dyke, but further up the fissure, the pattern becomes irregular and breccia fragments occur mixed with the

detritus. The breccia fragments, up to 5 cm in size, consist of different rock types. The clastic grains are mainly well-rounded quartz, cemented by calcite, which also appears as larger crystalline aggregates. Among the accessory minerals, glauconite can be mentioned. No microfossils were found in the dyke.

Siltstone and sandstone dykes

Siltstone and sandstone dykes are usually well lithified. The siltstones of the same Lower Cambrian age in Lumparn show a much weaker lithification. The dykes are usually massive and devoid of distinct bedding features, but in some cases as Mattson (1960, p. 87) points out a very weak »bedding» can be discerned parallel to the strike of the dykes. Only in the 20—60 cm wide dyke at Långbergsöda-öjen (No. 53) can a nearly horizontal variation in grain size be interpreted as layering. Rapakivi fragments are common and the long axes of the fragments in many cases run parallel to the dyke walls.

The mineralogical composition of eighteen thin sections is presented in Table 1. (cf. Simonen & Kouvo 1955, Table 7.). The first two analyses in the table represent reddish sandstones and the rest varieties of other colours. Particles smaller than 0.05 mm were classified as intergranular matrix and therefore the only siltstone in the table (Granskär, No. 29) contains very little material marked as detrital particles.

The sandstones are rich in quartz and the feldspar content varies from 0 to 15.7 %, that is, from pure quartz sandstones to arkosic sandstones. The quartz grains are subrounded to well rounded and the roundness seems to increase in the coarser grain sizes. They are either mono- or polycrystalline with undulatory and nonundulatory extinction. Quartz with undulatory extinction is very rare in the rapakivi granites. The feldspars are red-coloured orthoclase, colourless microcline and

Table 1.

Point-counter analyses of the modal composition of eighteen clastic dykes in the Åland rapakivi area.

No.	Locality	Detrital particles				Cement and intergranular matrix					
		Quartz	Feldspars	Rock fragments	Accessories	Glauconite	SiO_2	Fe-oxides, -hydroxides	Clay + chlorite	Calcite	Fluorite
11	Prästö	53.5	15.7	4.8	1.5	—		24.5	—	—	—
23	Lökskär	64.5	1.8	1.3	1.6	—		30.8	—	—	—
7	Kuggholm	75.9	4.3	1.7	0.7	—		17.4		—	—
32	Norrskatan	69.2	8.1	1.3	0.4	+		21.0	—	—	—
36	Sälskär	47.9	14.3	4.7	2.7	—		30.4	—	—	—
46	Lönnbådan	73.5	1.0	—	0.7	—	+	24.8		—	—
76	Väderskär	72.1	0.5	0.5	0.2	—		26.7	—	—	—
30	Kålgrund	57.4	10.5	1.8	3.1	—		27.2		—	—
29	Granskär	7.8	0.4	3.1	0.7	0.3		87.7		—	—
18	Hättskär	70.6	2.1	—	1.9	+	25.4	—	—	—	—
20	Svartholmsören	63.7	4.7	5.2	2.6	—	23.8	—	—	—	—
53	Långbergsöda	62.0	10.0	—	1.4	—	26.6	—	—	—	—
53	»	59.4	5.1	16.2	1.0	+	18.3	—	—	—	—
5	Östra Sundskär	73.2	—	—	3.8	+	—	—	—	23.0	—
8	Bötesholm	70.5	7.9	—	0.8	0.4	—	—	—	20.4	—
48	Österö	71.0	0.4	1.3	1.8	—		7.8		17.7	—
62	Alören	52.7	4.8	9.9	2.7	—		12.7		17.2	—
66	Bredören	67.1	0.9	—	0.2	—		11.0		—	20.9

to a small extent also plagioclase. The monoclinic symmetry was confirmed by Simonen and Kouvo (1955) with X-ray diffraction, which reveals that the orthoclase originated from the rapakivi granites. The angular orthoclase particles are usually fresh but also weathered and kaolinized grains occur. The larger polymictic fragments are very angular and consist almost exclusively of rapakivi granites. This indicates that the orthoclase particles and the fragments are not primary constituents of the sediments but are derived both from the walls of the dykes (Simonen & Kouvo 1955, p. 72) adn from the weathered parts of the sub-Cambrian peneplain, since the clastic dykes appear in unweathered rapakivi. Weathered material has also been observed in some of the clastic dykes in Sweden (e.g. Sundius 1939, p. 75 and Carlsson & Holmqvist 1968).

Microcline occurs frequently as fresh angular to subrounded grains in the dykes in the northwestern part of the rapakivi area, but it is almost completely lacking in the southern parts. Since microcline is not a constituent of the rapakivi granites in the area of the dykes it must have been transported there from outside the rapakivi complex, evidently from the northwest.

The most common accessories are chlorite, biotite, clay minerals, tourmaline, opaque minerals and glauconite, and more rarely apatite, rutile, monazite and hornblende. Glauconite is found in sixteen localities all over the rapakivi area, both as a constituent of the intergranular matrix and as separate, rounded, usually elongated grains up to 1—2 mm in size.

The cementing material of the dykes is mainly siliceous. Secondary outgrowths of the quartz grains are common and fine grained silica is encountered. Iron oxides or hydroxides are often seen to occur, to a greater or lesser extent, together with the siliceous cement. Calcite and fluorite appear sporadically as cement, which is also the case in Sweden (Mattson 1962). The regional distribution of the cements (Fig. 10) shows that calcite occurs in all parts of the rapakivi area while fluorite is confined to the Ådö region. On Ådö the fluorite is associated with galena, and in one place both share the same fissure with a previously lithified sandstone dyke (Bergman & Lindberg 1979, Fig. 5). No microfossils were detected in the samples from Ådö, but galena associated with the dated sandstone dykes on Loören shows a Lower Ordovician age of the sandstone (Tynni 1982, Fig. 22). This indicates that the galena associated with the clastic dykes in the rapakivi area could be of Lower Ordovician age, or younger.

Every dyke of Lower Cambrian age (Tynni 1982, Fig. 22) has siliceous cement, which in many cases contains iron compounds. Of the two Lower Ordovician dykes, one has SiO_2 cement, the other calcite cement. The remaining dykes with calcite cement did not contain enough microfossils for accurate dating.

The cement of the clastic dykes outside the rapakivi area in southwestern Finland are siliceous (Simonen & Kouvo 1955) with two exceptions, the dykes at Sälsö, Sottunga (Laurén 1968) and the dyke in the Laitila area, both having a cement of calcite.

The grain size of ten specimens representing dykes from all parts of the rapakivi area was determined by measuring 300—500 particles in each thin-section (Fig. 11, cf. Simonen & Kouvo 1955, Fig. 9). In the other thin sections, the grain-size distribution was semiquantitatively estimated from photomicrographs.

The median grain size has a wide range from silt to coarse sand (Fig. 11). The sorting also varies considerably. The histograms and cumulative curves show further the great variations in the dykes, e.g., normal and bimodal distribution and positive and negative

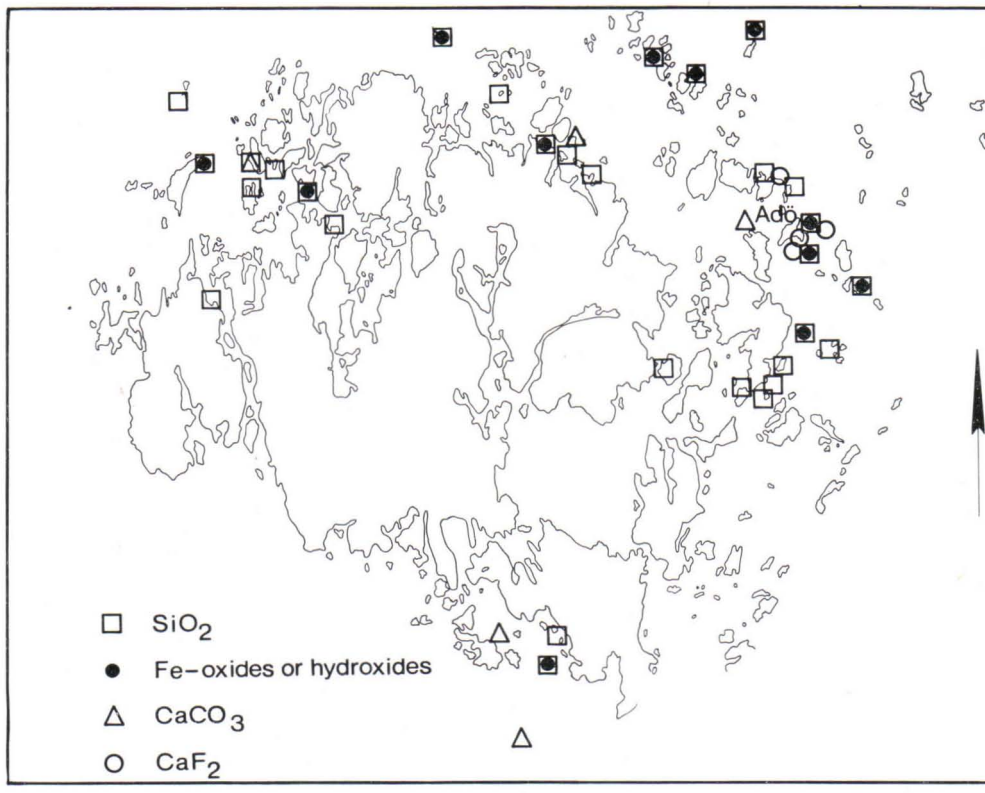

Fig. 10. The regional variation in cementing material of the clastic dykes in the Åland rapakivi area.

skeweness. Many of the dykes have a bimodal (Fig. 12) or polymodal grain-size distribution. The relation between the grain fractions varies but in the dykes consisting of very fine sand and silt, the coarse fraction is usually missing. There is a regional trend in the grain-size distribution; the coarser sand fractions dominate in the dykes of the northeastern part of the rapakivi area, while fine sand and silt material prevail in the western part.

Several exceptions from the regional grain-size trend occur. For example at Långbergsöda-öjen (No. 53) one of the dykes is exceptionally wide (20—60 cm, strike N—S) exhibiting a similar fissure pattern as sketch No. 1 in Fig. 7 (Tanner 1911, Tafel 1, III). The western side of the dyke in the branching part is made up of very fine sand and silt particles (Fig. 11, No. 53) while the eastern side consists of coarser sand with quartz grains up to 1—2 mm in diameter. Furthermore, the eastern side of the dyke has rounded inclusions of clay and very fine sand-siltstone reminiscent of the material on the western side. Evidently, the very fine sandy silt first filled up the fissure and consolidated, then the fissure was reopened and more coarse sand was injected. The ages of these different fissurings have been determined by microfossil analysis (Tynni 1982, Fig. 22). The fine-grained older dyke has Lower Cambrian while the younger dyke contains Lower Ordovician microfossils.

Locality	4	7	23	29	30	46	53	53	66	76
M_d (mm)	0,078	0,50	0,21	<0,0625	0,26	0,19	0,18	0,07	0,68	0,30
So	1,28	2,02	1,26	1,10	5,10	1,36	1,62	1,31	1,73	1,55

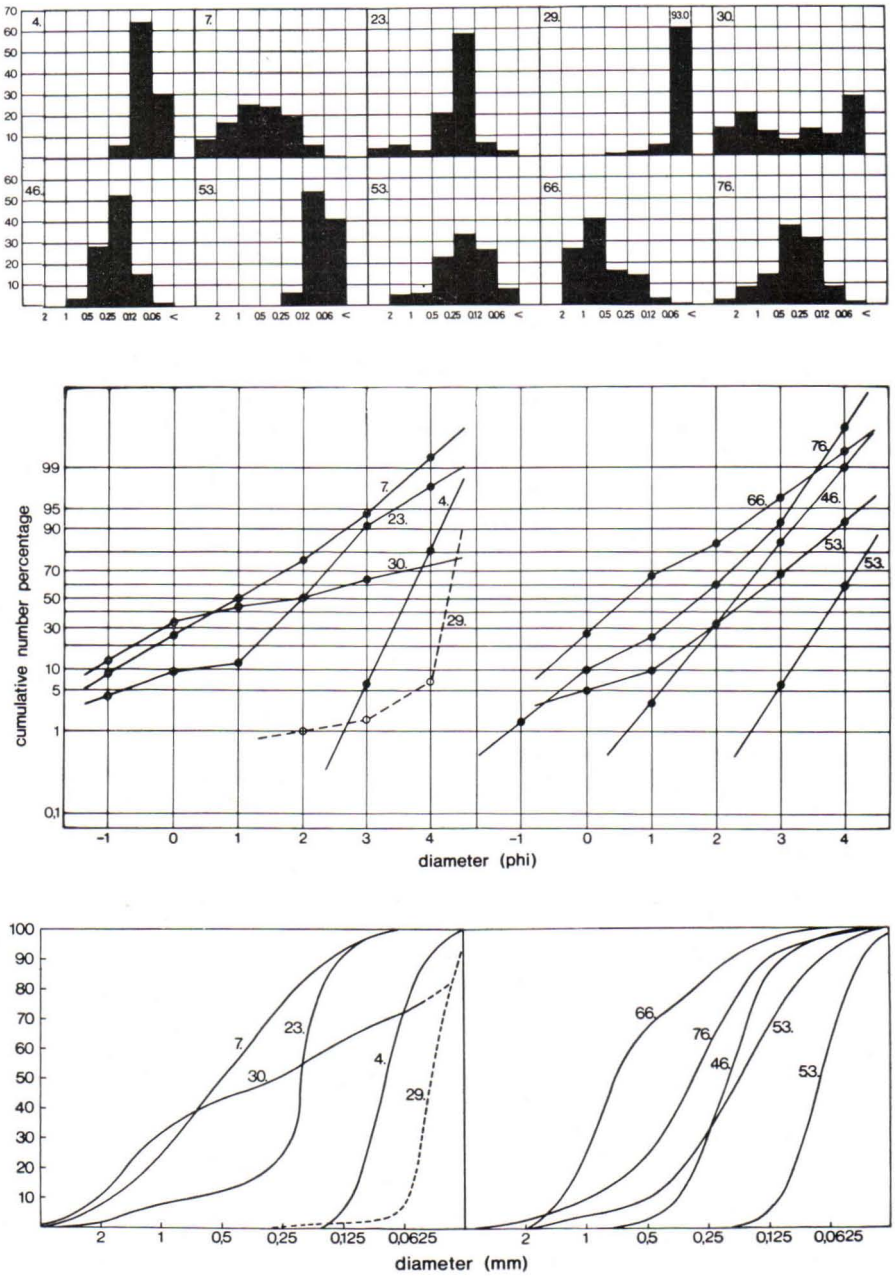

Fig. 11. Grain-size distribution of the clastic dykes in the Åland rapakivi area. No. 29 is broken because of the fine grain size and the cumulative curves are only estimated. The number of the specimens refer to Table 1.

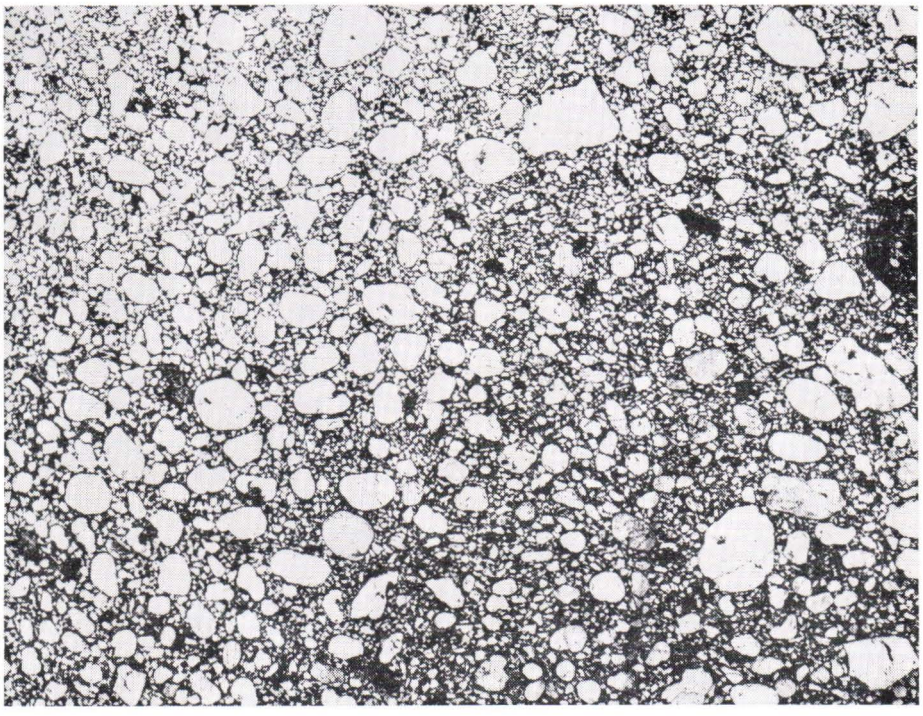

Fig. 12. Bimodal grain-size distribution in a clastic dyke. Ådö, No. 66 (x = 6689.07, y = 469.78). Optic pantographic photo of thin-section. 5 x

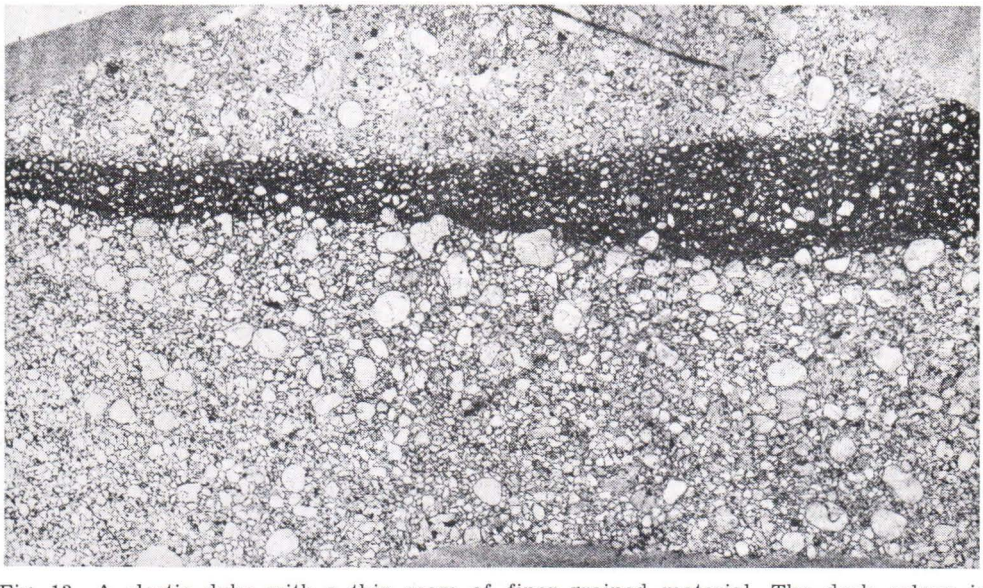

Fig. 13. A clastic dyke with a thin seam of finer-grained material. The dark colour is caused by a siliceous cement richer in iron. Låkan, No. 53. Optic pantographic photo of thin-section. 5 x

Fig. 13 illustrates another example of grain-size variation within a single dyke. Here a fine-grained material forms a thin seam in more coarse-grained clastics. The variation in grain size is further accentuated by the cement, which in the finer material is very rich in iron.

ORIGIN OF THE DYKES

The formation of clastic dykes has been widely discussed in geological literature in Scandinavia (Ussing 1899, Hadding 1929, Mattson 1959, 1962, Samuelsson 1975 and Larsson 1975). Two types of clastic dykes can generally be distinguished (Potter & Pettijohn 1963, p. 162). The first type is an open fissure, which has been filled from above, grain by grain. The second type originated by forceful injection of clastic material in fluidized state, either from above or below. The second mechanism presupposes opening of the fissure after sedimentation.

In the case of the clastic dykes in the Åland rapakivi area the probable mechanisms were fillings either by gravity or forceful injection from above. Which of the two alternatives, if not both, formed the dykes in the Åland area should be determined by comparing them to decide which one best explains the following characteristics:

1. both the simple and complex fissure pattern exhibited by the dykes in unweathered rapakivi, including the preferential orientation;
2. the marine constituents of the dykes, e.g., microfossils and glauconite;
3. the exotic detritus derived from outside the rapakivi area;
4. the great variation in grain-size distribution;
5. the difference in age even within the same epoch (Lower Cambrian, Tynni 1982);
6. the occurrence of dykes of different ages in the same fissure.

Considering the gravity mechanism, the infillings must have occurred in a transgressive beach condition, because of the marine components in many of the dykes. During subsidence an open fissure in the bedrock near the shoreline would be rapidly filled with detritus from the basal material once under sea level. The composition of the dykes is then supposed to be more conglomeratic to arkosic and not display the great variation in grain size, at least not in dykes situated close to each other. Some of the dykes lack marine constituents, and if the filling processes started in supramarine conditions, with blown eolian material (well-sorted) and other gravitationally deposited terrestrial material (more poorly sorted), and open fissures were repeatedly formed during subsidence one would expect great variation in grain size. But it does not explain e.g. the difference in age between the dykes with marine constituents. The different ages would imply either opening of fissures — filling of sediments — consolidation of the dykes — erosion of the older sediments — opening of new fissures — filling of younger material etc., or that the areas of the clastic dykes were never covered by sediments and very special shore conditions prevailed during the early Paleozoic. Such an explanation is difficult to visualize and furthermore a filling of open fissures, grain by grain, does not satisfactorily fulfil the majority of the abovementioned criteria.

On the other hand, if unconsolidated sediments did cover the bedrock prior to tectonic

fissuring, the variation in composition of the dyke material is also hard to explain by forceful injection (Mattson 1960, p. 100), because in this case the dykes would consist principally of basal material. This mode of formation was proposed by Ussing (1899, p. 98) for the dykes on Bornholm, and also by Tanner (1911, p. 12) for the dykes at Långbergsöda-öjen. The fissuring mechanism they proposed was earthquakes. This mode of formation explains a few of the characteristics, e.g. the regular strike directions and the complex fissure pattern, but it is not altogether satisfactory.

According to Hadding's (1929, p. 136) interpretation of the dykes on Bornholm both the gravity and the injection explanations are possible. As for the dykes that contained detritus of more than one kind, as in the Åland rapakivi area, he stated that »they must have been formed at two different epochs.» As Mattson (1960, p. 100) points out, the theoretical succession (according to Hadding, 1929) is that the dykes could have been formed also if the basement had been covered by consolidated sediments, which were also penetrated by the fissures. Samuelsson (1975, p. 18) also considered this possibility for the dykes of the Göteborg area; i.e. part of the sedimentary column must have consisted of unconsolidated sediments, but not necessarily the basal parts.

A model for the origin of the clastic dykes that best fits the characteristics of the dykes in the Åland area is an extended injection mechanism, as illustrated in Fig. 14. The model is based on a tectonic cause for the fissuring, combined with the assumption that the sediments were subsequently consolidated as the sedimentation proceeded and renewed fissuring injected detritus from the upper unconsolidated parts of the sedimentary column. The tendency for a regional preferential orientation of the fissures (Fig. 9), which seems to be a general rule even outside Scandinavia, e.g., in California (Peterson 1966) is indicative of a tectonic origin. Whatever the tectonic factor might be, opening of fractures in

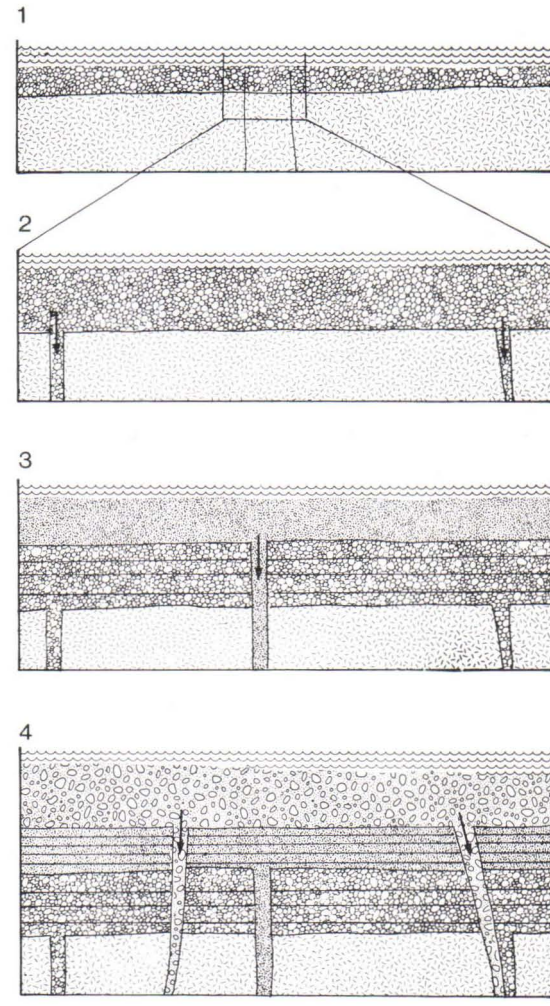

Fig. 14. A model for the origin of clastic dykes. 1. Tectonic activity (earthquake) open fissures in the bedrock. 2. Clastic material is injected into the fissures. 3. The lower parts of the sediments consolidate, while the upper sediments are still loose and saturated with water. New earthquakes open fissures in the bedrock and also in the more consolidated sediments, and unconsolidated sediments from the upper parts of the sequence are injected into the fissures. 4. Sedimentation continues and subsequent tectonic fissuring causes sediments from above to be injected again into the newly formed fissures. Older fissures can be reactivated and therefore clastic dykes of different ages can occur in the same fissure.

the bedrock beneath sediments is one possible geological outcome of earthquakes. Sandstone dykes resulting from earthquakes and faulting, both recent and fossil, have been reported by various authors (Harms 1965, Hiscott 1979, Reimnitz & Marshall 1965, Russ 1979, Shrock 1948 and Vitanage 1954).

The microfossil analysis showed that there are dykes of different age all, however, within the Lower Cambrian (Tynni 1982, p. 87), in addition to those dated to the Lower Ordovician. This leads to the conclusion that marine sedimentation started during the early Lower Cambrian in the Åland area. At the same time tectonic activity opened fissures in the bedrock and unconsolidated detritus was sucked in. The sedimentation continued more or less without interruption through the Lower Cambrian and fissures reopened subsequently in the bedrock including the lower consolidated parts of the sedimentary column, permitting the injection of a different lithological unit. This also explains the exotic detritus, for once the rapakivi bedrock was covered by sediments the superimposed deposits must be derived from elsewhere. A major break in sedimentation or a cessation of tectonic activity must have occurred during the Middle and Upper Cambrian, since no dykes containing microfossils from these epochs have been found. Sedimentation resumed again in the Lower Ordovician together with tectonic activity. A hiatus encompassing the Middle and Upper Cambrian is in accordance with the results of two drillings made through the Paleozoic sequence in the southern Bothnian Sea (Thorslund & Axberg 1979). The drillings also disclosed that the crystalline basement below the sedimentary cover was weathered.

Evidence of a weathered rapakivi granite beneath the Paleozoic sediments was also provided by drillings in Lumparn Bay, where the weathered crust is several tens of metres thick (Winterhalter 1982, p. 121). This indicates that the clastic dykes occurring in unweathered rapakivi also penetrated the weathered crust into fresh rapakivi and hence were originally very deep. The depth of the dykes in the Åland area is not known, but a dyke of alum shale was observed at a depth of 50 m below the basement surface in the Göteborg area (Samuelsson 1975, p. 20).

Fissuring followed by injection of overlying unconsolidated, detritus is the most probable mode of formation of the clastic dykes in the Åland area. The model (Fig. 14) also works in supramarine conditions and therefore the process may have started in the Precambrian, although the main events occurred in the early Paleozoic. Since life on land is not known from the Precambrian, dykes formed in supramarine conditions would yield no microfossil evidence, provided that the microfossils were not transported by wind from shore deposits. No indications of Precambrian sedimentary rocks are so far known from the drillings in Lumparn, which leaves this question open. The reddish colour of the two sandstone dykes (Nos. 11 and 23) possibly indicates a Jotnian age. One of the dykes contained no microfossils (No. 11) and petrographically it resembles arkosic Jotnian sandstone; the other, however, is an almost pure quartz sandstone. The colour is due to hematite pigmentation in the silica cement. The drillings through the Paleozoic sequence in the southern Bothnian Sea showed a thin layer of red sandstone of Lower Cambrian age (Thorslund & Axberg 1979, p. 39), which indicates that the same sedimentary condition causing the red colour also prevailed during the Lower Cambrian. Gavelin (1912, p. 23), however, mentions a sandstone dyke of Jotnian age in the Precambrian basement from Sweden, and G. Bergman (1980) reports post-depositional sandstone dykes within the Jotnian sediments in the Nordingrå area caused by earthquake shocks. This indicates that sandstone dykes of Jotnian age can pos-

sibly occur also in the Precambrian crystalline basement in the Nordingrå area. Since the Åland area has evidently been covered by Jotnian sediments the possibility of preserved clastic dykes of Jotnian age cannot be excluded.

CONCLUDING REMARKS

Field and microscopic observations supported by microfossil determinations show that clastic dykes of different ages occur even within a single fissure in unweathered rapakivi. Filling from above, grain by grain, into open fissures does not satisfactorily explain the characteristics of the dykes. Some of them might have been formed in this manner provided that denudation cleaned open fissures including the weathered parts. Such dykes could consist only of material from the undermost sedimentary layer. Observations from the Göteborg area (Samuelsson 1975, p. 22) reveal that there are two kinds of clastic dykes: fillings in open shallow fissures and injections into fissures formed below a cover of unconsolidated sediments. The unconsolidated sediments, however, need not necessarily have been derived from the basal parts (cf. p. 17). The injection mechanism seems valid for the clastic dykes in the Åland rapakivi area, but a further development was required to satisfy the mode of occurrence of the dykes there. The origin of the dykes is based on an extended injection model (Fig. 14) with tectonic activity (earthquakes) as the triggering mechanisms for the fissuring and subsequent filling from above with unconsolidated sediments. As the sedimentation proceeded, the lower parts of the sedimentary sequence consolidated. Sequential tectonic activity opened fissures in the bedrock as well as in the consolidated parts of the sedimentary column, permitting detritus from upper consolidated levels of the deposit to be injected as a slurry into the fissures. Older fissures can be reactivated, and therefore clastic dykes of different ages can occur in the same fissure.

The regular orientation of the clastic dykes, which seems to be the rule, points to a structural control of major tectonic importance (Fig. 9). Evidently the clastic dykes, if properly dated, will reflect the tectonic evolution of specific areas. The microfossil determinations from the Åland area show that the main tectonic events took place during the Lower Cambrian and Lower Ordovician epochs. The fissures that were opened during the formation of the dykes strike principally in the 0—90° quadrant. If the dominant orientations in the different parts of the rapakivi area are examined they show various frequency maxima, e.g., the southern part has mostly dykes striking 50—60°, 90° and 110°, while the northeastern part is dominated by strikes of 0°, 20° and 60°. These main directions reflect probably different ages. The microfossil determinations also point to this assumption. The older Lower Cambrian dykes at Stora Granskär (No. 29) and Loören (No. 63) strike 70° resp. 40—160°, while the younger Lower Cambrian dykes strike 0 ± 20°. This structural control and the tectonic evolution of the fissures in the rapakivi area will be treated in a separate paper.

A distinctive feature, which can give further information on the origin and age of the dykes, is the difference in lithification, including the cementing material between the dykes and the Lower Cambrian sediments in Lumparn. The dykes are usually well lithified

in contrast to the sediments. Further sampling of the dykes and a petrographical comparison with the drill cores from Lumparn are called for. The results of the drillings have, however, not yet been published.

The field work was carried out in connection with a regional investigation of the rapakivi massif and undoubtedly only some of the existing dykes were found. A thorough investigation of fractures, especially in the northern part of the rapakivi area, would yield more information about the clastic dykes.

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List of clastic dykes in the rapakivi area of the Åland islands (C = Lower Cambrian, O = Lower Ordovician).

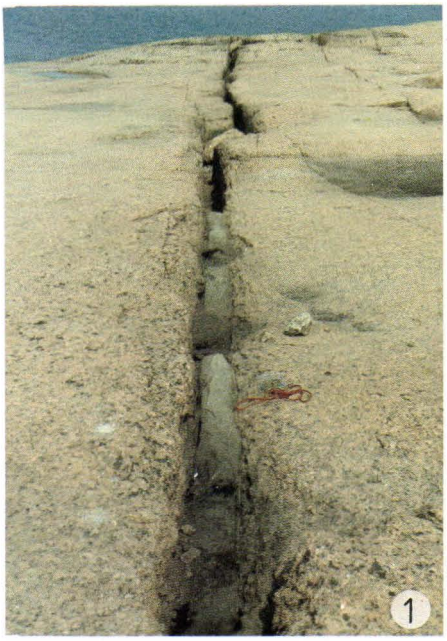
Number	Name of locality	Finnish map number and map coordinates				Width cm	Strike/dip # 90°	Thin-section	Micro-fossil determ.
1.	Töllingarna	0034	12	6676.00	579.60	2	30—60		
2.	Skarven	0043	11	6692.05	576.88	1,5	10		
	»	»	»	6692.10	577.04	1	50		
	»	»	»	6692.00	577.15	4	10		
3.	Yttre Borgen	»	10	6684.83	570.19	2—10	150		
4.	Östra Sundskär	1011	09	6645.85	448.70	5	110/80N	×	× O
5.	Kummelskär	»	»	6645.70	447.85	3	40/75S		
	»	»	»	»	»	1	60/80S		
6.	Stora Lökskär	1012	07	6652.82	445.77	2	110		
	»	»	»	6652.80	445.88	1—4	90/85N		
	»	»	»	6652.78	445.88	0,5	90/80N		
	»	»	»	6652.76	445.85	0,5	60/80N		
	»	»	»	6652.74	445.85	3	80/85N		
	»	»	»	6652.73	445.85	2	60—90		
	»	»	»	6652.72	445.85	1	80—110		
7.	Kuggholm	»	»	6654.46	448.75	5	20	×	
8.	Bötesholm	»	»	6657.46	445.18	11	50	×	×
	»	»	»	6657.48	445.25	4	50		
	»	»	»	6657.49	445.24	1	40		
9.	Rödö	»	08	6661.32	444.17	2	170	×	
	Lemböte	»	»	6663.18	443.24	3	60		
10.	Slättskär	»	10	6657.62	450.01	2	30		
	»	»	»	6657.40	450.00	1	10	×	
	»	»	»	6657.33	450.02	4—5	50	×	
11.	Prästö	»	12	6678.04	458.31	5	0	×	×
12.	Tranvikön	»	»	6675.84	455.44	2	30		
13.	Långholm	1014	02	6660.46	465.16	3	10	×	
	»	»	»	6660.70	465.57	1	10		
14.	NE Prästö	»	03	6679.22	460.32	1	0		
15.	Stenör	»	»	6674.75	466.55	3—6	140	×	
	»	»	»	6674.70	466.60	1,5	130/80S		
	»	»	»	6674.76	466.56	1—3	120/80S		
	»	»	»	6674.63	466.53	1—3	110/75S		
16.	Träskholm	»	»	6675.65	467.80	3	10		
	»	»	»	6675.60	467.65	5	10		
	»	»	»	6675.30	467.55	3	0		
	»	»	»	6674.89	467.22	2	30		
17.	Furholm	»	»	6674.30	467.06	2	90		
	»	»	»	6674.15	467.00	2	120		
	»	»	»	6674.35	467.05	2	170/80E		
	»	»	»	6674.44	467.65	1	110		
18.	Hättskär	»	»	6675.14	466.63	3—5	0		
	»	»	»	6675.18	466.71	12	0	×	×
	»	»	»	6675.18	466.68	4	170—20		
19.	Ballerö	»	»	6676.50	464.80	1	50	×	
20.	Svartsholmsörarna	»	»	6676.54	467.18	3	0—10		
	»	»	»	6676.53	467.20	4	170	×	× C
	»	»	»	6676.50	467.22	2	0		
	»	»	»	6676.39	467.22	2—5	160		
	»	»	»	6676.38	467.19	1—6	10	×	
	»	»	»	6676.95	467.56	5	0		
21.	Österholm	»	»	6678.16	467.96	2	170/80E		
	»	»	»	6678.06	467.96	3	80		
	»	»	»	6678.01	467.94	2	80		
	»	»	»	6677.93	467.88	2	10		
	»	»	»	6677.86	467.75	2	10		
	»	»	»	6677.86	467.76	20	10	×	×
	»	»	»	6677.70	467.57	2	170/70E		
	»	»	»	6677.85	467.68	3	20/80E		
	»	»	»	6677.75	467.57	3—5	10	×	×

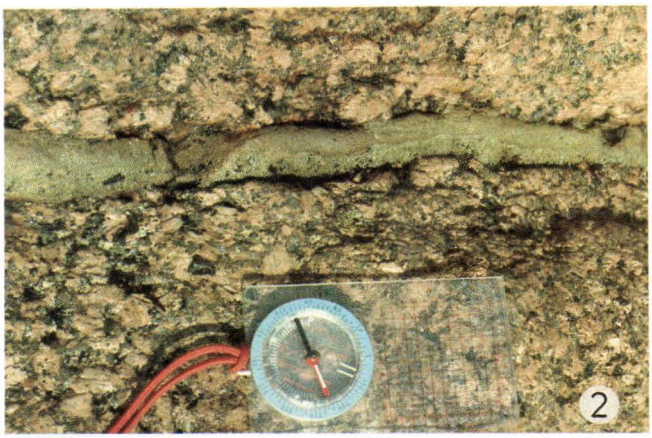
Number	Name of locality	Finnish map number and map coordinates				Width cm	Strike/dip # 90°	Thin-section	Micro-fossil determ.
	Österholm	1014	03	6677.74	467.54	2	40		
22.	Flatskär	»	»	6679.12	469.78	3—4	10		
23.	Lökskär	»	06	6678.95	470.69	5	60/65S	×	
24.	Bakskär	1021	01	6690.00	425.13	2	10		
	»	»	»	6689.86	425.42	1	10/30W		
25.	Nabbskatan	»	»	6684.38	419.42	2	70		
26.	Berghamn	»	»	6688.43	426.69	1	10		
	»	»	»	6688.39	426.82	1	30/80W		
27.	Juddskär	»	»	6688.80	428.45	1	10		
28.	Ekbolsviken	»	»	6685.02	424.90	2	120	×	×
29.	Stora Granskär	»	02	6695.82	429.90	2	20		
	»	»	»	6695.36	429.54	4	70/80N	×	× C
30.	Kålgrund	»	»	6695.90	424.36	4	50	×	×
	»	»	»	6695.82	424.35	6	50		
31.	Äppelö	»	»	6695.60	428.05	1	90		
	»	»	»	6695.52	428.08	2—6	70	×	×
32.	Norrskatan	»	»	6694.00	427.59	5	10	×	
33.	Norra Rönnskär	»	»	6696.63	423.36	3	0		
34.	Lammskär	»	»	6692.90	422.82	2	60		
35.	Ådskär	»	»	6694.33	418.80	0,5	0		
	»	»	»	6694.70	419.28	1	10		
	»	»	»	6694.32	419.00	3	80/60S		
36.	Sälskär	»	03	6700.60	422.82	1	20		
	»	»	»	»	»	3	50—30	×	×
37.	Barskär	»	05	6691.20	435.35	1	20		
	»	»	»	6691.05	435.47	1—2	20/70W		
	»	»	»	6690.96	435.48	1—3	20		
38.	Pantsarnäs	»	»	6691.26	435.66	1	20		
	»	»	»	»	»	0,5	30		
39.	Klobba	»	»	6690.58	434.16	1—3	70		
40.	Björkholm	»	»	6693.00	432.12	2	10		
	»	»	»	»	»	2—4	10	×	
	»	»	»	»	»	1—4	10		
	»	»	»	»	»	1	170		
41.	Saltflyttan	1021	06	6702.40	433.40	1	0		
42.	Öken	»	08	6695.84	441.86	1	30		
	»	»	»	»	»	1	170		
43.	Kopskär	»	09	6700.44	447.94	1	10		
	»	»	»	6700.52	447.65	1	0		
	Låkan	»	»	6700.30	447.00	2	0	×	×
44.	Rörvik	»	»	6701.92	440.00	1	20—30		
45.	Koxnan	»	»	6706.90	441.66	1	0—60		
	»	»	»	6706.94	441.65	1	0		
	»	»	»	6706.60	441.68	1	20		
	»	»	»	6706.96	441.70	1—2	0		
	»	»	»	6707.00	441.76	1	10		
	»	»	»	6707.07	441.85	1—1,5	0		
	»	»	»	»	»	1—1,5	0		
	»	»	»	»	»	1—1,5	0		
	»	»	»	6707.00	442.09	1	10—60		
	»	»	»	6707.14	441.88	1	110		
	»	»	»	6707.02	441.80	0,5	0		
46.	Lönnbådan	»	»	6706.00	444.90	2	10	×	
	»	»	»	»	»	1	10		
47.	Norra Boxö	»	11	6699.78	451.53	1—2	0		
	»	»	»	»	»	1—2	0		
	»	»	»	»	»	1—2	0		
	»	»	»	6699.60	451.02	0,5	0		
48.	Österörarna	»	»	6696.36	452.05	3	0		
	»	»	»	6696.50	452.35	2	20		
	»	»	»	6696.45	452.35	2	170		
	»	»	»	»	»	2	170		
	»	»	»	6696.58	452.59	2	30		

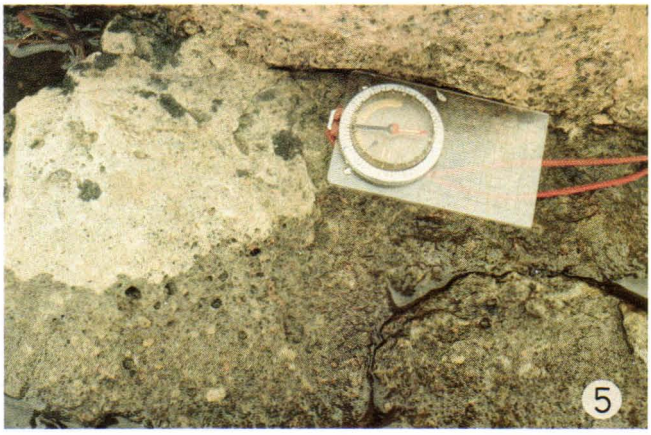
Number	Name of locality	Finnish map number and map coordinates				Width cm	Strike/dip # 90°	Thin-section	Micro-fossil determ.
	Österörarna	1021	11	6696.61	452.58	2	30		
	»	»	»	6696.56	452.60	3	40	×	×
49.	Boxö sund	»	»	6696.16	450.30	3	0	×	
	»	»	»	6696.14	450.45	1—2	90		
	»	»	»	»	»	1—2	90		
	»	»	»	6696.07	450.47	2	70		
	»	»	»	6696.00	450.77	5	0	×	
	»	»	»	6695.97	450.81	1—2	10		
	»	»	»	6695.91	450.89	1—2	170		
	»	»	»	»	»	3	30		
50.	Svalhällsbukten	»	»	6695.92	451.08	2—3	40		
	»	»	»	6695.82	451.12	5	80/75N		
	»	»	»	6695.55	451.38	1	0		
51.	Långholmen	»	»	6695.48	451.76	2—9	10		
	»	»	»	6695.26	451.92	2—20	10		
	»	»	»	6695.18	451.94	1—7	0—20	×	
	»	»	»	6695.16	451.96	1—5	10—30		
	»	»	»	6695.20	452.00	4—10	10—110	×	
	»	»	»	6695.10	452.03	1—7	0—110	×	×
	»	»	»	6695.09	452.04	15	0		×
	Långholmshällarna	»	»	6695.10	452.10	2—4	20		
	»	»	»	6694.94	452.16	5	150		
52.	Silverskär	»	»	6684.88	452.73	5	0		
	»	»	»	»	»	3	0		
	»	»	»	»	»	2	0		
	»	»	»	6694.86	452.88	2—8 (PbS)	0		
	»	»	»	6694.86	452.88	5—10	0		×
	»	»	»	6694.84	452.92	1—4 (PbS)	160—10	×	
	»	»	»	6694.88	452.97	0,5	10		
	»	»	»	»	»	1,5	10		
	»	»	»	»	»	3	10/80W		
	»	»	»	»	»	1,5	30		
	»	»	»	»	»	1	110/80S		
	»	»	»	»	»	1	0		
53.	Långbergsöda-öjen	»	»	6693.62	453.54	20—60	0	×	× C, O
	»	»	»	6693.55	453.55	6	10/80E		
	»	»	»	6693.75	453.45	3	90		
	»	»	»	6693.79	453.60	4	10		
	»	»	»	6693.30	456.00	10	0		
54.	Bergkläpparna	»	»	6693.55	454.14	2	80/80N		
	Herrön	»	»	6993.20	454.00	5	10/80E		
55.	Kastudd	»	»	6693.12	454.90	7	160/80W		
	»	»	»	6693.06	455.30	5	10		
	»	»	»	6693.04	455.40	2	160		
	»	»	»	6693.04	455.45	2	160		
56.	Ramsörarna	»	»	6692.82	458.30	0,5	10		
	»	»	»	6692.65	458.40	0,5	40		
57.	Furön	»	»	6693.70	459.43	3	50		
58.	Skerries E of Hamnö	»	12	6700.80	459.94	0,5	120		
	»	»	»	»	»	1	60		
59.	Torskär	»	»	6702.80	458.64	25	30—60	×	×
60.	Aspskär	»	»	6706.38	451.86	1—3	70	×	
61.	Risholm	1023	01	6685.50	462.00	1			
62.	Alören	»	»	6689.34	465.56	1	50		
	»	»	»	6689.42	465.58	4	10	×	×
63.	Loören	»	»	6680.36	469.87	20	40—160	×	× C
	»	»	»	6680.40	469.88	5—12 (PbS)	30	×	× O
	»	»	»	6680.46	469.87	15	60		×
	»	»	»	6680.47	469.88	2—5 (PbS)	10—160	×	× O
	»	Further information of the dyke systems in Bergman and Lindberg (1979, Fig. 2).							

Number	Name of locality	Finnish map number and map coordinates				Width cm	Strike/dip # 90°	Thin-section	Micro-fossil determ.
64.	Börsskär	1023	01	6688.26	463.86	1	20		
65.	Flatgrund	»	»	6687.68	465.18	3	20		
	»	»	»	»	»	3	20		
	»	»	»	»	»	3	130		
	»	»	»	6687.92	465.06	2	0		
	»	»	»	6687.92	464.90	1	110		
66.	Ådö	»	»	6689.07	469.78	2—5	40	×	×
	»	»	»	6689.00	469.72	0,5	30		
	Ådö, Träskholm	»	»	6688.67	469.88	2	40		
	»	»	»	6688.52	469.94	1,5	70		
	»	»	»	6688.04	469.65	4	0—30	×	
	»	»	»	6688.34	469.39	1—4 (PbS)	20	×	×
	»	»	»	»	»	1—4 (n ≈ 10)	20		
	Ådö	»	»	6688.50	468.21	3	100		
	Bredören	»	»	6687.80	468.50	5	30	×	
	Högskär	»	»	6687.46	492.12	3	130/80S	×	
67.	Hullvikholmen	»	»	6683.44	468.24	2	0		
	»	»	»	6683.48	468.00	2—3	40		
68.	Långholm	»	02	6691.30	460.62	3	30		
69.	Själö	»	»	6699.73	464.18	1	100		
70.	Västra Simskäla	»	»	6693.50	461.37	0,5	50		
	Östra Simskäla	»	»	6694.04	465.34	5	10		
71.	Granarna	»	»	6693.10	466.60	2	10		
72.	Pålskär	»	»	6690.49	466.38	2	0		
73.	Långö	»	»	6692.32	468.82	5	0	×	×
	»	»	»	»	»	2	10		
74.	Fåfängskär	»	»	6692.77	467.83	1—2	90		
	»	»	»	6692.72	467.92	1—3	0		
	»	»	»	»	»	1—3	0		
	»	»	»	»	»	1—3	0		
	»	»	»	6692.76	467.96	2	10		
	»	»	»	6692.77	467.98	10—20	20	×	×
	»	»	»	6692.76	468.30	1—3	30	×	
	»	»	»	»	»	1—3	30		
75.	Stora Pälsen	»	»	6691.03	469.30	1—2	110	×	
76.	Väderskär	»	03	6702.82	466.46	20	160	×	× C
	»	»	»	»	»	2	40		
	»	»	»	6702.50	466.28	15	170	×	
	»	»	»	6702.65	466.42	15	20	×	× C
	»	»	»	6702.78	466.30	1—5	150	×	
	»	»	»	6702.90	466.32	15	170	×	
	»	»	»	6703.00	466.00	1	50		
	»	»	»	6702.72	466.33	3—4	10		
	»	»	»	6703.04	466.44	1	30/75N		
	»	»	»	6702.95	466.43	2	20		
	»	»	»	6703.28	466.65	1	140		
	»	»	»	»	»	3	100		
	»	»	»	6703.70	466.60	2	10/80W		
	»	»	»	6703.00	466.33	4	40		
	Västra skäret	»	»	6703.20	465.62	5	160		
	»	»	»	6703.00	465.46	10	10		
77.	Rödskär	»	»	6703.40	470.00	2—3	10	×	
78.	Vinkelskär	»	»	6705.80	463.55	2	70		
79.	Långgårdsö	»	»	6701.10	461.30	3—7	30		
	»	»	»	»	»	2	0		
	»	»	»	»	»	2	20		
	»	»	»	»	»	0,5	20		
	»	»	»	»	»	3	20		
	»	»	»	»	»	2	0		
	»	»	»	»	»	3—4	170	×	
80.	Norra skäret	»	04	6689.64	470.78	4—8	0	×	×
	»	»	»	6689.57	470.63	1	20/80E		
	»	»	»	6689.40	470.68	6—7	10/80W	×	

Number	Name of locality	Finnish map number and map coordinates				Width cm	Strike/dip # 90°	Thin-section	Micro-fossil determ.
81.	Södra skäret	1023	04	6688.32	471.05	1	90		
	»	»	»	6688.53	470.88	4	40		
	»	»	»	6688.53	471.00	4	60/80N		
	»	»	»	»	»	1	60		
	»	»	»	6688.52	471.20	2—10	80	×	×
	»	»	»	»	»	1	60/85N	×	
	»	»	»	»	»	4	50		
82.	Norra grundet	»	»	6687.82	472.39	2	10		
	»	»	»	6687.78	472.27	2	50/80N		
83.	Magskär	»	»	6684.15	473.86	4	30	×	×
	»	»	»	»	»	4	30	×	
	»	»	»	»	»	3	170		
	»	»	»	»	»	1	80		
	»	»	»	6684.18	473.83	4	50		
	»	»	»	»	»	4	30		
	»	»	»	6684.18	473.58	2	20		
	»	»	»	6684.10	473.55	3	50		
	»	»	»	»	»	3	50		
	Krokskär	»	»	6684.15	472.84	1	130		
84.	Björkskär	»	05	6693.00	474.80	7	0		
85.	Lillkulla	»	»	6695.38	475.00	2	0		
	»	»	»	6695.37	475.04	3	0		
	»	»	»	6695.33	475.07	3	70		
	»	»	»	»	»	3	160		
	Gumsören	»	»	6694.80	475.60	1	0		
86.	Träskär	»	»	6696.50	477.30	1—7	0—60		
	»	»	»	6696.00	477.50	1	140/80S		
	»	»	»	»	»	2	60/85S		
	»	»	»	»	»	2	50		
87.	Hemörarna	»	»	6698.40	478.20	1	0		
	»	»	»	»	»	1	0		
	Yxskär	»	»	6698.60	479.30	2	120		
88.	Söderörarna	»	»	6696.96	479.70	2	60		
89.	Västra Borgskär	»	08	6691.35	482.00	0,5	30		
90.	Buskhäran	»	09	6704.16	482.00	2	60		







1. Österholm, sandstone dyke, 2. Österholm, detail of No. 1, 3. Loören, sandstone dyke, 4. Silverskär, galena dyke, 5. Långbergsöda-öjen, silt-sandstone dyke.

ON PALEOZOIC MICROFOSSILS IN CLASTIC DYKES ON THE ÅLAND ISLANDS AND IN THE CORE SAMPLES OF LUMPARN

by

Risto Tynni

CONTENTS

INTRODUCTION

The investigation of the Paleozoic microfossils in the Åland Islands became of current interest in 1976, when the Paraisten Kalkki (Partek) company made available to the Geological Survey of Finland drill-core samples from the Lumparn Bay. Around the same time, Leif Bergman carried out investigations of sandstone dykes and made this material available for palynological studies. Also Veli Suominen collected Paleozoic *in situ* and boulder material for the present study in connection with a geological bedrock survey in the region.

Microfossils had been previously studied from material of the same nature as that found in the Åland Islands in the southwestern Finnish archipelago. Eisenack has described Paleozoic microfossils found in the material collected by Martinsson (Eisenack 1958, 1959, 1962, 1965, Martinsson 1956). Comparative material closely related to the present study is further offered by Kjellström's (1971 a, b) research in Sweden. Microfossil investigations of earlier Paleozoic formations in the southern and southeastern parts of the Baltic region have advanced the development of microfossil dating to its present stage (Eisenack 1931, Timofeev 1966, Volkova 1968, Fridrichsone 1971, and Jankauskas 1975). In these investigations, marine microplankton relicts are of central importance. The cutinoid shell of the acritarchs in question has been well preserved in the sediments.

The upper part of the limestone deposit at Lumparn is poor in fossils compared with the lower part, in fact too few acritarchs for a proper dating. On the basis of Merril's (1979) conodont study, the deposit referred to can be dated to the late Caradocian age. The conodont *Amorphognatus superbus* is characteristic of the upper part of the Lumparn limestone deposit (25 m), thus being contemporaneous with the Nabala stage (F_1a) in Estonia and the limestones of Kullsberg and Slandrom in Sweden. The acritarchs of the present work represent mainly Middle Ordovician and to a lesser extent Lower Ordovician and the Lower Cambrian forms.

RESEARCH METHODS

The sandstone dyke were examined with a magnifying glass in the field to determine the presence of possible fossils. The previously known sandstone of Långbergsöda—öje, found by Tanner, offer an example of fossils — c. 1—1.5 mm in diameter — that can scarcely be distinguished without the aid of a magnifying glass. Samples from the fissure-fillings were sawn into slices and studied under a stereo-microscope.

For the microfossil study, about 30 g of rock was used, from which the weathered

surface had been sawn away. The loose, powdery surface layer was removed from the drill-core samples. After clearing the surface, the rock was crushed mechanically. The crushed rock was treated with 10 % HCl and 40 % HF solutions to dissolve and remove the limestone and silicate mineral matter. The galena and pyrite were removed with a strong HNO_3 solution.

The residue was treated with a $CHBr_3$ solution with a density of 2.2 for the separation of the organic matter from the remaining mineral matter. The slides were made from the residue containing microfossils by using Clophen-Harpix as a medium.

In following the names with numbers refer to localities used by Bergman (1982).

CLASTIC DYKES WITH ACRITARCHS IN RAPAKIVI BEDROCK

I Lower Cambrian siltstones and sandstones

A. Stora Granskär (No. 29)

The dyke is dense and fine of grain, and it contains mainly fine sand and fractions of silt. In color, the sediment is a brownish green-gray, but is also contains bluish gray spots, which possibly formed during deoxidation of the sediment. The coarser, reddish rapakivi fragments can be distinctly identificated in the sedimentary rock.

The fine sandstone has a fairly high density of microfossils. *Leiosphaeridia* species of different sizes occur most abundantly. Their structure is in many instances affected by pyrite crystallization. To some extent, they have been otherwise deformed as well through foldings and wear.

Tasmanites sp., Ø 110 μ is an extremely rare occurrence, but its existence has been recognized on the basis of its thick shell, perforations and brownish red color.

Granomarginata squamacea, Volkova 1968, which is a wellknown Lower Cambrian form, occur with a frequency of no more than 10 %. In general, it appears in a position where the equatorial veil is totally visible; only one observation was made of the trend of the equator, the veil in that instance running in the direction of the diameter of the sphere.

Leiomarginata simplex, Naumova 1960, is fairly commonly present in the acritarch community under discussion.

Cymatiosphaera aff. *solfensis* occurs in sandstone also fairly commonly, though not with the same frequency as the preceding type.

Trachysphaeridium is a type resembling Leiosphaeridia, except that tiny nodules cover its surface. The diameter of the observed individuals was c. 90 μ.

Baltisphaeridium, sp. 1, with its small spines, is likewise a fairly common occurrence in the samples. The diameter of body is c. 33 μ, the length of the spines being c. 5 μ. The spines are relatively dense. This form has a fairly thick vesicle wall of a brownish color. Slighty smaller than the preceding form, B. sp. 2 also has a thinner vesicle wall and a sparser occurrence of spines. Figs. 1 and 2 shows a selection of acritarch types.

Palynological dating: The species met with are characteristic of the microplankton of the Lower Cambrian. Notable points in common can be observed in this respect with the part of the series of strata at Sulva inter-

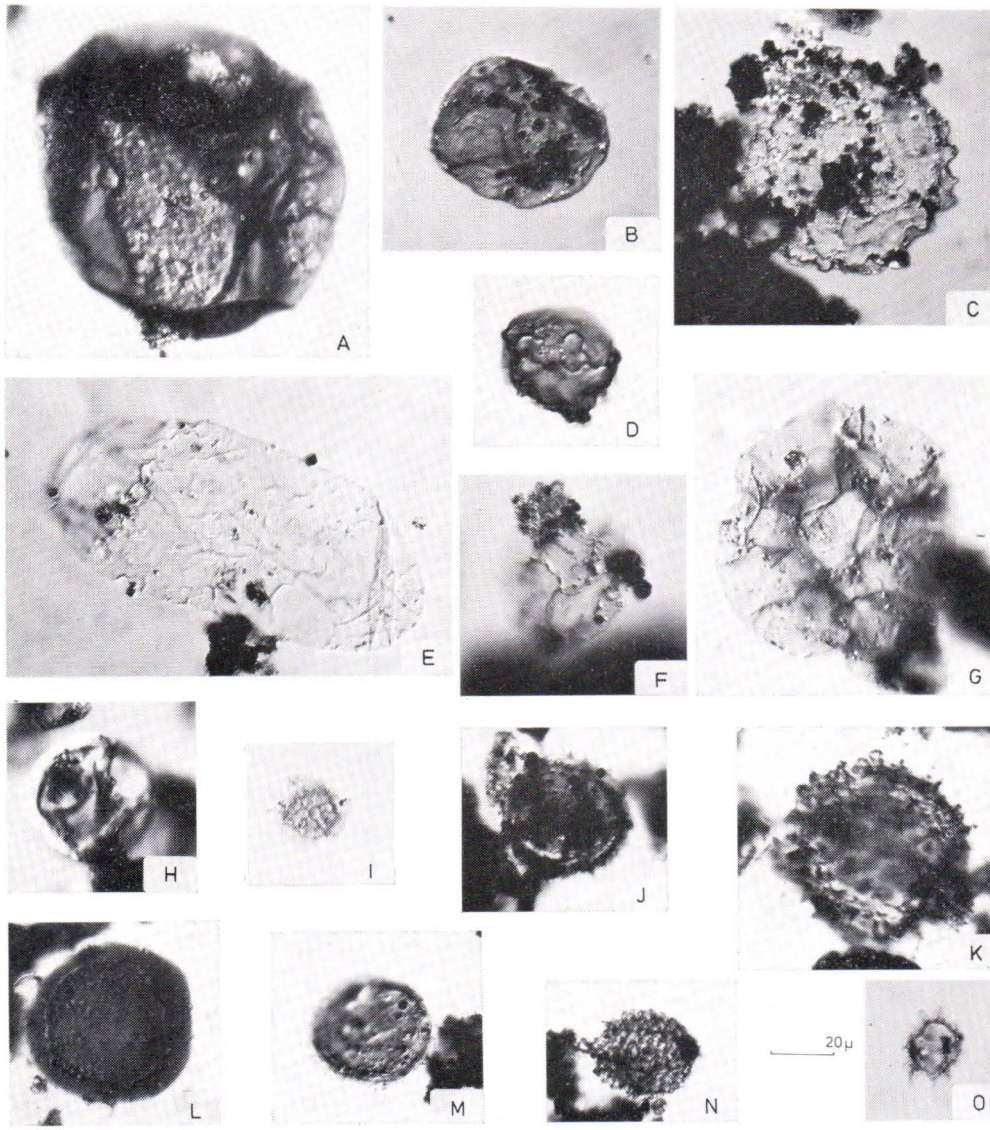


Fig. 1. A selection of acritarch types from the clastic dyke of Stora Granskär (No. 29): A. *Tasmanites bobrowskii*, B—D. *Leiosphaeridia* sp., structure of pyrite grains, E. *Leiovalia* sp., F. *Cymatiosphaera* sp., G. *C. solvensis*, H. *Leiomarginata simplex*, I. *Granomarginata squamacea*, J. K. *Baltisphearidium sp.*, L. acritarch + secondary margin, M. *Baltisphaeridium* sp., N. *B.* sp., O. *Micrhystridium* sp.

preted to date from the Lower Cambrian (Laurén *et al.* 1978). Missing from the Stora Granskär dyke are also acritarchs of younger than Lower Cambrian age. The sandstone dyke referred to in all probability dates to the Lower Cambrian.

B. Loören (No. 63)

In the inhomogeneous, coarse and densely packed sandstone there can be visually distinguished spherical inclusions of clay as well as shell fragments of mollusks. Exami-

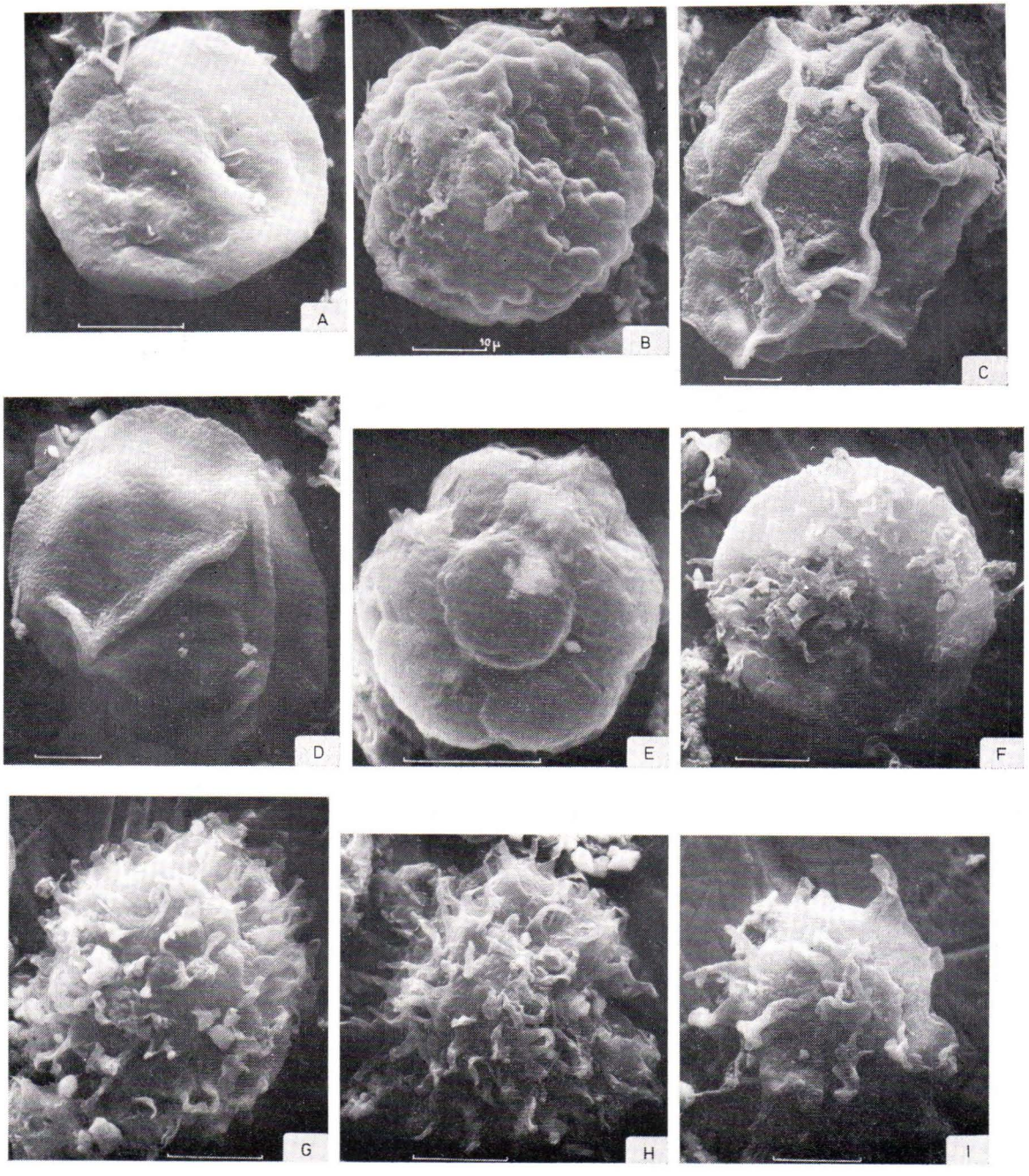


Fig. 2. Acritarch types from Stora Granskär (No. 29): A, B. *Leiosphaeridia* sp., B. with secondary pyrite structures, C. *Cymatiosphaera* sp., D. *Tasmanites* sp., E. ? *Symplassosphaeridium* sp., F. *Baltisphaeridium ciliosum* Volkova -typ, G, H. *Archaeohystrichosphaeridium flexile* Timofeev -typ, I. A. sp. SEM-figure.

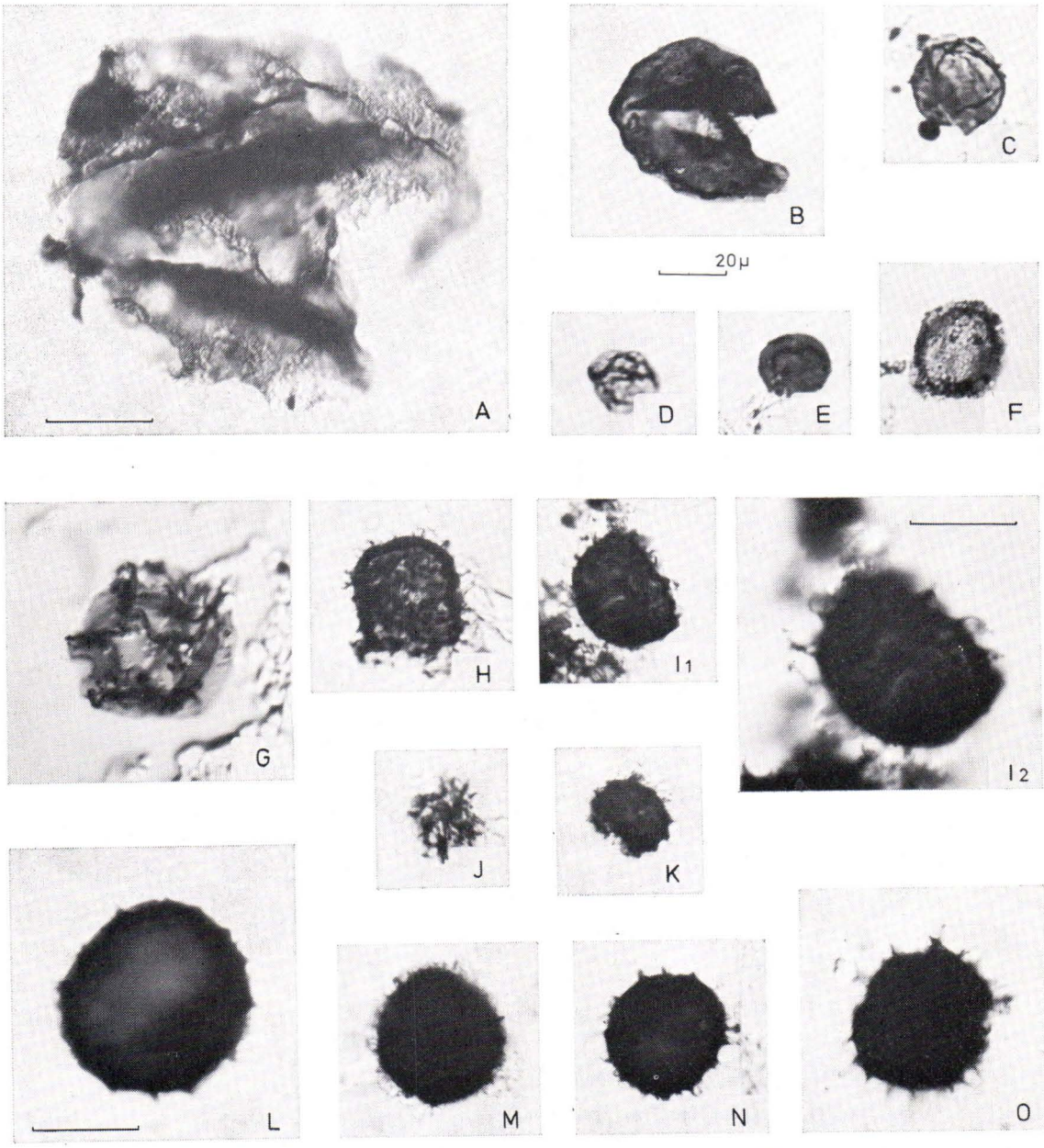


Fig. 3. Selection of acritarch types from the fissure filling of Loörarna (No. 63): A. large *Leiosphaeridia* sp., B—E. small *Leiosphaeridia* sp. individuals, F. *Lophosphaeridium* sp., G. *Cymatiosphaera* sp., H, I 1, I 2. *Cymatiogalea* sp., J. *Cymatiosphaera* sp., K—M. *Baltisphaeridium* species, N, O. *Stelliferidium* sp.

nation of a polished section reveals it to contain collophane. The shell fragments are rounded.

In the sandstone dyke of Loören shell fragments probably representing broken off Brachiopoda are rather common. The fragments may represent different species. Only one shell is fairly intact (Plate I: 3). It is about 2 mm broad and remarkably thick. Owing to the foliated wearing away of the shell, its form cannot be distinguished accurately. On the basis of its general shape and thickness, it might be also compared to certain species of *Mobergella*. The last-mentioned has a phosphatic composition (cf., Bengtson 1977). It is not, however the same Brachiopoda as on Långbergsöda. The slight curvature of the fragments suggests a large size.

In the Loören sandstone, the abundance of microfossils suffices for the composition of a microfossil community. The worn condition of the microfossils limited the possibilities of identifying the forms. The prevailing form is of the *Leiosphaeridia* type. Present are a possible worn *Tasmanites* sp., diameter c. 106 μ, and a *Cymatiosphaera* sp., with a diameter of c. 32 μ.

Among the Acanthomorphidea types, the plankton community has included *Baltisphaeridium* sp., diameter 39 μ, and *Stelliferidium* sp., which resembles *S. ålandicum*. One of the spiny forms resembles *Cymatiogalea*, but it might be a *Baltisphaeridium* with a large pylom. Taken as a whole, the diversity of the species is rather limited. Fig. 3 offers a selection of types occurring among the acritarch species.

Palynological dating: The prevalence of the *Leiosphaeria* type, the possible *Tasmanites*, *Cymatiosphaera* and smallish *Baltisphaeridium* occurrences indicate a deposit dating back to the Cambrian period. In type, it is older than the younger assemblage of Långbergsödan and resembles the Stora Granskär assemblage. A Lower Cambrian formation is probably in question despite the occurrence of *Stelliferidium* found in Lower Ordovician sediments.

C. Väderskär (No. 76, orientation 160°)

The sandstone is dense and brown in color. The density of occurrence of microfossils is moderate. Owning to the compactness of the sandy sediment secondary forms are seldom encountered. The prevailing type is the relatively large *Leiospharidia* form. In question is the *Leiosphaeridia* sp. proper, with a diameter of c. 50 μ. The shell is relatively thick. A commoner type has a rough surface and belongs to the *Trachysphaeridium* genus. In the preparation, there occur *Trachysphaeridium* species about 50 μ and 78 μ in diameter. The smaller is the form most generally present in the preparation.

Tasmanites bobrowskii (Wazynska 1967) is a thick-walled form, the pore patterns of which are distinguishable on the surface. The diameter is approximately 100—110 μ. The color is a yellowish brown. In the preparation, a number of these specimens were observed.

A complicated acritarch type is represented in the material by one individual about 35 μ in diameter, the vesicle aperture of which is roughly 20 μ. It may correspond to the genus *Cymatiogalea*.

Stelliferidium sp., diameter c. 34 μ. The form resembles to a high degree *Baltisphaeridium*, for its spines are only slightly forked or thickened at the ends. It brings to mind *Stelliferidium ålandicum* (p. 46).

The diversity of species in the microplankton community of Väderskär is rather limited, especially in regard to Acanthomorphitae forms that are scarce. Fig. 4.

Palynological dating: The sparse occurrence of Acanthomorphitae forms and the

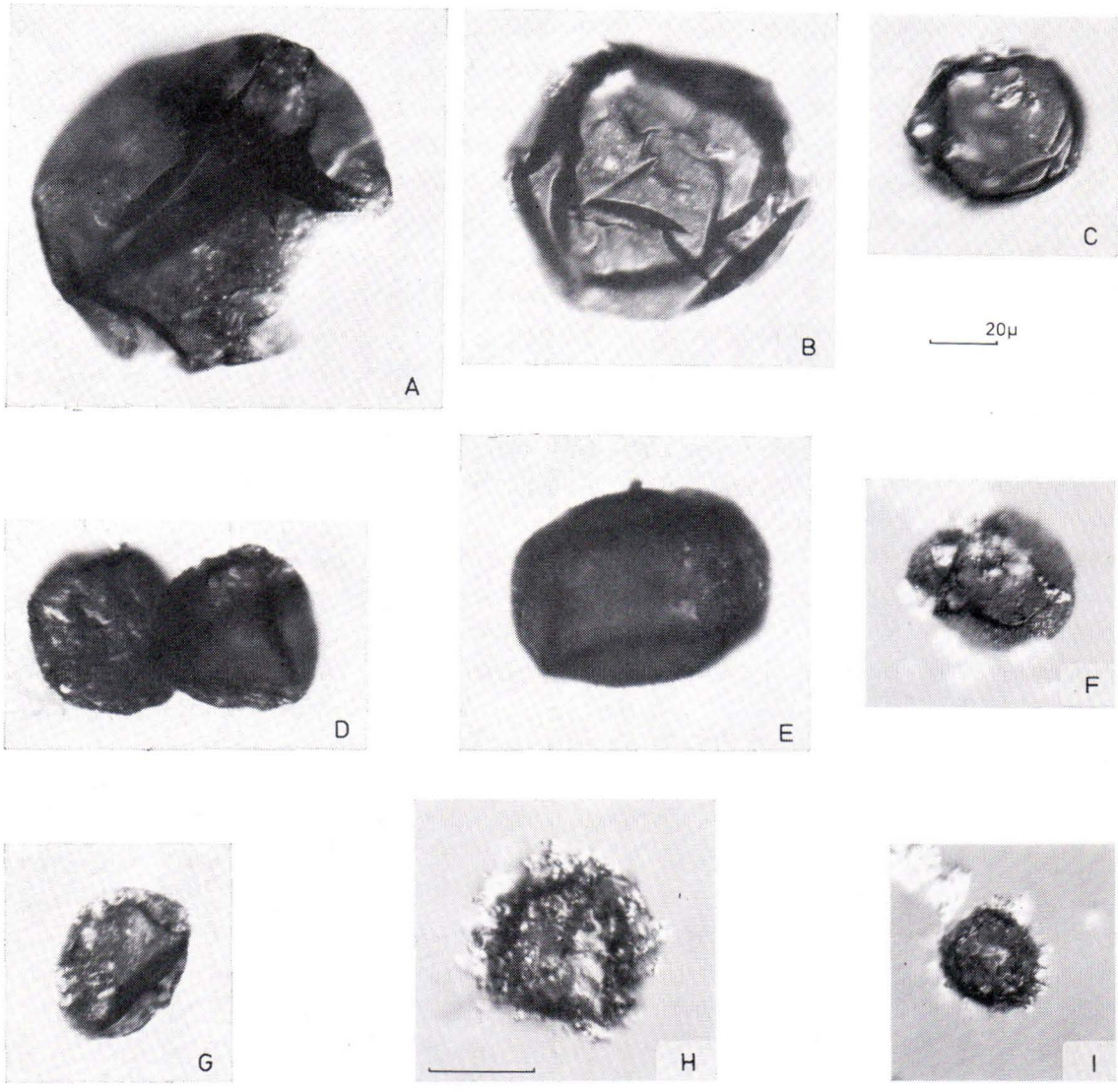


Fig. 4. Selection of acritarch types from the fissure filling of Väderskär (No. 76, orientation 160°): A, B: *Tasmanites bobrowskii*, C. *Leiosphaeridia* sp., D, E, G. *Trachysphaeridium* sp., F. ? *Trachysphaeridium* sp., H.? *Cymatiogalea* sp., I. ? *Stelliferidium* sp.

prevalence of leiosphaeridia forms point to the early Cambrian. From the standpoint of more accurate dating, an important form is *Tasmanites bobrowskii*. It has been met with in Cambrian deposits in Poland (Wazynska 1967) and Estonia (Umnova, Fanderflit 1971). In Poland, the form has been identified as belonging to the Lower Cambrian; in Estonia, it has been found to occur in Pirita and Tiskre formations dating from the Lower Cambrian. The same form occurs at Sulva, where it has been interpreted to be of Lower Cambrian age. To the same age class also belongs the sandstone of Väderskär.

D. Vädeskär (No. 76, orientation 20°)

The sandstone type is dense, and it resembles the sandstone dyke of Väderskär trending 160°. The occurrence of microfossils is sparse but among them are a few forms of importance from the standpoint of dating. Included in this category are *Granomarginata squamacea* and a worn *Tasmanites* sp., possibly *T. bobrowskii.*

The primitive *Baltisphaeridium* species has a diameter of c. 35 μ. Its spines are rather short and have been poorly preserved. The form resembles *B. ciliosum* (Fig. 5) described by Volkova (1969).

Typical of the acritarchs of Väderskär (348 d) is the high degree of wear they have undergone. For this reason, the share of the probably delicate *Leiosphaeridia* forms prevalent elsewhere is relatively small in this dyke.

Palynological dating: Although the species deviate from the ones found in the 160°-trending fissure filling, the microfossils of this fissure filling are nevertheless likewise Lower Cambrian. This dating is confirmed especially by the occurrence of *Granomarginata squamacea* and *Baltisphaeridium ciliosum*-typ. These are present also in the sandstone dyke of Stora Granskär. *Granomarginata squamacea* is characteristic of, in particular, Lower Holmian deposits (cf., Mens & Pirrus 1977).

Sediment of roughly the same age (based on microfossil determinations) has been found in the Väderskär area in sandstone dykes of various orientation. Thus the differently trending dykes do not differ from each other appreciably in age i.e. a Lower Cambrian. Only the dyke running in the 20° direction may probably be somewhat older.

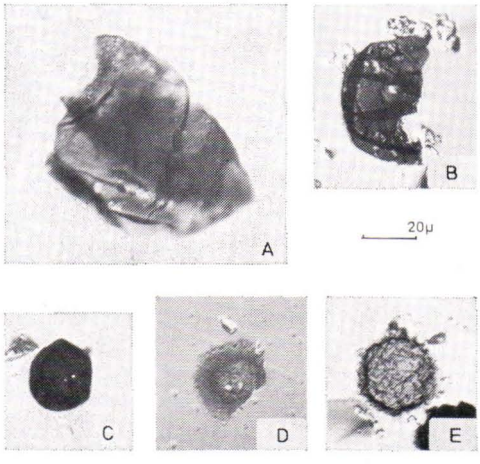


Fig. 5. Selection of acritarch types from the fissure filling of Väderskär (No. 76, orientation 20°): A. *Tasmanites bobrovskii*, B, C. *Leiosphaeridia* sp., D. *Granomarginata squamacea*, E. *Baltisphaeridium* sp.

E. Svartholmsöarna (No. 20, orientation 170°)

The sandstone type is even-grained and greenish gray in color. It evidently contains more organic material than the more dense sandstones do. The microfossil material interpreted as primary is as follows (cf., also Fig. 6).

Leiosphaeridia sp., with a diameter of c. 25—30 μ,, is the most abundant acritarch form. In question are relatively dark and folded forms, which in many instances exhibit a rough surface. They appear old, bringing to mind the *Protosphaeridium* type. Present are a few measuring 50 μ in diameter. *Tasmanites* also belongs to the collection of species present. It is worn, but in size it corresponds to the *T. bobrowskii* species.

Lophosphaeridium sp., diameter 28 μ, is exceedingly rare. *Pterocystidiopsis* sp. *(baltica* n. sp.) is a rarity in the preparation. Its surface membrane forms ridges, separating from the surface of the shell irregularly shaped fields. The diameter measures 26 μ. The form closely resembles *Cymatiosphaera,* but it is structurally more irregular.

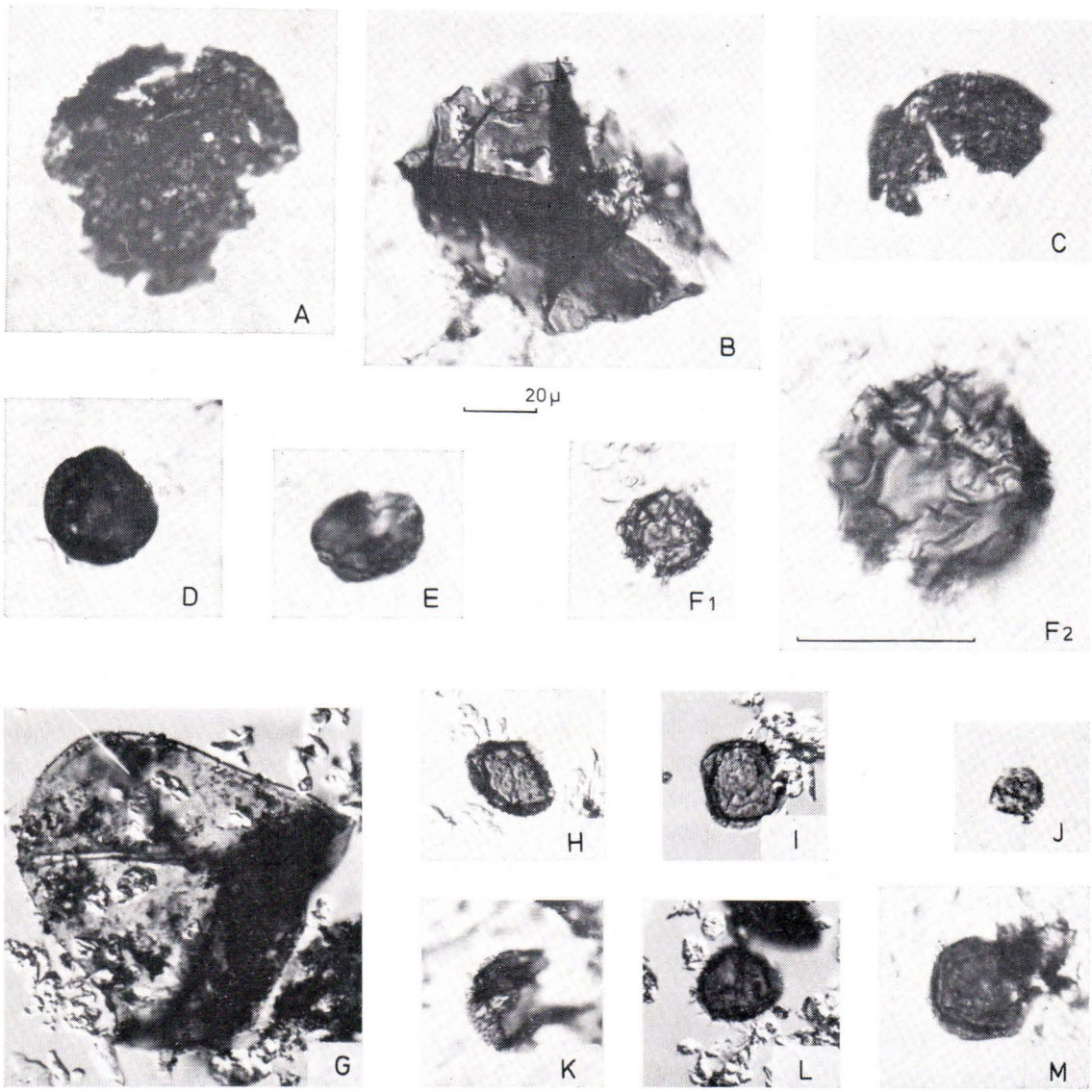


Fig. 6. Selection of acritarch types from the fissure filling of Svartholmsöarna (No. 20, orientation 170°): A. worn *Tasmanites*, B. *Tasmanites bobrovskii*, pores visible at right, below, C—E. *Leiosphaeridia* sp., F 1, F 2. *Pterocystidiopsis* sp., G. ? *Trachysphaeridium* sp., H, I, K. *Lophosphaeridium* sp., J. *Micrhystridium* sp., L, M. *Baltisphaeridium* sp.

Baltisphaeridium sp. This small and short-spined form is also exceedingly rare in this sandstone.

Micrhystridium sp. is likewise a great rarity.

Palynological dating: Characteristic of the sandstone is the prevalence of the *Leiosphaeridia* type among the species taken as a whole, which in addition includes an old-type *Baltisphaeridium* form and from which

younger acanthomorphitae forms are missing. The species identified, mainly *Tasmanites*, indicate Lower Cambrian sedimentation.

The occurrence of *Pterocystidiopsis* sp. is rare, and it has not been met with in other sandstone dykes.

F. Långbergsöda Öjen (No. 53, sample C)

The sandstone is fine grained, gray, dense and well sorted. It deviates from the fossil-bearing sandstone described in the following.

The density of microfossils in the fissure filling of the sandstone is rather slight; but, because the species include forms of significance from the standpoint of dating, conclusions relevant to dating can be drawn even on the basis of scanty microfossil material.

The amount of the diacrodium forms is very limited. On the other hand, present are tiny *Baltisphaeridium* forms. The largest of the forms measures c. 48 μ in diameter, and it has delicate hairlike spines, c. 10 μ in length. On the rim, the spines are about 10 μ apart. Only a single specimen of this form has been identified. Commoner is a smaller and thicker type, with a diameter of c. 25—30 μ. The spines are broader than on the preceding form, and they are spaced about 7 μ apart. This form resembles to some extent the *Stellisferidium ålandicum* occurring in the fossil-bearing sandstone (No. 53), but no forking has been observed at the ends of the spines. It also resembles *Baltisphaeridium ornatum* Volkova 1968.

The third *Baltisphaeridium* type is c. 40 μ in diameter, and it has fairly short processes. The base of the processes are constricted.

A rarity is the *Acanthodiacrodium* type, the diameter of which is c. 35 μ.

The small *Lophosphaeridium* type is c. 23 μ in diameter.

Leiosphaeridia is a common occurrence in the material, but, darker than the rest, of a sepia color, whereas the forms of the *Acanthomorphitae* group are yellowish brown (Fig. 7).

Palynological dating: The primitive species of the *Baltisphaeridium* type observed in the sandstone dyke, *Lophosphaeridium* and *Leiosphaeridia*, suggest a Cambrian dating, especially in view of the fact that the diacrodium type is missing or present only extremely scantily. Possibly, in question might be a Cambrian sand younger than that in, for example, the sandstone of Stora Granskär. The material might also have originated through the mixing of sediments of different ages, as the color differences in the microfossils indicate. (Cf., Långbergsöda, Lower Ordovician sandstones).

II Lower Ordovician sandstones

A. Långbergsöda Öjen (No. 53, site discovered by Tanner)

The sandstone type is dense and poorly sorted. The sandstone exhibits horizontal stratification. The lower part consists of fine-grained and the upper part of coarser sediment. The rock contains, among other things, fragments broken off the surrounding rapakivi bedrock, clay lenses as inclusion and pyrite.

The density of microfossils present in the sandstone is fairly high. The prevailing type belongs to the *Acanthomorphitae* Downie acritarchs equipped with spines (Figs. 8—10). The commonest genus is probably *Stellisferidium* Deunff *et al.* 1974.

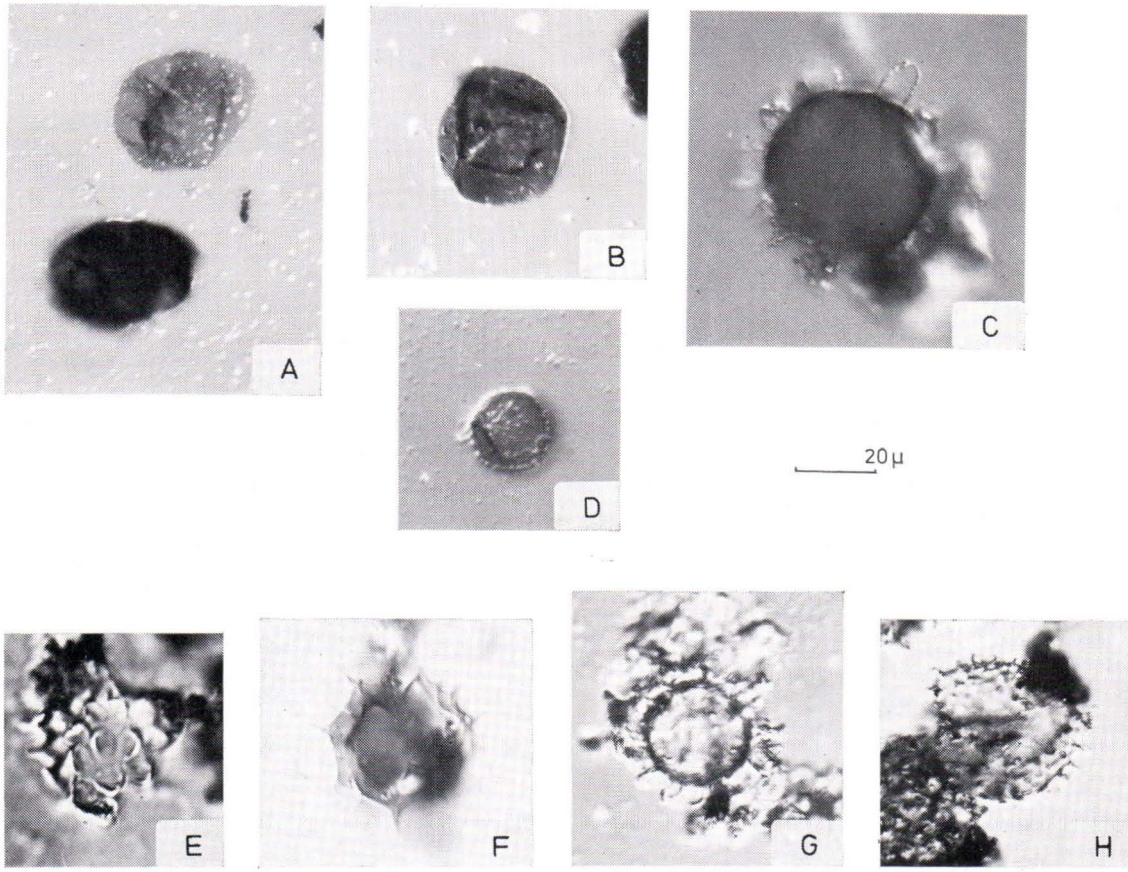


Fig. 7. Långbergsöda-öjen (No. 53, sample C) fissure filling, acritarch types: A, B. *Leiosphaeridia* sp., C. *Baltisphaeridium* sp., D. *Lophosphaeridium* sp., E. *Estiastra* sp., F. *Acanthodiacrodium* sp., G. *Baltisphaeridium ornatum* typ, H. *B.* sp. The color at points A, B is sepia gray, at points C, D orange brown. The former are possibly older than the latter.

Stelliferidium ålandicum n. sp.
(Fig. 9 D—I, Fig. 10 A, B.)

HOLOTYPE: GSF (Geol. Surv. Finl.) prep. no. 367/SEM, Fig. 10 A, B.

TYPE LOCALITY AND TYPE STRATUM: Långbergöda-Öjen, Åland, Lower Ordovician.

DERIVATION OF NAME: after province Åland.

DIAGNOSIS: The vesicle is round, the diameter c. 30 μ and the processes c. 6—10 μ. Around the pylom the length of the processes is c. 3 μ. These processes are spaced at intervals equivalent to their length. The forking at the ends of the processes is slight but distinguishable. The pylom is exceedingly large, about 2/3 of the vesicle diameter. It generally has a cover. Around the base of the processes there are radial folds as in the genus *Stellisfaeridium* Deunff *et al.* 1974.

The *Baltisphaeridium* genus is represented by at least two forms: The more prevalent form has slender spines and measures c. 40—50 μ. It resembles the *Comasphaeridium* genus, which, however, has more delicate spines. The larger form resembles the *B. globosum,* with a diameter of c. 60 μ, described

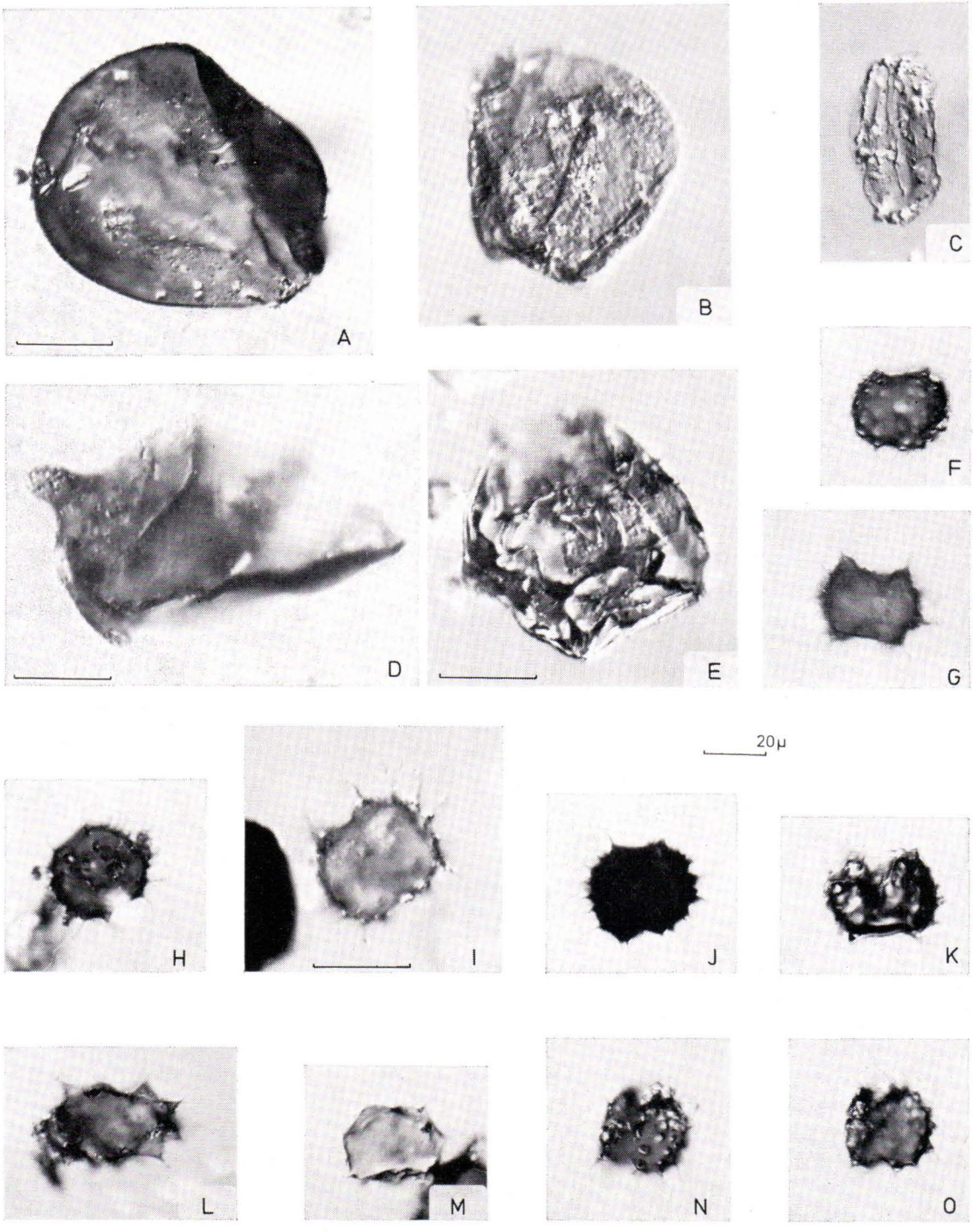


Fig. 8. Acritarch types from fissure filling at Långbergsöda-Öjen (No. 53, dyke described by Tanner): A. *Leiosphaeridia* sp., B. *Trachysphaeridium* sp., C. *Eliasum* sp., D. *Pirea ornata* ?, E. *Polyedrizium* sp., F, H, J. *Acanthodiacrodium angustizonale*, G. *Dasydiacrodium* sp. 1, I. *Acanthodiacrodium* sp. 1, K, L. A. sp. 2, M, N, O. *Dasydiacrodium* sp. 2.

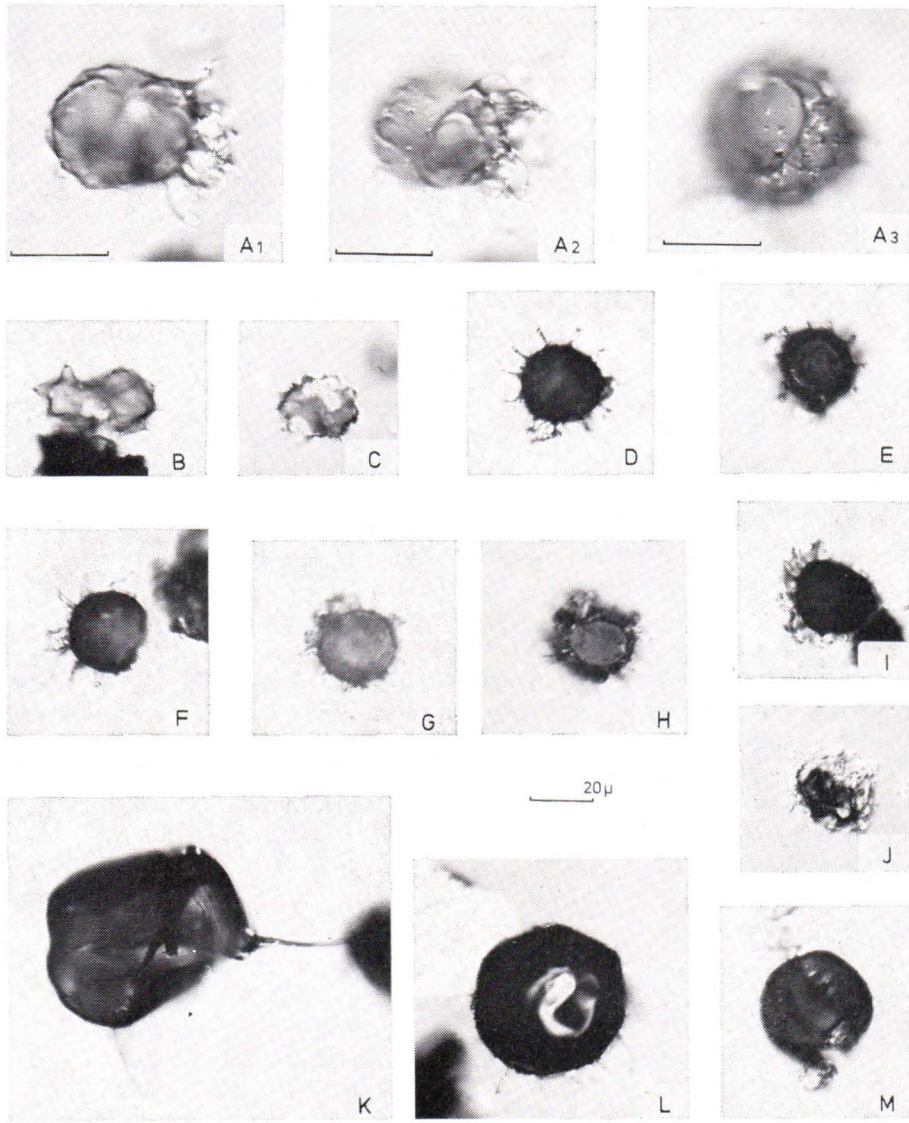


Fig. 9. Acritarch types from fissure filling at Långbergsöda-Öjen (No. 53, dyke described by Tanner), continued: A 1, A 2, A 3. *Dasydiacrodium* sp. 3, B, C. *D.* sp. 4, D—I. *Stelliferidium ålandicum,* J. undetermined acanthomorphidae type, K. *Baltisphaeridium* sp. 1, L. *B.* sp. 2, M. *B.* sp. 3.

from Middle Ordovician limestone from the Bothnian Sea (Tynni 1975).

The genus *Acanthodiacrodium* (Timofeev 1958) is represented likewise by at least two forms. These are c. 30—45 μ long, and slightly contracted in the middle. They resemble forms described by Timofeev from, *inter alia,* Upper Cambrian deposits. The same form-type has, however, also been met with in Lower Ordovician deposits. Comments on these important species will be made later on in this text.

The type of form representing the genus *Dasydiacrodium* (Timofeev 1959) at Långbergsöda is heteromorphic only to a slight degree; accordingly, it resembles the genus *Acanthodiacrodium*. Only a single individual on the conspicuously heteromorphic type has been found. This oval shell has at one end sinuous and forking appendages, but at the opposite end only a few curved spines can be distinguished.

Pirea sp., a rounded elongated shell, at the apical end of which is one noticeable short horn. The form met with at Långbergsöda was partially compressed. Length c. 50—60 μ, with the surface, especially at the structure, nodular. It resembles *P. ornata* (Burmann 1970), which has been described from the Upper Llanvirnia of the Lower Ordovician.

In all likelihood, the following form, which was found in a Långbergöda dike, belongs to the genus *Eliasum* Fombella 1977. The length of the oblong shell is c. 60 μ and the width 30 μ. The aristae situated lengthwise extend near to the apical ends. It resembles certain Acanthodiacrodium forms, without, however, the distinct spines at the ends.

Eliasum is described from the Middle Cambrian deposit in Spain (Fombella 1977). It is extremely rare in the present material (Fig. 8 C).

Polyedrizium sp. (Fig. 8 E). The surface of the vesicle has irregularly positioned facets. Diameter c. 45 μ. Rare form, only one observation. It resembles *Polyedrizium lagoviense* described from the Upper Famennian by Górka (1974).

Palynological dating: The species identified are distinctly of the younger type than at Stora Granskär. The forms are early Paleozoic, predating the Middle Ordovician. An Upper Cambrian dating is supported by, among other things, the results reported by Timofeev (1959) from the southwestern part of the Paleozoic Russian platform. In the above-mentioned investigation, the genera *Acanthodiacrodium* and *Dasydiacrodium* have been predominantly dated to the Cambrian. In the most recent studies, the dating of these forms appears to gravitate toward the Lower Ordovician. Burmann (1968) criticizes Timofeev's observation of the abundance or lack of *Diacrodium* forms at the transitional stage between *Dictyonema* schists and glauconite deposits. In her view, the change is due to a facies change rather than being biostratigraphic. According to Timofeev (1963, 1966), the diacradiums disappeared during the Tremadocian whereas, according to Burmann, the development of the stratigraphically important heterodiacrodien continues into the Arenig and Llanvirnian stages of the Ortovician, as evidenced by the pelitic facies.

The occurrence of Diacrodium forms during the Tremadocian stage has also been reported by Naumova (1950), Deunff (1961), Combaz (1967), Martin (1975), Fournier-Vinas (1978) and others. According to Fournier-Vinas, the following features appeared during the Cambri-Ordovician in the microfossil community: The Early Cambrian communities have become somewhat differentiated, consisting mainly of sphaeromorphs. The Middle Cambrian communities are highly differentiated (leisosphaerides, lophosphaerides, acanthomorphs). The Lower Ordovician communities are differentiated to a large extent. In the Monts de Lacaune area, *Acanthodiacrodium* species were described from only the Tremadocian and Arenigian, but not the Cambrian. In this light, it appears more likely that the sandstone of Långbergsöda is Lower Ordovician rather than Upper Cambrian. The species *A. angustizonale* Burmann (1968) has previously been described from the Upper Llanvirnian material of Arkona (Burmann) and the Arenigian deposit of Montagne Noire (Rauscher 1974).

The *Ceratreta tanneri* (Metzger) Martinsson (Plate I: 1, 2) present in the sandstone dyke also leaves open the afore-mentioned alter-

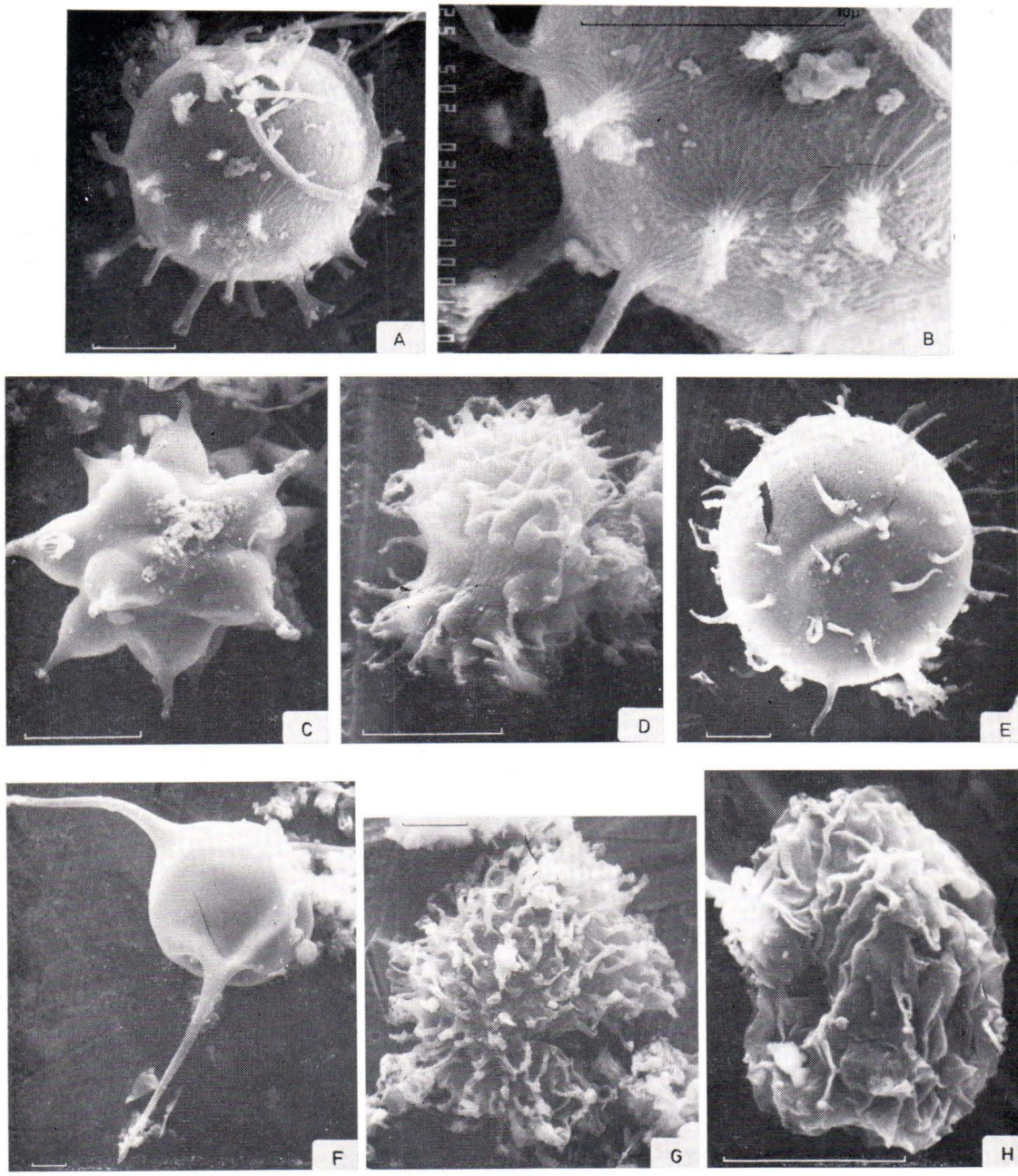


Fig. 10. (SEM) Acritarch types from dyke at Långbergsöda-Öjen, A, B. *Stelliferidium ålandicum*, holotyp, C. *Acanthodiacrodium* sp., D. *Dasydiacrodium* sp., E. *Baltisphaeridium* sp. 2., F. Baltisphaeridium sp. 1., G. ? *Baltisphaeridium* sp., H. *Pterocystidiopsis* Defl. sp.

natives, for, according to Martinsson (1968), the fossil in question is Upper Cambrian or possibly Lower Ordovician. On the basis of achritarch occurrences, the latter alternative is the one arrived at here.

Discussion: The older Cambrian achritarch community met with in one of the two samples from the same sandstone fissure filling — a community that might also be regarded as a mixture of different communities — indicates that the fissure had formed as early as the Cambrian period. It had opened anew, however, during the Lower Ordovician stage. The exceptionally large width of the fissure further supports its complicated genesis.

B. Östra Sundskär (No. 4)

A light-colored, fine- and even-grained, poorly cemented sandstone. The fairly dense, light brown, pitted surface had probably formed as a result of partial carbonate dissolution. The cementing material is calcium carbonate.

Despite the porosity of the sediment, the proportion of young secondary pollens and Dinophyceae occurrences in the samples is rather small. Even primary acritarchs are scarce.

In the first preparation, there occurs as a rarity a primitive type of *Baltisphaeridium* with a diameter of c. 34 μ, the densely situated, curved spines of which are c. 7 μ long (Fig. 11). This type probably corresponds to *Baltisphaeridium compressum,* which Volkova (1968) has described from a Lower Cambrian deposit in Estonia (Lontova Beds). According to Jankauskas (1972, 1974) *B. compressum* occurs in the Vergale horizon in Estonia, corresponding to Holmia 2.

In the other preparation, made from another sandstone sample, there occurs as a rarity a large, thick-shelled *Baltisphaeridium* or *Peteinosphaeridium* sp. Its diameter is 57 μ. Spines are, with three exceptions, broken. Broken-off spines appear as round patterns. Number: about 20. The length of the spines is c. 12 μ, the diameter at the base being about 4 μ, narrowing to a sharp point; and, hollow in the middle, they are not directly connected with the interior of the vesicle. The species resembles the Middle Ordovician form *B. calicispinae* Górka. The coloration is yellowish brown, as in the case of the Middle Ordovician species of the Bothnian Sea region (Tynni 1975).

The majority of the acritarch forms consists of small *Leiosphaeridia* species ranging in diameter between 12 and 20 μ. They are smooth, thin-shelled and generally provided with a cleft. Also the larger leiosphaeridias are thin. The leiosphaeridias might be secondary. Fairly common is a small, smooth-surfaced *Leiomarginata* sp., with a diameter of c. 17—20 μ. It generally possesses a pylom or tear. An uncommon form is a thin-shelled *Lophodiacrodium* sp., possessing nodules and measuring c. 18 μ in length. All the aforementioned species are yellowish brown, deviating in this respect from the darker, sepia-colored acritarchs met with in other fissure formations.

In this brittle sandstone, there is a fair abundance of membranous black fragments, which give the impression that they are fragmente of Chitinozoans. The forms resemble closely those met with in Middle Ordovician limestones at the bottom of the Bothnian Sea (Tynni 1975).

Palynological dating: The sedimentary material occurring as fissure filling is difficult on the basis of the foregoing to date. The scanty primitive *Baltisphaeridium* species suggests a Lower Cambrian age. Large *Baltisphaeridium* sp. and the worn fragments of the Chitinozoa type represent the younger component of sedimentation during the Lower Ordovician.

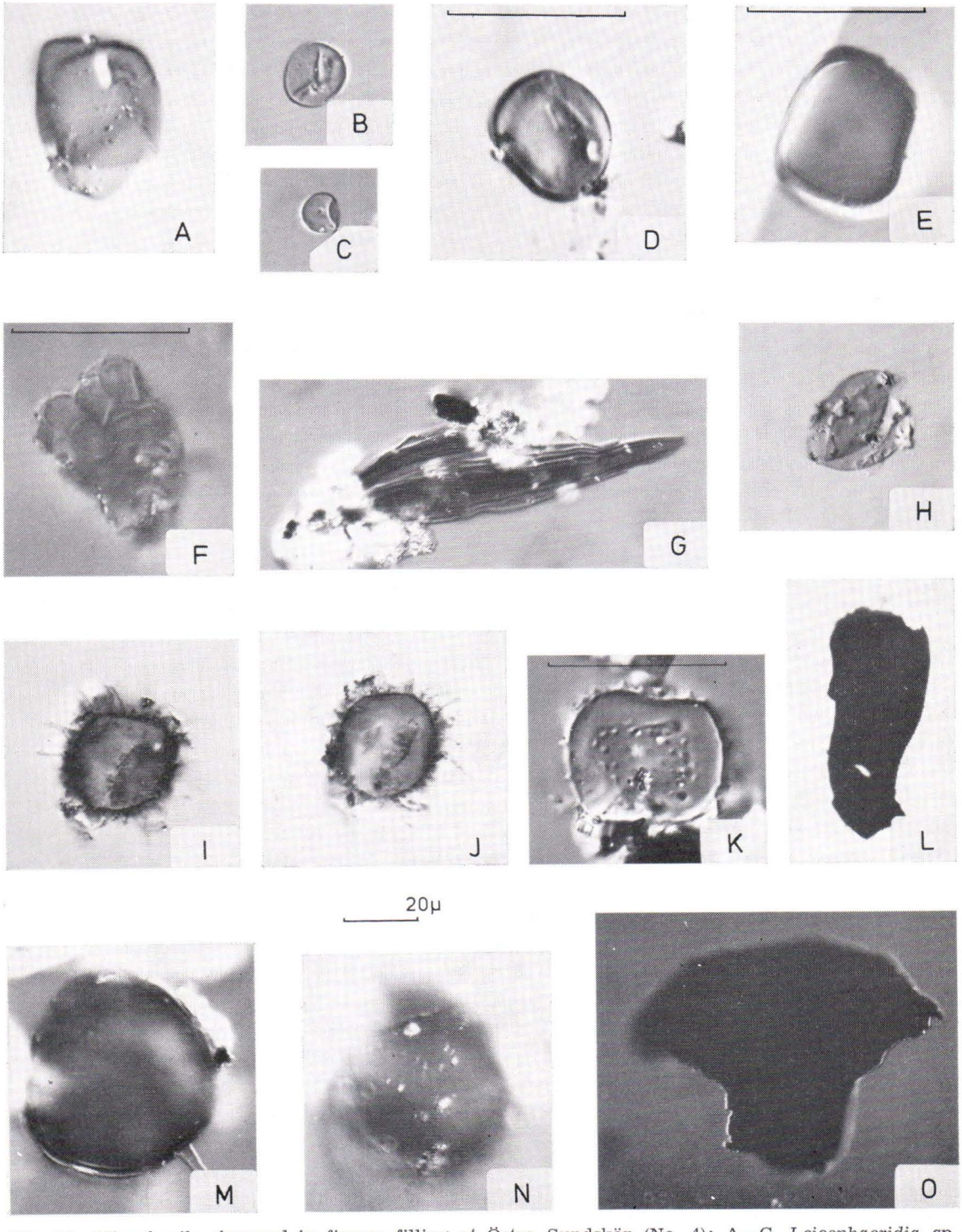


Fig. 11. Microfossils observed in fissure filling at Östra Sundskär (No. 4): A—C. *Leiosphaeridia* sp., D, E. *Leiomarginata* sp., F. *Synsphaeridium* sp. G. ? *Leifusa* sp., H. *Archaeodiscina umbonulata* Volkova, I, J. *Baltisphaeridium compressum*, K. *Lophodiacrodium* sp., M, N. *Baltisphaeridium/Peteinosphaeridium* sp., L, O. ? Chitinozoa fragment.

III Galena-bearing dykes

A. Loören (No. 63, greenish sandstone with a high content of galena)

Microfossils were found in only the latter of the two fissure fillings containing galena in the study area, those of Ådö and Loören. The galena dyke of Ådö is younger than the sandstone fissure filling penetrating it and proved to lack microfossils.

The predominantly galena-bearing sandstone of Loören is dense and characterized more accurately by Bergman and Lindberg (1979). It is greenish in color. The microfossil content of the sample is rather slight. Besides, the microfossils are in nearly every case broken and dark. *Leiosphaeridia* species occurring in isolation are the prevalent types. Among them, as a rarity, are aggregations of fairly large spheres of different sizes, forming colonies (Fig. 10).

A primitive *Baltisphaeridium* also belongs to the species of this formation. The individual best preserved resembles *Baltisphaeridium ciliosum*. The diameter of the sphere is c. 30 μ, and the spines are short and curved.

Present as a rarity in the material is also *Ooidium* aff. *rossicum* Tim. It measures 45 μ in length. The form is egg-shaped with staplelike curved appendages characteristic of *Ooidium rossicum* and *O. timofeevi* species (Loeblich 1970). Owing to its being broken, the structure in question give the appearance of partly curved spines.

Palynological dating: On account of the rather slight density of microfossils and the scantiness of forms to be dated, no unambiguous dating can be presented. The rudimentary *Baltisphaeridium* species would suggest Lower Cambrian sedimentation. On the other hand, *Ooidium rossicum* is a typical *Obolus*-sandstone form (Loeblich 1970). This occurrence is indicative of a Lower Ordovician age.

B. Loörarna (No. 63, gray, 2—5-cm thick galena-bearing sandstone)

The gray, fine-grained galena-bearing sandstone was observed to contain acritarchs in abundance. The species in question deviate distinctly from the ones described in the foregoing, with the exception of the *Leiosphaeridia* group. The prevailing species are the Leiosphaeridia (18—130 μ) and the *Micrhystridium* (Fig. 13). In the case of each genus, some are rounded and some evidently deformed. This appears clearly from the angular shaping of the pyrite grains or the *Leiosphaeridia* types producing an angular surface structure. As a rarity, there are, in addition, a few *Granomarginata squamacea* individuals.

Micrhystridium sp., with a diameter of c. 10 μ, makes up the maximum of the genus. The shell is thin, the color yellowish and the spines exceedingly small. The species resembles *M. tornatum* Volkova 1968. Some of the small forms are longish, resembling the *Aranidium* type (Jankauskas 1975). In many instances, the longish form has undergone one-sided contraction, less commonly symmetrically, with the result that the type brings to mind the small *Acanthodiacrodium* species.

As a curiosity in the material, there occurs an extremely small form that should be classified as belonging to the genus *Ovulum* (Jankauskas 1975). Because of its structure, the following label is proposed for the species: *Ovulum punctatum* n. sp. The form is fairly round but reduced in size at one end owing to a comparatively wide pylomlike aperture. It measures about 5 μ in diameter and its surface is granulated.

As an isolated observation, a *Rhabdochitina* sp. belonging to the *Chitinozoa* group was identified.

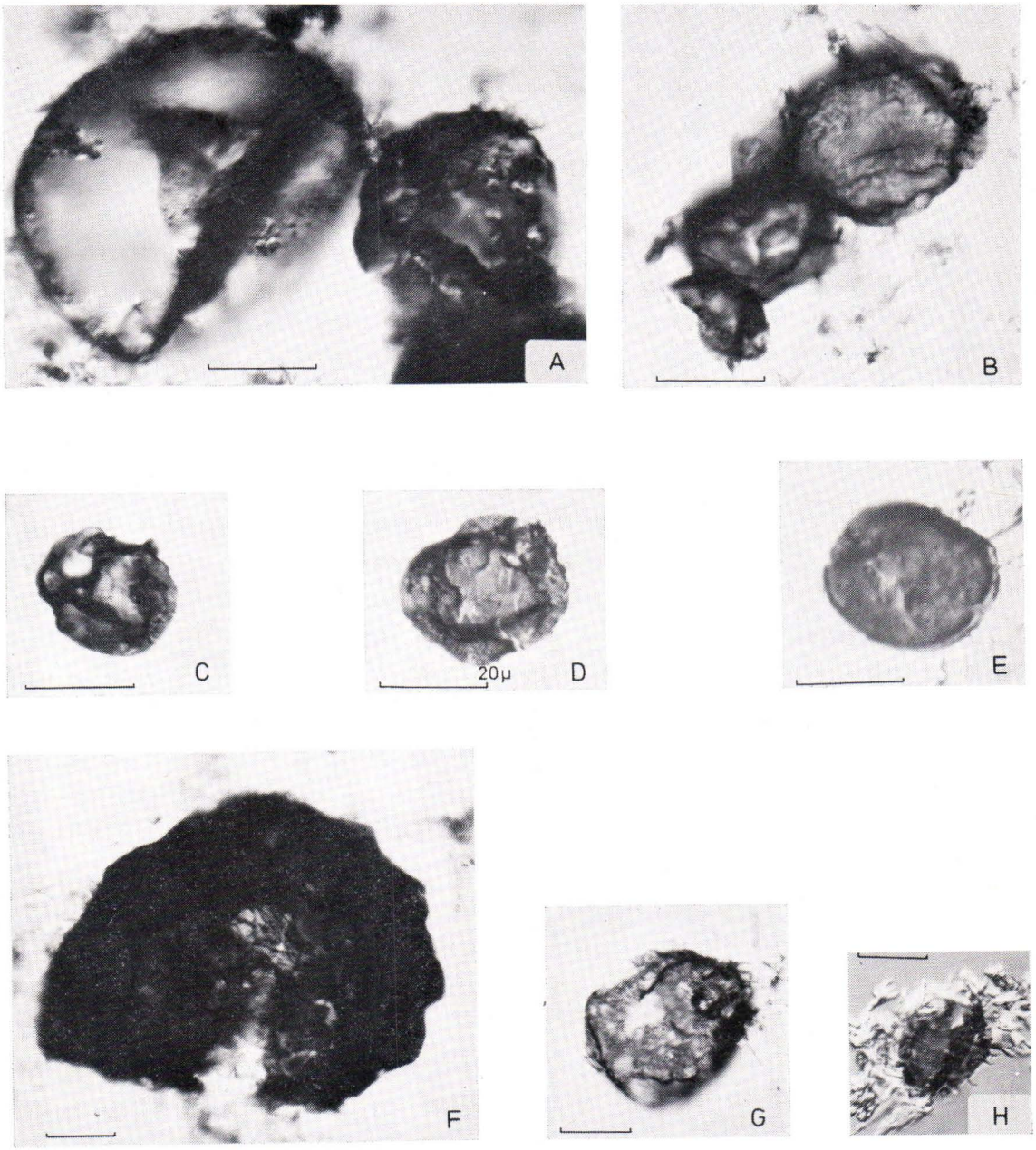


Fig. 12. Loörarna (No. 63, greenish galenaferous sandstone dyke), acritarch types: A—C. *Leiosphaeridia* sp., D. *Ooidium* sp., E. ? *Lophodiacrodium* sp., F. undetermined, G. *Ooidium rossicum*, H. *Baltisphaeridium ciliosum* typ.

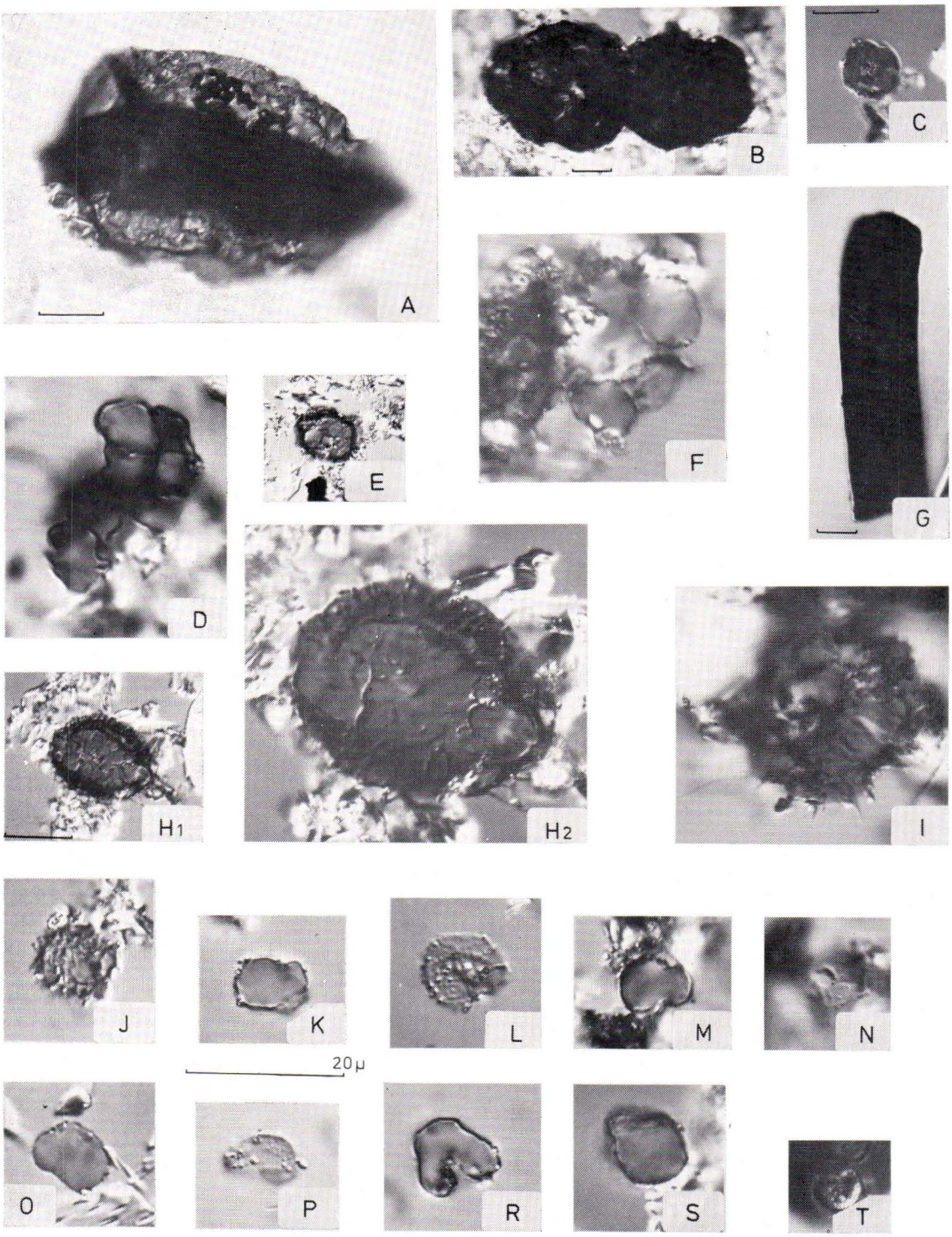


Fig. 13. Loörarna (No. 63, gray galenaferous sandstone dyke 2—5 cm thick), microfossils: A—C. *Leiosphaeridia* species, D, F. *Synsphaeridium* sp., E. *Granomarginata squamacea*, G. *Rhabdochitina* sp., H 1, H 2. *Aranidium* sp., I. *Baltisphaeridium* sp., J. *Aranidium* sp., K—S. *A.* sp., T. *Ovulum punctatum*.

Palynological dating: The species observed, *Micrhystridium* aff. *tornatum*, *Baltisphaeridium* and *Granomarginata squamacea*, indicate that the sediment consists mainly of Lower Cambrian components. *Rhabdochitina* indicates a component of the Ordovician period. Also the previously described galena-bearing dyke (III A) exhibits Lower Ordovician microfossils containing in addition a Lower Cambrian component.

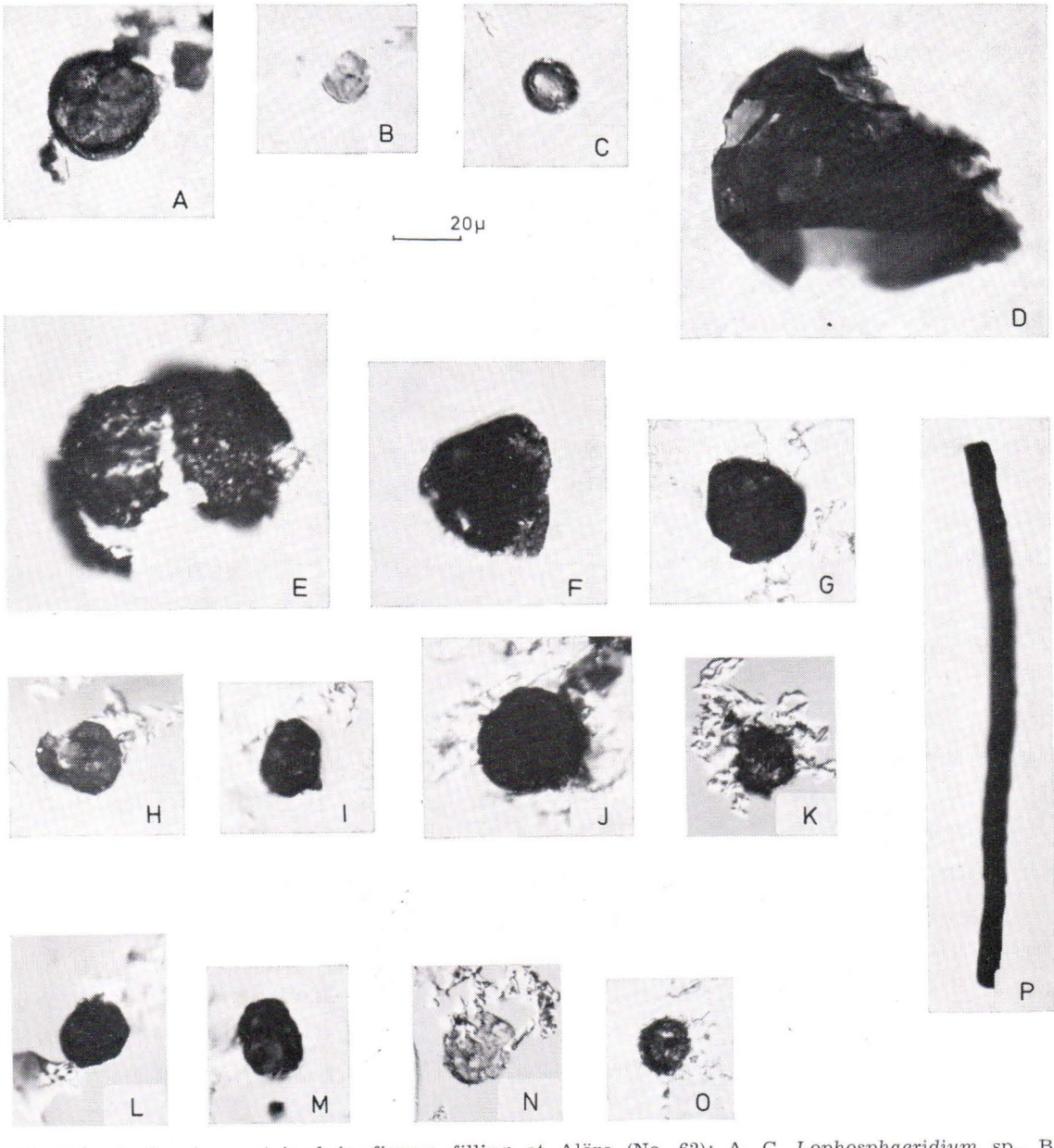


Fig. 14. Acritarchs contained in fissure filling at Alöre (No. 62): A, C. *Lophosphaeridium* sp., B. *Leiosphaeridia* sp.; microfossils contained in fissure filling at Hättskär (No. 18): D—M. acritarchs varia, N. *Lophosphaeridium* sp., O. *Baltisphaeridium* sp., P. Chitinozoa, group form.

CLASTIC DYKES IN WHICH NO MICROFOSSILS COULD BE FOUND

A microfossil analysis has been carried out on 46 of the largest fissure fillings. Only nine of these contain acritarchs sufficiently to permit dating. Hättskär (No. 18) probably belongs to the category of Lower Cambrian sandstone dykes, also judging by its content of acritarchs (Fig. 14). In Figure 15 are examples of rare microfossils. In addition, to the dykes mentioned in fig. 15 very few microfossils were observed in 13 of the studied fissure fillings.

At Prästö (No. 11) and Lökskär (No. 23) the sandstone type is exceptionally reddish in comparison with the rest. Lithologically and structurally, however, it does not noticeably deviate from other sandstones. Nevertheless, visually this type resembles to some extent the Jotnian sandstone of Satakunta.

No microfossils could be found in the sandstone and no palynological dating could be made. Deviating as it does in some degree from the majority, this type of sandstone might correspond to fissure filling of a different age, possibly Precambrian.

It should be stressed that an absence of microfossils does not necessarily indicate an age differing from the sandstones in which acritarchs have been found. The microfossil content in sandstones might vary owing to local differences in currents and wave action.

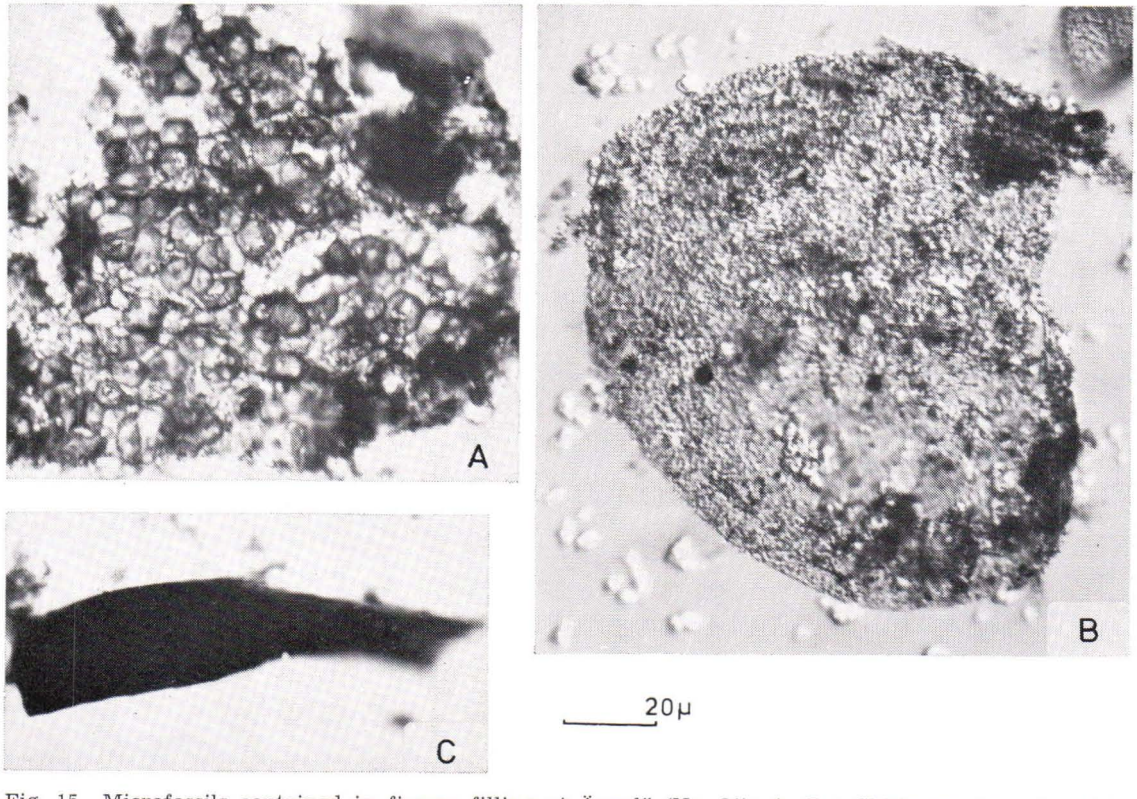


Fig. 15. Microfossils contained in fissure filling at Äppelö (No. 31): A, B.,; Chitinozoa type found in the fissure filling at Bötesholm (No. 9): C.

The most abundant microfossils are generally found in rather fine-grained rocks composed of fine silty sand and also in poorly sorted coarse- and fine-grained sediments. In well sorted sandstones microfossils are often lacking.

The oldest dated sandstone is of Lower Cambrian age. This probably pertains also to the majority of sandstone fissure fillings in which no microfossils were found. If during the Late Precambrian the region had been covered by the sea and fissures had then formed, acritarch types belonging to this time should have been expected to be found. On the other hand, in the event that during the Late Precambrian fissure fillings had formed on the land surface, neither marine phytoplankton nor other microfossils would occur in them. Life on land is not known to have existed at that period.

PALYNOLOGICAL INVESTIGATION OF DRILL CORES BORED IN 1954 BY THE PARAISTEN KALKKI COMPANY IN THE AREA OF LUMPARN

The Lumparn Paleozoic occurrence, general observations

Owing to its scant content of fossils, parallels could not evidently be drawn with assurance before Merrill's (1979) study between the limestone of Lumparn and the stratigraphy of the Ordovician period. Metzger's designation 'Lumparn limestone' (Hausen 1946) is more appropriate as a concept than 'Baltic limestone.' Eisenack (1965) drew attention to the difference between the microfossils of Baltic limestone in different boulder fans. He nevertheless described a number of microfossils from Baltic limestone boulders occurring in different areas, including the southwestern Finnish archipelago.

The Lumparn limestone (south of Tranvik) is divided into two distinctly differing types. The upper limestone (calcilutite) is densely packed, fine-grained, light gray and, especially in the area of small cracks, dappled reddish by hematite. The lower limestone is greenish gray and coarser than the other. The limestone of the upper part can be seen outcropping near Tranvik. According to Metzger (1965), it bears a close resemblance to the so-called Baltic limestone. With regard to its fineness of grain and density, the Lumparn limestone is comparable to the limestone of Rakvere, Estonia, which was previously classified as belonging to the Upper Ordovician; but, according to Männil (1966), Rakvere belongs to the upper part of the Middle Ordovician. According to Sauramo (1942), the Lumparn limestone strikingly resembles that of Wesenberg (corresponding to the Rakvere stage) and it is exceedingly poor in fossil content. Calcilutite occurs also in the sediments of the younger Pirgu stage (Jaanusson 1963, Floden 1980). Corresponding to it is the Järrestad stage of central Sweden. The Rakvere and Pirgu stages extended, according to Jaanusson's (1963) paleogeographic maps, across the Åland Islands.

The Vaasagaard and Järrestad stages of Baltoscandia include, according to Jaanusson (op. cit.), quite different stages: black shale, green and red siltstones, several calcilutite types, calcarenites and reef limestone. The upper and main portion of the Baltic lime-

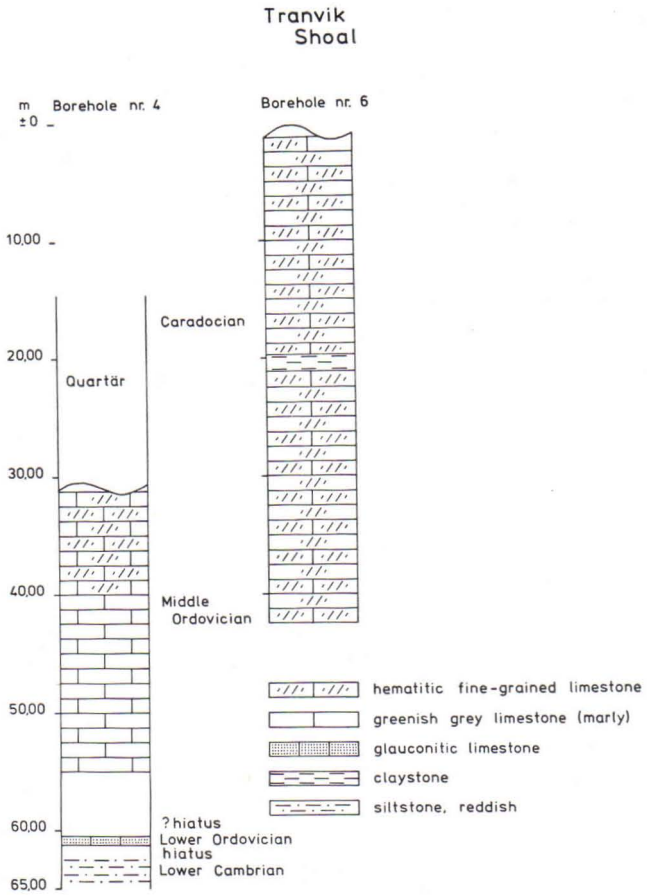


Fig. 16. Core sections no 4 and 6 of the Tranvik shoals (Lumparn).

stone is calcilutite belonging to the aforementioned stages in which there often occurs an abundance of bioherms (*Palaeoporella* limestone). It occurs as boulders in, among other places, the Åland Islands (Wiman 1907, Kulling 1926). The Vaasagaard and Järrestad stages followed the Rekvere stage and belong to the Upper Ordovician.

From the Tranvik drill cores (Lumparn), Merill (1979) has recently presented the results of conodont studies. The species identified indicate sedimentation during the Upper Caradocian. Merrill failed to find in the Tranvik drill core No. 6 any of the species characteristic of older orthoceratite limestone occurring in local erratics.

For the palynological study of the Lumparn occurrence, material was obtained from drill cores Nos 4, 6, 10, 18 and 21. The total number of samles studied is 59. Drill core No. 4 is most representative of the middle and lower stratal parts while drill core No. 6 is most representative for the higher located strata. The Palaezoic formation shown in Fig. 5 p. 122, and the core sections in Fig. 16.

Paleontological observations in the upper limestone (drill hole No. 6)

Drill hole 6 is located on the shoal just south of Tranvik. The upper fine-grained limestone met with in the drill cores corresponds to the limestone in the outcrop. According to a thin-section study, the limestone is composed at a depth of 4.3 meters of very fine-grained, densely packed carbonate grains (averaging 3—7 μ in size). Carbonate crystals of larger size form almondshaped and veinlike concentrations. In addition, there are quartz grains and a small amount of opaque minerale. In thin section, there can be seen a few calcareous fossil fragments, spherical or triangularly rounded little rings and prickles, evidently the spines of sponges (Plate II: 5—7). The foregoing resemble Hyolithus or Brachiopoda in cross section. The *Hyolithus* type is met with in Lower Cambrian — Middle Permian deposits (Fisher 1962), and accordingly are not suitable for dating.

The thickness of the microfossil-poor limestone is at least 42.8 m, for the predominant material in the drill hole referred to is a gray, very fine-grained limestone with reddish flecks or cracks. The sedimentary rock varies, however, in that in places there are also coarser and, in addition, greenish portions. The microfossils have become brittle and broken up into unidentifiable fragments. Wear of various degrees appears in the sample taken from a depth of, for example, 6.5 m, where the acritarchs have darkened and the sphaeromorphs either become cracked or disintegrated. Not a single member of the *Baltisphaeridium* species with spines intact could be found. The weathered microfossils resemble those charred microfossils met with in the central European Variscian folded area (Burmann 1969, among others).

At the 19.9—21.8 m interval, there is a noteworthy intercalation, a light brown clay bed, which also contains coarser material. An Z-ray diffraction analysis of the clay showed no traces of benthonite. In the very fine sandy fraction (25—50 μ) of the intercalation, quartz registers a maximum of 80 %. The remaining portion consists mainly of feldspar and mica, and no limestone except for a few tiny calcareous crinoid fragments.

At a depth of 21.2 m in the clayey layer, two small disklike crinoid joints were found. The diameter is c. 1.5 mm, and from the central aperture radial lines run to the outer rim (Table 1: 4, 6). The same type occurs also in a limestone boulder found on the island of Segelskär, east of Hanko. It contained an abundance of crinoids, brachiopods and bryozoans. A microfossil analysis was also made of the fossil-rich limestone of Segelskär, and the result is presented in the comparison to follow.

The microfossil analysis made of the clay-bearing layer at a depth of 21.2 m in the core from Lumparn yielded a poor assortment of acritarch species. Mostly, it includes various *Tasmanites* species (Fig. 17). The commonest is a species in which the surface pores are only faintly distinguishable and the diameter of which is c. 70—88 μ. Exceptional is a fragment representing a large *Tasmanites* species, the estimated diameter of which exceeds 200 μ (? 500 μ). The color is a brownish yellow. The wall thickness is c. 4 μ, with the distinct pores situated roughly 4 μ apart.

The large form described in the foregoing differs from the *T. martinsson* species on the basis of the pores and from the *T. huronensis* on account of its thinner wall. The last-mentioned species have been found in Baltic limestone erratics and dated to the Lyckholmer stage (Eisenack 1958). Subsequently, Eisenack (1965) described in addition from the Tammisaari area the species *T. balticus, T. verrucosus* and *T. minutus*. The latter two measure 67—109 and 50—70 μ, and the former in many cases exhibits a vague patterning of

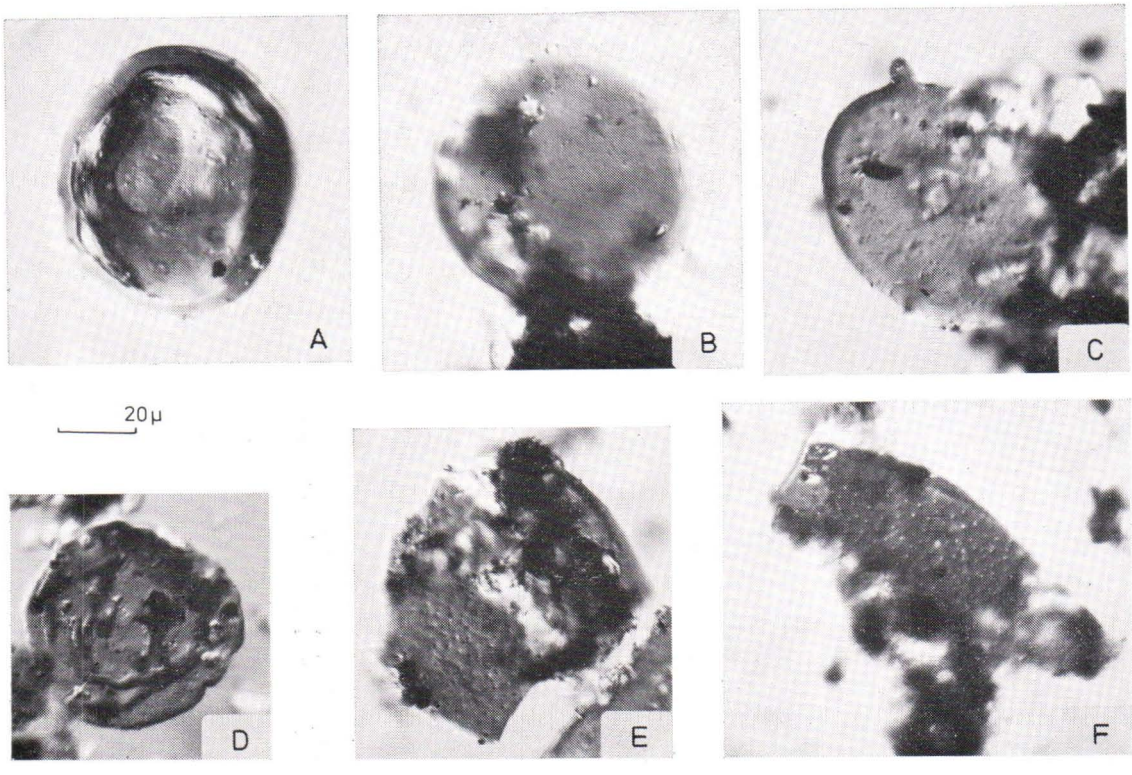


Fig. 17. Acritarch forms met with at the depth of 21.2 m in the diamond drillcore No 6 in Lumparn: A—D. *Tasmanites* aff. *verrucosus*, E, F. *T.* sp.

pores. Possibly the commonest type met with in the clay bed of Lumparn corresponds to this species. No distinct pore pattern can be distinguished in the species from Lumparn, but in its marginal portion there does occur a radial patterning. *T. verrucosus* has been met with in the Jewe-Lyckholmer stages of Estonia (Eisenack 1962 b) as well as in the Jörden stage, i.e. from the Middle Ordovician to the Silurian.

Leiosphaeridia is the second most common acritarch form occurring in the clay-bearing deposit of Lumparn. It varies in size from 90 to 10 μ, which means that at least two species are involved.

The preparation likewise contains in fragmentary form brown, 5- or 6-angled cellular tissue, the diameter of the cells being c. 0.2 mm. In form they resemble the shield-shaped theca of crinoids.

No microfossils undissolvable in HCl could be found in the portion of the deposits investigated between the depths of 21.3 and 45.2 m. The limestone from the surface to a depth of 45.2 meters was probably the result of rapid sedimentation also explaining the scantyness of microfossils. It is younger than the coarser grayish green limestone, which, again, contains microfossils in quantities sufficient for dating.

A comparison between the Lumparn limestone and the limestone in the Boulders of the Hanko area

On the island of Segelskär, located east of Hanko there is a fair abundance of calcareous boulders of various types. A noteworthy type is a nearly white, fine-grained calcilutite, with a rich content of fossil fragments and microfossils. The rock resembles externally the Lumparn limestone, except that the reddish traces of ferric oxide are lacking. Moreover, it is somewhat coarser of grain than the limestone of Lumparn. Characteristic of the Segelskär rock is that its surface weathers in the open air and turns powdery. A comparison with the Lumparn occurrence is warranted on the basis of the crinoid fossils, for the fossil found at a depth of 21.2 m in the clayey intercalaction of the Lumparn limestone is probably of the same form as the tiny crinoid fragments present in the Segelskär rock. It deviates in type from the dolomitized boulder with abundant large Pelmatozoans described by Martinsson (1955) from Lillgrund, near Bönholm, Tvärminne. This boulder is, according to Martinsson, petrographically similar to the variety of rock of the Vasalemma stage in Estonia. It differs from the afore-described Segelskär type, where, again, there also occurs as a rarity dolomitized limestone. At Andalskär, south of the Hanko peninsula, there occur dolomite boulders also containing smaller Pelmatozoa fragments (Martinsson, op. cit.), which may correspond to the tiny crinoid fragment found at Segelskär and at Lumparn. In Martinsson's view, the Ordovician boulders of the Hanko archipelago are rather closely related. Their stratigraphic affinity should be sought in the Vasalemma (D_3), Rekvere (E) and Saunja (F_{1a}) stages.

The light-colored, fine-grained limestone of Segelskär, in which there are tiny crinoid fragments, also contains microfossil material. In type it corresponds to the chitinozoa fauna described by Eisenack (1965) from the Baltic limestone occurring in the south Finnish archipelago, but certain differences are to be noted as well. Mention should be made of the following Chitinozoa forms: *Desmochitina minor* and *Conochitina micracantha* as well as the rather tiny *Rhabdochitina* forms (the largest part of which are fragments). As for the various *Baltisphaeridium* species, these are noteworthy: *B. longispinosum, hirsutoides, microspinosum, calicispineae, multipilosum, ingerae, B.* sp. species resembling *multipilosum* except for the diameter, which averages 35 μ. The genus *Gonisphaeridium* is well represented: *G. polygonale* as well as, among others, *Veryhachium estrellitae* (Gramer), as it was previously known, and closely related forms are fairly prevalent.

Multiplicisphaeridium bifurcatum, Leiovalia simplex, Lophosphaeridium sp., *Peteinosphaeridium breviradiatum* f. *coronata* constitute the species present in the lightcolored type of Segelskär boulder. The same forms appear among the afore-mentioned species as have been met with in, for example, the Middle Ordovician limestone of Poland and Sweden (Górka 1969, Kjellström 1971), but some of the species are also known from younger deposits. *Desmochitina minor* and *Conochitina micracantha* are met with in a fairly broad stratigraphic sector composed of deposits dating back to the Orodivician period (Lower/Middle — Upper) (Eisenack 1965). In this case, microfossils afford no opportunity for accurate dating. It may be stated, by way of suggesting a conclusion, that the light-colored limestone boulder of Segelskär falls into the Middle/Upper Ordovician.

Ordovician limestone in the drill core of hole No. 4 and observations of algae and acritarchs in it

Borehole 4 is located c. 600 m to the south from hole 6. The samples obtained from hole 4 are from a depth of about 31—56 m consisting of greenish gray limestone with reddish flecks. In a thin section from the depth of 52 m, the coarser groundmass proved to be composed of fossil fragments. A substantial part of the grains varies in diameter from 50 to 100 μ and is thus clearly coarser than the exceedingly fine-grained calcilutite. The opaque mineral and quartz contents are slight.

The prevalence of fossil fragments can also be observed at depths of 31—40 m, where there are few acritarchs as sepia-colored fragments. At depths of 40—56 m, the greenish gray limestone differs from the limestone higher up in that the hematite stains are lacking. In the same zone, the microfossils are generally well preserved and enable one to do a dating of the sedimentary portion.

Girvanella occurrences

Known for producing a certain type of stromatolite, the *Girvanella* alga is a combination of tiny tabular cells forming successive arches. *Girvanella* (Nicholson & Etheridge) composes a dendritic microfabric, the predominantly vertical growing unit of which has achieved a thickness of at least 5 cm (Ahr 1971).

In hole No. 4, at a depth of 47.30—48.30, the concentrated residue treated with HCl solution is found to contain algae consisting of three differend *Girvanella* species.

The most prevalent *Girvanella* species from the Lumparn very closely resembles *G. problematica* var. *lumbricalis* described by Johnson (1966) from the Welsh Borderland. The cell diameter is c. 15 μ, and the length up to ten times greater. Besites elongated cells, spherical forms are observed likely to corresponding to cross sections of the cells. (Table XVIII: 150).

Girvanella problematica is actually typical of Silurian and Ordovician limestone, but it also is present in, for instance, Devonian deposits (Faber 1980). The genus dates, according to Arnold (1969), from the Late Cambrian to the Jurassic period.

Girvanella pusilla Johnson 1966

A *Girvanella* species noticeably smaller than the foregoing. Diameter of tubes c. 4 μ, cells fairly long (and loosely coiled). Occurs at a depth of 47.30—48.30 m as a rarity on the surface of *Dasycladaceae* alga.

The species has previously been described in Woolhope and Wenlock limestone (Johnson 1966) as well as in Silurian biomicrites from the Oslo area (Lauritzen & Worsley 1974).

A rare type consists of a ring-shaped cell colony. The diameter of each semicircular cell is c. 7 μ and the length roughly three or four times that (Plate XVIII: 151). The name *Girvanella rotaeformis* n. sp. is suggested for this type.

Discussion: The type designated as *Girvanella* is known from the 1.3 Gy old Precambrian Kingston Peak formation located in eastern California (Pierce and Cloud 1978). More certain occurrences date from the Early Cambrian (Johnson 1966). Known from Gotland are algal limestones dating back to the Wenlockian and Ludlovian periods, containing fossils of the *Girvanella* genus. They have been described by Hadding (1959), who has interpreted the deposition to have taken place in shallow water. Lauritzen and Worsley (1974) have reported on the *Girvanella prob-*

lematica var. *lumbricalis* form among the biomicrites of the Lower Llandoverian period from the Oslo region. These researchers likewise interpret the water depth during sedimentation depth to have been slight, less than 60 m. According to Playford *et al.* (1976), *Girvanella* is one of the algae belonging to the fore-reef and inter-reef facies, occurring posssibly in depths exceeding 100 m.

Girvanella algae have been observed to promote the sedimentation of ferric oxide on its surface. This, again, possibly happened through the influence of iron bacteria closely associated with the algae (Playford *et al.* 1976). Thus the ferric oxide in the limestone of Lumparn could likewise have been precipitated by bacteria, a process that might also have involved the acritarchs and caused their partial destruction.

Acritarch observations

At the depth zone of 31.28 to 40.80 m, in core No. 4 the acritarchs are weathered to the extent of hampering identification of species. At depths of 40.80 to 61.67 m, the acritarchs are, however rather well preserved. At this level, variations can be observed in the occurrence of different species, although for the most part they comprise common acanthomorphs typical of the Ordovician. In the main, they are the same forms that Eisenack (1931, 1951, 1958, 1962, 1965) has described from limestone strata in Estonia and erratics in Germany, Sweden and Finland. Kjellström (1971 a, b) as well as boreholes on Gotland and also from Östergötland (1976). The present author has previously described the same types in boulders from the bottom of the Bothnian Sea (Tynni 1975). Further, the similarity of the forms in Ordovician limestone in Poland to the types found in the Baltic region and the Åland Islands is closer (Górka 1969, 1979) than to the species present in the deposits of western Europe. In addition, among the samples taken from borehole No. 4 there were found a number of forms not previously reported from Fennoskandia.

The acritarch genera observed of depths between 40.80 and 61.67 m are represented in the form of a diagram in Fig. 23. A limited but clearly defined *Tranvikium polygonale* occurrence is found at the depth of 49.34 to 55.37.

The *Leiovalia similis* type occurs at the depth of 48.3 to 49.34. *Veryhachium triangulatum* occurs in the 53.0—55.37 m zone. *Peteinosphaeridium trifurcatum* is comparatively rare. This form, membranes around the appendages, is concentrated at a depth of approximately 50 to 51 m.

Certain *Baltisphaeridium* species (B. *longispinosum, B. brevispinosum*), *Goniosphaedium mochtiensis, Veryhachium trispinosum* a. o. occur in a rather wide depth range. Their significance in the matter of dating is slighter.

The following concise description of acritarchs refers to observations made on samples prepared from drill core No. 4 in Lumparn south of the Tranvik peninsula.

Acanthodiacrodium sp. Fig. 18 a, Plate XVIII: 148

DIMENSIONS: Length of central body c. 40 μ, length of processes 15—20 μ, conical in shape and numbering 4—6 at the ends.
OCCURRENCE: Only one observation at a depth of 60.0—61.67 m.

The genus *Actinotodissus* described by Loeblich & Tappan (1978) from Middle and Upper Ordovician deposits in Midwestern North America resembles *Acanthodiacrodium* Timofeev 1958, but differs in that *Actinotodissus* possesses many long processes at opposite ends communicating freely with the vesicle interior.

Actinotodissus baltica n. sp. Plate III: 1—3

HOLOTYPE: GSF prep. no. 32, Plate III: 2.

TYPE LOCALITY AND TYPE STRATUM: Lumparn, drill core no. 4. Some ten individuals at a depth of 61.0—61.7 m. Lower Ordovician.

DERIVATION OF NAME: after Baltic area.

DIAGNOSIS: The vesicle is roundishly oval, 75 μ long and 55 μ wide. The spines are curved and turned from the central area toward each end; they are more numerous at the ends than in the zone between, altogether amounting to about 20. Length 30—50 μ, width at the base part 3—4 μ. In the middle part occurs a thin duct broken off at each end. Distinguishable on the surface of the spines are tiny nodules. The surface of the vesicle is shagrinate.

REMARKS: In the type included in the Lumparn material, the processes appear to be separated from the vesicle interior in spite of its rather broad base. Two-sidedness has not developed distinctly, and it constitutes an intermediary form between *Baltisphaeridium* and the clear-cut diacrodium type.

Aremoricanium Deunff 1955

Surrounding the spherical, rather thick inner vesicle is a thin, smooth vesicle, which has become enlarged at one end, taking a cylindrical or conical shape. Processes are present in the spherical portion.

Aremoricanium sp. Plate III: 4

DIAGNOSIS: The shell is evidently thin, and neither the ectoderm or the endoderm can be clearly distinguished. The enlargement is not cylindrical, for it tapers conically, like *A. rigaudea* Deunff. The species differs, however, from the latter, being smaller and possessing shorter spines. The inner vesicle is c. 25 μ in diameter, the outer one c. 30 μ, and the length of the spines is about 10 μ.

OCCURRENCE: It is an extremely rare occurrence at the depth of 51 m.

Baltisphaeridium anneliae Kjellström 1976

DESCRIPTION: Diameter of vesicle c. 60 μ. Characteristic are densely situated echinate processes, with a length of about one-half the diameter of the vesicle. Plate III: 5.

OCCURRENCE: Observations made at the depth of about 51 m.

Earlier observations reported from the limestone of Folkeslunda and Furudal (Kjellström 1976), the Middle Ordovician deposit of Odinsholm in Estonia and the drilling at Olszty in Poland (Górka 1979).

Baltisphaeridium brevifilicum Kjellström 1971

DESCRIPTION: Diameter of vesicle in Tranvik material c. 50 μ, smaller than in holotype (cf. Kjellström 1971, Górka 1979). Characteristic features, are the thin processes with sharp tips and the shagrinate surface of the vesicle. Plate III: 6.

OCCURRENCE: Observations at depths of 51—53 m.

Earlier observations reported from Middle Ordovician deposits at Grötlingbo (Kjellström 1971) and from the IG 2 drilling at Olszty (Górka 1979).

Baltisphaeridium brevispinosum (Eisenack 1931) Eisenack 1958

Synonym: *Ovum hispidum brevispinosum* Eis.

DESCRIPTION: Diameter of vesicle c. 50 μ, length of processes 14—18 μ (Kjellström 1976), as much as half the diameter of the

vesicle (Eisenack *et al.* 1973). Characteristic features are processes with wide base and rounded distal end, which in some instances tends to be forked. Plate III: 7.

OCCURRENCE: Fairly commonly present in lower limestone strata at the depth of 54 to 61.64.

Earlier observations from Lower and Middle Ordovician deposits and corresponding erratics. Mostly, the observations point to a Lower Ordovician age (Eisenack *et al.* 1973).

Baltisphaeridium brevituberculatum Kjellström 1971 b

DESCRIPTION: Diameter of vesicle c. 55 μ. Processes are short and cylindrical. Plate III: 8.

OCCURRENCE: Rare occurrence at depth of 50.20—50.80 m. Reported previously from Lower Viruan deposits in Gotland and Öland (Kjellström 1971 b, 1976).

Baltisphaeridium bulbosum Kjellström 1971 a

DESCRIPTION: Diameter of vesicle and length of processes c. 60 μ. Ends of processes are rounded. Plate IV: I, Plate VIII: 35.

OCCURRENCE: Rarely met with at depth of 49.70—50.20 m.

The holotype has been described from Middle Ordovician strata in the Grötlingbo borehole on Gotland.

Baltisphaeridium calicispinae Górka 1969

DESCRIPTION: Diameter of vesicle c. 60 μ, processes shorter than diameter and numbering 6 to 17. Tiny prickles on surface. Plate IV: 10, Plate VIII: 36.

OCCURRENCE: Rare occurrence at depth of 51 m.

Reported previously from Polish Upper Arenigian and Caradocian material (Górka 1969) as well as from the Middle Ordovician material of Gotland, Öland and Östergötland (Kjellström 1976).

Baltisphaeridium constrictum Kjellström 1971 a

DESCRIPTION: Diameter of vesicle 75 μ, surface granulated. Processes broad but slightly contracted at base. Numbering 7 to 8, evenly spaced. Length c. 90 μ, broadest portion 20 μ. Tiny grains on surface. Resembles *B. lancettispinae* Górka and *B. latiradiatum* (Eis.) types, which, however, are smoother. Plate IV: 11, 12.

OCCURRENCE: Rare at the depth of, for example, 50.80—51.34.

Reported previously from Lower Viruan deposits on Gotland and Öland (Kjellström 1971 a, 1976).

Baltisphaeridium aff. *eisenackianum* (Deunff 1958) Downie & Sarjeant 1963

DESCRIPTION: Diameter of vesicle 55 μ, processes (four in number, some detached), curved, 40—60 μ long, 4 μ in diameter in the main portion. Vesicle and spines granulated. Lacerated, but fairly thick-shelled and dark reddish brown. Plate IV: 13.

REMARKS: The form closely resembles that described by Deunff, though the number of processes is smaller. According to Deunff, the hollow processes are connected with the interior of the vesicle. According to the terminology developed by Kjellström (1971), the species would in this case belong to the genus *Goniosphaeridium*. In the Lumparn material, it cannot be seen whether the inner portion of the hollow process is connected with the inside of the vesicle or is separated from it,

for the thickness of the shell and the granularity of the point of attachment limits the visibility.

OCCURRENCE: A rare form at the depth of 42.31 to 45.34 m.

Most of the information on the distribution of the form points to the Upper Ordovician (Deunff 1958, Henry 1966, Konzalová-Mazancová 1969, Moreau-Benoit 1971, Lister, Cocks & Rushton 1969, Vavrdová 1965). It has also been observed in the Llandvirnian deposit of Roche-au-Marle (Paris & Deunff 1970).

Baltisphaeridium filosum Kjellström 1971

DESCRIPTION: Diameter of vesicle c. 60 μ, processe thin and stringy (filiformis), c. 30 μ long, numerous. Plate IV: 14.

OCCURRENCE: Fairly common at the depth of 51 m.

Previously reported from Middle Ordovician strata on Gotland and in Olszty (Kjellström 1971 a, Górka 1979).

Baltisphaeridium hamatum (Downie 1958) Kjellström 1976

Synonym: *B. hirsutoides* var. *hamatum* Downie (Downie & Sarjeant 1964).

DESCRIPTION: Diameter of vesicle 34—40 μ, length of processes c. 5 μ. Plate IV: 15.

OCCURRENCE: The form met with at the depth of 53 to 54 m.

Previously reported from the Tremadoc deposit in England and the Lower Viruan deposit in Östergötland (Kjellström 1976).

Baltisphaeridium hirsutoides (Eisenack 1951) Eisenack 1959

DESCRIPTION: Diameter of vesicle c. 50—60 μ, length of processes (about 20) c. 25 μ, sharp tips. Surface smooth. Plate IV: 6.

OCCURRENCE: It is a common species, especially in the lower partion of the deposit containing acritarchs in the Lumparn material.

Earlier observations reported from many Lower and Middle Ordovician deposits.

Baltisphaeridium ingerae Kjellström 1976

DESCRIPTION: Diameter of vesicle c. 50 μ, surface granular. Numerous processes, length about 15 μ, width 1 μ, with spines covering surface. Species differs from *B. anneliae* mainly in the respect that the latter's vesicle has a smooth surface. Plate V: 17.

OCCURRENCE: Form rarely met with at depth of 42.31 to 45.34.

Previously, the species has been observed to occur in connection with the Lower Viruan stage of Östergötland (Kjellström 1976) and the Uhakuan stage of Odinsholm, in Estonia (Bockelie & Kjellström 1979), both of which stages belong to the Middle Ordovician.

Baltisphaeridium lancettispinae Górka 1969

DESCRIPTION: Diameter of vesicle is c. 60 μ, processes c. 60 μ in length, 5—12 in number, and c. 10—15 μ in width. Processes lack distinct spines, which separates the form from certain other closely related species. Cf., *B. trophirhapium* Loeblich & Tappan 1978, Plate V: 18, 19.

OCCURRENCE: Rarely met with at depths of 46.34—47.30 m and 51 m.

Previous observations reported from Polish Middle Ordovician strata (Caradoc) (Górka 1979) and Ordovician material from the Bothnian Sea (Tynni 1975).

Baltisphaeridium latiradiatum (Eisenack 1959) Staplin, Jansonius & Pocock 1965

DESCRIPTION: Diameter of vesicle c. 70 μ, processes (c. 80 μ long) broad and thin with-

out clear-cut surface structure. Slightly contracted at base. Plate V: 20.

OCCURRENCE: Rare, at depth of 51 m.

Previous observations reported from Lower and Middle Ordovician deposits.

Baltisphaeridium longispinosum (Eisenack 1931)

Synonym: *B. longispinosum* (Eis.) subsp. *longispinosum* Staplin, Jansonius & Pocock 1965; Górka 1969

DESCRIPTION: Diameter of vesicle c. 50—55 μ, length of processes 70—90 μ. Surface of vesicle is shagrinate, and that of processes is smooth. Common form at depth of 40.8 to 61.67 m. Plate V: 21.

OCCURRENCE: Previous observations reported from many Middle and Lower Ordovician deposits.

Baltisphaeridium microspinosum (Eisenack 1954) Downie 1959

DESCRIPTION: Diameter of vesicle c. 60 μ, length of processes 6 μ, spaced 7 μ apart. Surface of vesicle is shagrinate. Plate V: 22.

OCCURRENCE: Rare, occurs at depth of 51 m. Previous observations reported from Lower Silurian to Middle Ordovician.

Baltisphaeridium multipilosum (Eisenack 1931) var. *minor* n. var.

HOLOTYPE: GSF, prep. 113, Plate VI: 23.

TYPE LOCALITY AND TYPE STRATUM: Lumparn, drill core No. 4 at a depth of 53—54 m., Middle Ordovician.

DERIVATION OF NAME: a small form, resembling *B. multipilosum.*

DIAGNOSIS: Diameter of vesicle on the average 35 μ. Numerous, densely situated thin spines. Length c. 5 μ. Plate VI: 23.

Occurrence: Rare occurrence.

Baltisphaeridium nanninium Eisenack 1965

DESCRIPTION: Diameter of vesicle 60—65 μ; length of processes c. 4 μ, thin and faintly distinguishable. Plate VI: 24.

OCCURRENCE: Observed at, e.g., the depth of 48.30—49.34 m, as a rarity.

Previous observations reported from Silurian and Middle Ordovician deposits.

Baltisphaeridium oligopsakium Loeblich & Tappan 1978

DESCRIPTION: Diameter of vesicle c. 60 μ, with an angular to subangular outline. Number of processes in holotype 34. Their length does not exceed the diameter of the vesicle. The processes are rarely bifurcate. The species resembles *B. calicispinae* Górka, 1969, but it possesses a larger number of processes and a different kind of surface structure. *B. oligopsakium* has sparse grana on the processes. Plate VI: 25, VII: 34.

OCCURRENCE: This species occurs sparsely at depths of 51 and 53—54 m. Previously, the species has been reported from shales in Sylva, Oklahoma, its dating corresponding in the European classification to the Ashgillian or in the local Estonian system to the Harjuan stage.

Baltisphaeridium psilatum Kjellström 1971 a

DESCRIPTION: Diameter of vesicle c. 50 μ, length of processes c. 10 μ, spaced about 13 μ apart. Species resembles *B. hirsutoides,* but it has more processes, which are broader in the base than those of the *hirsutoides* species. Plate VI: 26, VIII: 39.

OCCURRENCE: Sparse occurrence at 61—61.67 m. Previously, the species has been reported from the Middle Ordovician on Gotland.

Baltisphaeridium pustulatum
Kjellström 1971 b

DESCRIPTION: Diameter of verrucated central vesicle c. 60 μ. Length of processes shorter than diameter. Shell thin and single-layered. Plate VII: 33.

OCCURRENCE: Rare, at a depth of c. 51 m. Described previously from Folgeslunda — Lower Uhaku beds, Middle Ordovician, on Gotland (Kjellström).

Baltisphaeridium regnellii Kjellström 1971 b var. *densespinosum* n. var. Plate VI: 27

HOLOTYPE: GSF prep. no. 71, plate VI: 27.

DIAGNOSIS: Diameter of vesicle c. 50—60 μ. Processes short, about 4 μ, tip sharp. The processes stand out as pale, smooth protuberances from the rough surface of the vesicle. It bears a resemblance to *B. regnellii* Kj. 1971, which is characterized by short processes on circular psilate areas — but in the Lumparn form, the density of the spines is greater. The species is also closely related to *B. tranvikensis*.

OCCURRENCE: Rarity at depths of 45.34—46.34 and 47.30—48.30.

B. regnellii has been observed at the depth of 46.34 to 47.30. It was first reported from the Middle Ordovician (Lower Viruan) on Gotland.

Baltisphaeridium simplex
Deunff (1961) 1964

Synonym: *Priscogalea simplex* D., non *Baltisph. simplex* Stockman & Williere 1963

DESCRIPTION: Diameter of vesicle 20—40 μ, surface smooth, diameter of aperture 35 μ. Plate VII: 28.

OCCURRENCE: A few occurrences at 61.0—61.67 m.

The species has previously been reported from deposits in Sahara, and Belgian Tremadoc (Deunff 1961, Vanquestaine 1967). *B. simplex* (Timofeev 1959) reported by Fournier—Vinas (1978) from a Middle Cambrian deposit in Montagne Moir bears a resemblance to Deunff's form, but it is somewhat larger.

Baltisphaeridium spinigerum Górka 1969

DESCRIPTION: Diameter of vesicle c. 60 μ. Length of processes (numbering 15—20), approximately 25—60 μ, spiny on surface. Plate VII: 29.

OCCURRENCE: Sparsely present in core no. 4 at depths of 42.31—45.34 and 51 m.

Previously reported from Ordovician erratic boulders in Poland (Górka 1969) and the bottom of the Bothnian Sea (Tynni 1975).

Baltisphaeridium tranvikensis n. sp.

HOLOTYPE: GSF prep. no. 70, plate VII: 30.

DIAGNOSIS: Diameter of vesicle c. 50 μ, dense growth of processes, spaced at intervals of 5 μ. Length of processes 5—7 μ, with diameter of their base 1.5—3 μ, distal end sharp. On surface of vesicle dense granularity with small patterning, against which the main portions of the processes stand out conspicuously as light and nearly smooth circles and cones. Interior of processes probably separated from interior of vesicle. Structurally, species resembles *B. regnellii* Kjellström, but the processes on the Lumparn form are longer and the surface structur of the vesicle rougher.

OCCURRENCE: Met with as rare occurrence at depth of 42.3—45.34.

Baltisphaeridium verrucatum Kjellström 1971

DESCRIPTION: Diameter of vesicle and length of processes c. 60 μ. On the surface of the vesicle and the processes, there is a structure composed of tiny nodules. Shell is double walled.

OCCURRENCE: Sparse occurrence at depth of 46.34—47.30 m.

Species has previously been reported from, e.g. the Middle Ordovician on Gotland (Kjellström 1971 a), material from the bottom of the Bothnian Sea (Tynni 1975) and the Middle Ordovician at Olsztyn, Poland (Górka 1979).

Buedingiisphaeridium Schaarschmidt 1963, Staplin *et al.* 1965, Lister 1970

The vesicle has berrucae or conical, short, hollow tubercles. The tubercules of the genus *Lophosphaeridium,* which resembles the form in question, are solid.

Buedingiisphaeridium sp. Plate XI: 72

DESCRIPTION: Diameter of vesicle averages 35 μ. On the surface are densely grown, tiny, pyramidal tubercles with sharp tips. The species resembles *B. pyramidale* Lister 1970, which has been described from an Upper Silurian deposit.

OCCURRENCE: Only one specimen identified at a depth of about 50 m.

Cymatiosphaera (Wetzel 1933) Deflandre 1954

Spherical or ellipsoidal vesicle, the outer surface of which is divided into polygonal patterns by vertical membranous folds. Comp., *Tranvikea* n. genus.

Cymatiosphaera aff. *canadensis* Deunff 1954

DESCRIPTION: Total diameter c. 55 μ, polygons fairly straight (diam. c. 30 μ), pentagonal, clearly distinguishable. Surface smooth.

OCCURRENCE: A few occurrences at 43.0—54.0 m. Plate IX: 41.

Previously, the type has been reported from Devonian layers (Deunff) as well as from Upper Tremadocian outcrop at Zbilutka, Poland (Górka 1969).

Dasydiacrodium Timofeev 1959 emend. by Deflandre & Deflandre-Rigaud 1962

Dasydiacrodium sp. Fig. 18 b, Plate XVIII: 149

DIAGNOSIS: Vesicle comparatively square, c. 45 μ long. Processes more numerous at one end (7). The few (4) processes in the opposite end are larger and wider spaced. In the intermediary zone there are also processes at sparse intervals.

OCCURRENCE: Only a single observation at a depth of 61.0—61.67 m.

Florisphaeridium Lister 1970

Processes of spherical or elliptical vesicle are broad-based, hollow, rosette-like; distally, process wall invaginated, opening into vesicle cavity. Distribution of processes apt to be irregular, and their size to vary in the same individual.

Florisphaeridium sp. Plate XVIII: 145, 146

DIAGNOSIS: Vesicle is triangular, length of side being c. 35 μ. At angles are conical processes, covered with nodules. The triangular form strikingly resembles the larger *Florisphaeridium lavidensis* Cramer & Diéz 1976 species (Eisenack *et al.* 1976).

OCCURRENCE: Met with as rare occurrence at depths of 50.20—50.84 and 53—54 m.

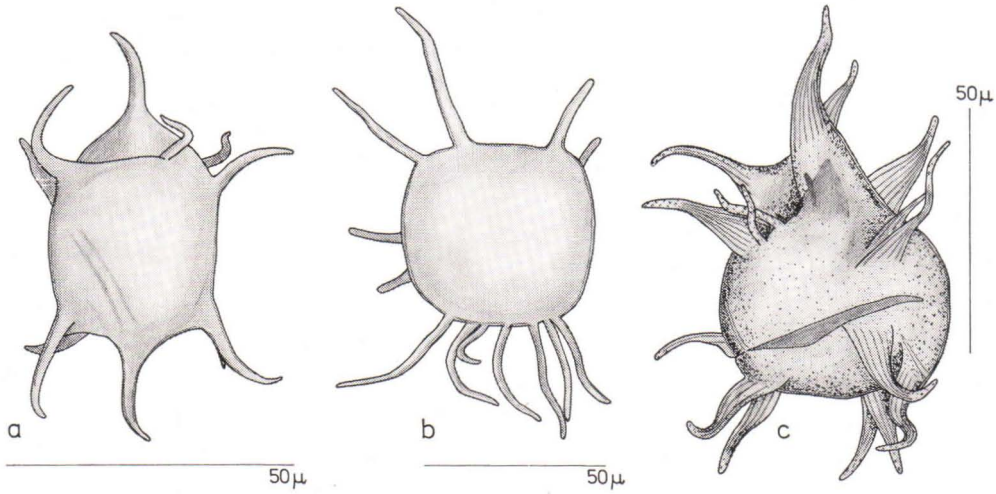


Fig. 18. Acritarch types found in borehole 4 at Tranvik: a. *Acanthodiacrodium* sp., b. *Dasydiacrodium* sp., c. *Tectitheca complicata*.

Goniosphaeridium (Eisenack 1969) Kjellström 1971

Diameter of spherical or polygonal vesicle is > 20 μ. On the inside, processes are connected with central vesicle; closed at ends, uniform. Surface smooth, rough or covered with tiny spicules.

Goniosphaeridium christianii Kjellström 1976

DESCRIPTION: Largish form, with diameter of vesicle measuring about 65—75 μ; length of processes 25—40 μ, numbering about 29. Color dark brown. Surface rough. Plate IX: 45.

Discussion: Species is closely related to *G. macrosphaericum* Eisenack 1970 and *G. mochtiensis*. Processes of *G. christianii* are relatively shorter than those of the species *G. mochtiensis* but longer than those of *G. macrosphaericum*. The surface structure also differs in these species. *B. brevispinosum* likewise resembles the *G. christianii* species, except that its processes are shorter and different in type.

OCCURRENCE: The species occurs as a rarity only at the depth of 51.34—52 m.

Previously reported from the Ekö drillcore sample taken from the Middle Ordovician deposit in Östergötland (Kjellström 1976), the stratum representing the Uhakua stage in Estonia (Bockelie & Kjellström 1979) and the Middle Ordovician of Olszty (Górka 1979).

Goniosphaeridium mochtiensis (Górka 1969) Kjellström 1971

DESCRIPTION: Diameter of vesicle c. 60—70 μ; length of processes c. 30—60 μ, of which one or more are apt to be bifurcated. Number 12—20. Shell thick, color dark brown. Plate IX: 46.

OCCURRENCE: Common occurrence in 51—56 m depth zone.

Previously reported from Ordovician boulders in Poland and drilling at Olszty (Górka 1969, 1979) as well as Grötlingbo drilling (Kjellström 1971).

Goniosphaeridium peregrina n. sp.
Plate IX: 47

DIAGNOSIS: One tattered individual was met with in large vesicle estimated to be 160 μ in diameter. Conically tapering little processes, 5—10 μ long, with rounded ends. Its interior is connected with interior of vesicle. Processes spaced about 10 μ apart. Surface fairly smooth, but on the surface of the processes, streaks running lengthwise can be distinguished.

OCCURRENCE: At the depth of 61.0—61.67 m, very rare.

REMARKS: The species resembles *Baltisphaeridium brevispinosum castaneoides* (Sannemann 1955). Clearly distinguishable in the Lumparn form is the direct connection between the interior of the vesicle and that of the processes, and the species thus falls into a relationship with *Goniosphaeridium.*

Gonisphaeridium polygonale (Eisenack 1931) ssp. *conjunctum* (Kjellström 1976) n. comp.

DESCRIPTION: Diameter of rounded vesicle c. 30—35 μ, with processes of similar length. Many of them are curved. Plate X: 48.

OCCURRENCE: Observed from five samples in the 42.31—55.37 depth zone. Previously observed in Lower Viruan deposits in Sweden (Kjellström 1976).

Goniosphaeridium polygonale (Eisenack 1931) ssp. *pellicidium* (Timofeev 1959) n. comp.

DESCRIPTION: Diameter of vesicle averages 40 μ, length of processes 30 μ. Processes form a starlike pattern; number of projecting corners in the equatorial zone is c. 10. They are smooth, except at the very tip, which has tiny spicules. Cf., Eisenack 1931, Taf. 4: 18. Plate X: 49.

OCCURRENCE: Rarely seen form at depth of 54.0—55.37 m.

Occurrences previously described from Lower Ordovician deposit at Vologda (Timofeev 1959) and Ordovician material taken from the bottom of the Bothnian Sea (Tynni 1975).

Goniosphaeridium polygonale ssp *polyacantha* Eisenack 1968 n. comp.

DESCRIPTION: Diameter as much as 220 μ Processes relatively long and densely situated, with tiny prickles. In the Lumparn material there are smallish forms with a total diameter of 85 μ. Plate X: 51.

OCCURRENCE: At depth of 53—54 m, rarely observed.

Previously observed in, among other places, Ordivician limestone boulder (F2) (Eisenack 1968).

Goniosphaeridium polygonale ssp. *uncinatum* (Downie 1958) n. comp.

Synonym: *Goniosphaeridium uncinatum* (Martin) Kjellström 1971 b

DESCRIPTION: Spherical-polygonal vesicle averages 30 μ in diameter; length of curved processes c. 30 μ. Their number, according to Bockelie & Kjellström 1979, about 15. Echinate surface conspicuous. Plate X: 52.

OCCURRENCE The form observed to be present in the majority of the samples from levels containing acritarchs.

Previously reporterd from Ordovician deposits in England (Downie 1958), Belgium (Martin 1965, 1968), Gotland (Kjellström 1971 b), Estonia (Bockelie & Kjellström 1979) as well as the Silurian in Spain (Cramer 1970).

REMARKS: In the classification of Eisenack *et al.* (1976), the category of *Goniosphaeridium polygonale* includes a diversity of types, ranging from tetrahedral to multiradial. In Eisenack *et al.* (1973), the diameter of the

vesicle was reported to be as large as 350 μ, while in 1976 an individual is listed with an overall diameter of 80 μ, it being stressed that the difference in size has no special significance. Thus also *G. conjunctum* is given as a synonym for the species, and morphologically it is comparable to the form identified as Eisenack 1931 Pl. 4: 19. Missing from the Finnish material are the large *polygonale* forms. A more detailed classification has been adapted in the present work, because differences in size might be of signify a difference in age. This is suggested by the fact that the various forms do not always occur in the same connections. On the other hand, certain *Goniosphaeridium* forms are hard to distinguish from multi-angular *Veryhachium* or *Stellinium* species.

Goniosphaeridium pungens
(Timofeev 1959) Rauscher 1974

DESCRIPTION: Diameter of vesicle c. 25—40 μ, spines tapering from the lower portion to the tip; length 10 μ; number 12; majority located near the rim. Surface smooth. Plate X: 53.

OCCURRENCE: At depths of 61.0—61.67 m rare.

Leiofusa (Eisenack 1938) 1965, restricted; emend. Combaz, Lange & Pansart 1967 and Cramer 1970

Spindle formed vesicle, the ends of which taper into simple processes. Length of processes varies from less than 1/10 to more than 5 times the length of the vesicle. Vesicle wall simple with smooth or microgranulated surface, in which case the sculptural elements are not grouped in lengthwise rows. Longitudinal axis straight.

Leiofusa granulacutis Loeblich 1970

DESCRIPTION: Ellipsoidal vesicle, at the apical ends of which are two processes. Surface slightly granulated. Total length c. 80 μ. Plate X: 55.

OCCURRENCE: Only one observation at depth of 53.0—54.0 m.

Reported previously from Middle Silurian Maplewood Shale in Rochester, New York (Loeblich 1970).

Leiofusa sp.

DESCRIPTION: Length 80—115 μ, maximum width 20—25 μ. Ends exceptionally broad. Somewhat deformed. Plate X: 54.

OCCURRENCE: A rare form found at depths of 55.37 to 56 and 61.0 to 61.67 m.

Leiosphaeridia (Eisenack 1958) Downie & Sarjeant 1963

Leiosphaeridia is present throughout the series of strata in which acritarchs occur. No analysis of the various species has been attempted due to the lack of other distinguishing features than the size, which varies between c. 150 and 10 μ. The large (150—70 μ) species are represented by *L. baltica* Eisenack 1958, and it is a fairly common occurrence in the material. The smallest forms are generally provided with a pylom, and they resemble the round *Palaeostomocystis* Deflandre 1937 forms. The form with a pylom bordered by nodules has been tentatively designated as *Leiosphaeridia granulatopylum*. Plate X: 56—58.

Leiovalia Eisenack 1965; emend. Combaz et al. 1967

Oval vesicle without pointed ends. Surface is relatively smooth.

L. similis Eisenack 1965

DESCRIPTION: Oval vesicle, the ends of which are broadly rounded. Length c. 135 μ, breadth 70 μ. Plate XI: 61.

OCCURRENCE: At depth of 48.30—49.34 m, rare occurrence. Reported previously from Baltic limestone on Gotland (Eisenack 1965) and from Ordovician limestone on bottom of the Bothnian Sea (Tynni 1975).

Lophosphaeridium Timofeev 1959, Downie 1963

Type species *Lophosphaeridium rarum* Timofeev. Surface sculpture of vesicle composed of solid tubercules.

Lophosphaeridium citrinipeltatum Cramer & Diéz 1972

DESCRIPTION: Diameter of vesicle c. 55 μ, that is, slightly larger than dimensions reported by Cramer & Diéz: 30—50 μ. Plate XI: 62.

OCCURRENCE: Met with only rarely at depth of 53.0—54.0 m. Species previously reported from certain North American Silurian deposits.

Lophosphaeridium aff. *diplicativum* (Timofeev 1959) Martin 1968

DESCRIPTION: Diameter c. 17 μ; small tubercules with pointed ends, 0.5—1 μ long. Plate XI: 63.

OCCURRENCE: At depths of 46.34—47.30—49.70—50.20 m, rare occurrence. Reported previously from Middle Cambrian and Lower Tremadocian in USSR (Timofeev) as well as Cambrian deposit in Belgium (Martin 1968).

Lophosphaeridium sp. 1

DESCRIPTION: Diameter c. 20 μ; relatively large pylom, diameter c. 13 μ. Tubercules sparsely situated and very small. Plate XI: 64.

OCCURRENCE: Observations from depths of 46.34—47.30 and 49.70—50.20 m.

Lophosphaeridium sp. 2

DESCRIPTION: Diameter c. 20 μ. Small nodules, sparsely scattered (spaced about 5 μ apart). Sepia colored. Y-shaped depression or opening. Plate XI: 65—68.

OCCURRENCE: Rare at depth of 46.34—47.30.

Micrhystridium (Deflandre 1937) Downie & Sarjeant 1963

Genus composed of spherical vesicles less than 20 μ in diameter, on the surface are spines without forks. Differs from *Aranidium* Jankauskas 1975 genus, which has ovate shell. In the fossil material, it is sometimes impossible to differentiate between them.

OCCURRENCE: In the Lumparn occurrence, the share of *Micrhystridia* is in a few samples notable, and therefore the most clearly defined forms are described in the following.

Micrhystridium campoae Stockmans & Williére 1966

DESCRIPTION: Diameter of vesicle c. 10—18 μ, shell fairly thick. Length of spines 4—6 μ, broad base, numerous, spaced c. 4 μ apart. Plate XII: 73, 74.

OCCURRENCE: At depths of 45.34—46.34, 49.70—50.20 m, fairly common.

Reported previously from Ordovician and Silurian deposits (Martin 1968) as well as Devonian layers (Stockmans & Williére 1966).

Micrhystridium nannacanthum
Deflandre 1942

DESCRIPTION: Diameter of vesicle c. 15 μ. Prickles extremely short (1 μ) and relatively dense. Plate XII: 77.

OCCURRENCE: Observed at a depth of 46.34 to 47.30 m.

Previously reported from many Ordovician-Silurian formations, but also from younger ones.

Micrhystridium pseudocoronatum n. sp.
Plate XII: 75, 76

HOLOTYPE: GSF prep. no. 71, plate XII: 75.

DIAGNOSIS: Diameter of vesicle c. 18 μ. Length of spines c. 4 μ, conical and hollow at base but solid at tip. Number of spines in the equatorial zone c. 15. Shell thick and double-walled.

REMARKS: Species resembles *M. coronatum* St. & W. and *M. parinconspicuum* Defl., but differs from these on account of its exceptionally thick vesicle wall.

OCCURRENCE: Observations reported from depths of 45.34—46.70 and 49.70—50.20.

Micrhystridium aff. *stellatum* Deflandre 1942

DESCRIPTION: Diameter of vesicle c. 18 μ, processes rather short, total diameter c. 35 μ. Plate XII: 78.

OCCURRENCE: Rare occurrence at depth of 46.34—47.30 m.

The species has been reported from Paleozoic and even certain Mesozoic deposits of different ages, the reason being, perhaps, that the description of the species has not been sufficiently delineated.

Micrhystridium sp.

DESCRIPTION: Diameter of vesicle c. 20 μ, length of spines about 7 μ, number on equator about 16. Species resembles *G. connectum* Kj., but the processes are shorter and narrower as well as more numerous. Plate XII: 79—81.

OCCURRENCE: Met with as rare occurrence at depth of 42.31—45.34.

Multiplicisphaeridium Staplin 1961, restr.
Staplin, Jansonius & Pocock 1965

Processes covering vesicle are proximately slender but distally furcate, or expanded or otherwise modified. They have closed tips, and only a particular type of process occurs in the same vesicle. According to Eisenack (1969), however, a few of the processes are likely to be unfurcated. The hollow interior of the processes is in open connection with the interior of the vesicle.

Multiplicisphaeridium aff. *alloteaui*
(Deunff 1955)

DESCRIPTION: Diameter of vesicle c. 18 μ, length of spines c. 4 μ. They are furcated at the end into three or two short forks. Plate XII: 82.

OCCURRENCE: Common at the depth of 45.34—47.30 m.

Previously reported from a Devonian deposit in Canada (Deunff 1955), Upper Ordovician deposit in England (Lister, Cocks & Rushton 1969) and the Ordovician limestone from the bottom of the Bothnian Sea (Tynni 1975).

Multiplicisphaeridium bifurcatum
Staplin, Jansonius & Pocock 1965

DESCRIPTION: Diameter of vesicle c. 25 μ, length of processes c. 1/3 the diameter of the vesicle. Number about 20. The ends of the processes are bifurcated into two tips. The

species differs from the *Multiplicisphaeridium bifurcatum* (Thusu 1973) form. Plate XII: 84, 88.

OCCURRENCE: Observations made at the depths of 46.34—47.30, 53—54 m.

Previously reported from the Middle Ordovician stratum in Gotland (Kjellström 1971 a) and the Middle Ordovician in Canada (Staplin et al. 1965).

Multiplicisphaeridium gotlandicum
(Eisenack 1954) Eisenack *et al.* 1973

DESCRIPTION: Diameter of vesicle c. 50 μ. Processes on the surface of the sphere short, densely distributed and bacculate, expanded at the ends. Length of processes c. 5 μ. Plate XII: 87.

OCCURRENCE: Very rare at depth of 46.34—47.30 m.

Previously reported from Lower Silurian in Gotland (Eisenack 1954, 1965), Silurian in Spain (Cramer 1967), and the Silurian of Ontario (Cramer 1970, Cramer & Díez 1972) and Ohio (Cramer & Díez 1972).

Multiplicisphaeridium raspa
(Cramer 1964) Eisenack *et al. 1973*

DESCRIPTION: Diameter of vesicle 15 to 18 μ. The length of the processes c. 7 μ. The processes are bifurcated and branched often of the second to third order. Plate XII: 83, XIX: 159.

OCCURRENCE: Rather common at depth of 52.0 to 54.0 m.

Known to range Middle Ordovician to Lower Devonian (Eisenack *et al.* open cit.)

Multiplicisphaeridium sartbernardense
(Martin) Eisenack *et al.* 1973

Synonyma: *Veryhachium sartbernardense* Martin 1965, *Frankea sartbernardense* (Martin) Burmann 1970

DESCRIPTION: A fragment found at the depth of 52.0—52.5 m probably corresponds to the species described by Martin. It exhibits a triangularly curved vesicle and process, which has become furcated like an anchor into three curved tips. Plate XII: 86.

OCCURRENCE: The species has not been previously reported from the Baltic region, but certainly from many other Ordovician sites younger than the Arenig stage (Dean & Martin 1978, Kalvacheva & Dimitrova 1973).

Multiplicisphaeridium sp. 1.
Plate XII: 88 a, b

DESCRIPTION: Diameter of vesicle c. 23 μ. Numerous small (about 5 μ long) slender processes with bifurcated tips. The tips are oriented nearly radially. In this respect, the type resembles the species *Micrhystridium shinetonensis* Downie 1958.

OCCURRENCE: Observations made at the depth of 52.0—52.5 m.

Multiplicisphaeridium sp. 2

DESCRIPTION: Diameter of vesicle c. 30 μ. The processes have a broad base, narrowing into sharp tips or forking out. Plate XIII: 89.

REMARKS: The species resembles *M. juliae* Cramer 1964, but no spherical swelling of the processes has been noticed.

OCCURRENCE: Extremely rare and only one observation made at a depth of about 54 m.

Navifusa Combaz, Lange & Pansart 1967

Vesicle has the shape of an elongated ellipse or a rod, with rounded ends and without any extremities.

Navifusa aff *tenuis* (Eisenack 1951) Combaz et al. 1967

DESCRIPTION: Narrow ovate vesicle with rounded ends. Length 150—160 μ, width 32—38 μ, i.e., somewhat smaller than type species: 210/50 μ. Plate XIII: 92.

OCCURRENCE: Occurrence at depths of 46.34—47.30, 50.8—51.34 and 53—54 m.

The species has been reported from the Ordovician Vaginata limestone in Estonia (Eisenack 1951).

Navifusa navicula (Eisenack 1951) Combaz *et al.* 1967

DESCRIPTION: Relatively large form. Narrows ovate shape resembling a boat. Length c. 450 μ, breadth c. 110 μ (length of type species 550 μ, breadth 110 μ). Plate XIII: 93.

OCCURRENCE: One observation made at depth of 61.0—61.67 m.

Previously reported from Lower Ordovician glauconite sandstone deposits in Estonia (Eisenack). According to Combaz *et al.* 1967, the occurrence of the species is limited to the Ordovician period.

Orthosphaeridium Eisenack 1968 emend. Kjellström 1971

Vesicle is rectangular. Excystment structure produced along a transversal suture line, median split, which divides vesicle into two parts of nearly equal size. Processes (commonly 4 or 8) generally located near the corners. The interior of the processes are separated from the vesicle cavity.

Orthosphaeridium aff. *octospinosum* Eisenack 1968

DESCRIPTION: Length of vesicle c. 50 μ, breadth 46 μ. Length of processes c. 55 μ.

OCCURRENCE: At depth of 61 m, only one observation.

Species has been reported from Baltic erratics, Upper Ordovician, F_2 (Eisenack 1968).

Peteinosphaeridium Staplin, Jansonius & Pocock 1965, emend. Eisenack 1969

Spherical vesicle is covered with processes, which are closed at their distal ends and furcated into 2 or more furca-tips. Also secondary furca may occur. Processes and furcas may be covered with a sheathlike mantle, or peteino. Certain species have a pylom. The interior of the processes is separate from the interior of the vesicle (Kjellström 1971 a). At the point where a process has become removed, there can be seen on the surface of the vesicle a membrane.

Tappan & Loeblich (1971) have limited the genus *Ordovicidium* to species lacking a pylom and peteino enveloping the processes. In the present work, a more general systematics has been followed.

Peteinosphaeridium breviradiatum (Eisenack 1959, 1969)

DESCRIPTION: As to the diameter of the vesicle, report vary, but according to Eisenack et al. (1973) it is 40—44 μ. The form met with in Lumparn is smaller (f. *minor*); 36 μ. In type, it corresponds to the main form: exceedingly short processes forking at the ends into three tiny points. Plate XIII: 94.

OCCURRENCE: Only one observation at the depth of 51 m.

Larger forms have been met with in erratics of Ordovician rocks (Eisenack 1938, 1959, 1965, 1968, 1969) and in Middle Ordovician material (Górka 1969, Kjellström 1971 b).

Peteinosphaeridium elegantulum (Tappan & Loeblich 1971) Eisenack et al. 1976

DESCRIPTION: The species resembles *P. nudum* but differs from it because of its larger processes. The processes are microgranulated. Plate XIII: 95.

OCCURRENCE: A rare occurrence at 51 m.

Reported previously from the Middle Ordovician in Oklahoma (*Ordovicidium elegantulum,* Tappan & Loeblich 1971).

Peteinosphaeridium heteromorphicum Kjellström 1971

DESCRIPTION: Diameter of the Lumparn form c. 45 μ, length of processes c. 10 μ. The ends of the processes are generally divided into two asymmetrical points; some processes are not forked. Plate XIV: 97, 98.

OCCURRENCE: Rare occurrence at the depth of 53 m.

Reported previously from the Middle Ordovician on Gotland.

Peteinosphaeridium heteromorphicum subsp. *granulataspinosa* n. ssp.

HOLOTYPE: GSF prep. no. 72, plate XIII: 96.

DIAGNOSIS: Diameter of vesicle c. 65 μ, thickness of wall c. 2 μ, length of processes c. 20 μ. Diameter at the base 4 μ, generally bifurcated· Forks in many cases irregular and imperfect. It resembles *P. heteromorphicum,* and it can be classified as a subspecies of it. The most characteristic feature is the distinct granularity of the processes except for part near the base, which is smooth. The granules form lengthwise rows.

REMARKS: Cf., *Ordovicidium elegantulum* Tappan & Loeblich 1971: both the vesicle and the processes are microgranulated.

OCCURRENCE: A rare occurrence at depths of 46.34—47.30 and 51 m.

Peteinosphaeridium aff. *hystrichoreticulatum* (Eisenack 1938) Eisenack *et al.* 1973

DESCRIPTION: Detailed features appear so faintly as to make identification uncertain. Diameter c. 27 μ. Processes are delicate, sinuous, dense, length c. 5 μ. Plate XV: 107, 108.

OCCURRENCE: Rare at the depth of 53.0—54.0 m. Previously reported from Ordovician limestone in the Baltic region.

Peteinsosphaeridium macropylum (Eisenack 1959) f. *coronata* n. fo.

HOLOTYPE: GSF prep. no. 298, plate XIV: 100.

DIAGNOSIS: Diameter of vesicle c. 70 μ, length of processes 7—10 μ, trifurcated, length c. 3 μ. Double ringed pylom border, diameter of outer ring c. 27 μ.

OCCURRENCE: Only one observation in Ordovician boulder at Segelskär.

Peteinosphaeridium majorfurcatum Kjellström 1971

DIMENSIONS: Diameter of vesicle c. 50 μ, length of processes c. 15 μ, ends bifurcate. Length of forks 6—8 μ. Space separating processes c. 10 μ. Plate XIV: 99.

OCCURRENCE: A few individuals met with at the depth of 51 m.

Previously the species has been reported from the Middle Ordovician on Gotland.

Peteinosphaeridium nudum Eisenack (1959) 1969

DESCRIPTION: Diameter of vesicle c. 50—60 μ: length of processes c. 7—20 μ. A notable proportion of the processes are trifurcate. In addition, there are short secondary tips. Plate XIV: 101, 102.

REMARKS: Closely related species in the Lumparn material are *P. heteromorphicum* and *P. majorfurcatum,* the ends of the processes of which are predominantly bifurcate.

OCCURRENCE: Observations at depths of 46.34—47.30, 48.30—49.34 and 51 m.

Common form in European Middle Ordovician. According to Eisenack (1969), it occurs in Ordovician stages C_1 (Revaler), C_2 (Kucker), D_2 (Kegel) and F_1 (Baltic limestone).

Peteinosphaeridium polyfurcatum n. sp.

HOLOTYPE: GSF prep. no. 13, plate XIV: 103.

DIAGNOSIS: Diameter of vesicle c. 55 μ, length of process c. 15 μ. Numbers of forks 4—6, length of forks c. 7 μ. Processes covered with peteino. Number of processes 13—15.

OCCURRENCE: Exceedingly rare at depth of 51 m.

Peteinosphaeridium trifurcatum
Eisenack (1931) 1969

Synonym: *Peteinosphaeridium bergströmii* Staplin, Jansonius & Pocock 1965

DESCRIPTION: Diameter of vesicle c. 40—60 μ, length of processes 15—20 μ, for the most part trifurcated. Peteino envelopes processes. Plate XIV: 104.

OCCURRENCE: Observations at depth of 50—51 m.

Common species from Middle Ordovician rocks, but observations have been made even from glauconite limestone (B_2) (Eisenack 1969).

P. trifurcatum ssp. *cylindroferum*
Eisenack (1968) Eisenack *et al.* 1973

DESCRIPTION: Diameter of vesicle c. 55 μ, length of process 15 μ, number of forks 3—4, length of forks c. 5 μ. Peteino envelopes the processes. Plate XIV: 105.

OCCURRENCE: Exceedingly rare at depth of 51 m.

P. trifurcatum ssp. *hypertrophicum*
Eisenack 1976

DESCRIPTION: With relatively long processes with forks of primary and secondary order, is covered with peteino. The forks form angles of 30—60°. Plate XIV: 106.

OCCURRENCE: A few observations have been made at the depth of 51 m.

A subspecies has been previously reported from the Vaginatum-Limestone of Hälludden, Öland, (Kunda) (Eisenack 1976) and the Llandvirn stage IG 2 drilling at Olszty, Poland (Górka 1979).

Pterospermella Eisenack 1972

The central body is circular. In the equatorial zone, the body rimmed by transparent membrane. Marginal portion secured by swellings, which in some cases project radially from the base of the rim.

Pterospermella tranvikensis n. sp.
Plate IX: 44, XX: 167

HOLOTYPE: GSF prep. no. 370/SEM, Plate XX: 167.

DIAGNOSIS: Diameter 90 μ, body 50 μ. Form is like a rounded. Rim veily and densely provided (c. 8/10 μ) with radial veins, which are also fairly delicate.

REMARKS: Form resembles certain *Duvernaysphaera* (Staplin 1961) Deunff 1964 species, which have radial folds or thin veins on rim.

OCCURRENCE: Only tree individuals observed at depth of 52.0—52.5 m.

Synsphaeridium Eisenack 1965

Spherical vesicles from aggregates on, for the most part, plane surfaces.

Synsphaeridium sp.

DESCRIPTION: Diameter of vesicles c. 7 μ. Met with cylindrical colonies only at the depth of 45.34—46.34. Plate XV: 109.

Tasmanites Newton 1875

Tasmanites nanus n. sp. Plate XV: 110

HOLOTYPE: GSF prep. no. 70, plate XV: 110.

DIAGNOSIS: Vesicle is thick-shelled and clearly pierced by pores. Diameter of vesicle 21 μ, thickness of shell c. 2 μ, interval between pores c. 3 μ.

OCCURRENCE: Only one observation at depth of 42.21—45.34.

Tectitheca Burmann 1968

Pentagonal contour, conical upper part and cylindrical lower part, compressed or extended in line with longitudinal axis. Gradually tapering processes are unforked and generally long and in free connection with central vesicle. The compressed or extended conical upper part tapers into an apical process composed of a single unit, the location of which on the long axis of the vesicle is important in orienting the form. In the border zone of the conical and cylindrical part, there are four processes; on the basal level, there are two peripheral processes. The number of processes is limited by their regular location, but it varies on account of, for example, the additional processes situated on the cylindrical part, with these extra processes following an alternating order as compared with the main processes.

Tectitheca species have been previously reported to occur in the Upper Llanvirnian material (lower part of the Middle Ordovician) in e.g. Arkona, DDR (Burmann 1968) and in Ordovician material of the borehole in Caubon, western France (Rauscher 1974).

Tectitheca complicata n. sp.
(Fig. 18 c. Plate XV: 111)

HOLOTYPE: GSF prep. no. 109, plate XV: 111.

TYPE LOCATION AND TYPE STRATUM: Lumparn borehole n:o 4, Middle Ordovician, 50.80—51.34 m.

DERIVATION OF NAME: latin: complicata, complicated process placing and structure.

DIAGNOSIS: The vesicle consists of a cylindrical lower part and a conical upper part, which culminates in the vesicle's largest apical process. At the base of the conical part, there are three relatively large processes. In the upper portion of the cylindrical part, there are at least six processes, of which some are noticeably smaller than the others. In the lower part of the cylinder, there are probably tree or four processes and on the margin of the basal level four more. In the medium-sized and large processes, there are lengthwise lines, but the upper end of some of them is granulated. The thickness of the shell of the vesicle is c. 1.5 μ, and it consists of two layers. The surface is microgranulated. The breadth of the cylindrical part is c. 45 μ, and its height c. 35 μ. The total length, including processes is c. 100 μ.

REMARKS: The form is more complicated in structure than the species described by Burmann; but this species has evidently evolved from *Tectitheca,* for the main features are similar i.e. a cylindrical lower part and the conical upper part rising above the other processes.

The form strikingly resembles the genus *Unellium* described by Rauscher (1969), but

Unellium is of smaller size than the *Tectitheca* species described earlier. The form is intermediate between the genera *Tectitheca* and *Unellium*.

OCCURRENCE: At the depth of 50.80—51.34 m, only one individual was found.

Tranvikium n. genus

DERIVATION OF NAME: Tranvik, locality north of the Lumparn bay·

TYPE SPECIES: *Tranvikium polygonale*, n. sp.

DIAGNOSIS: The vesicle is a bell-shaped combination of hemisphere and plane surfaces. The polygonal side or basal level is composed of a hexagonal figure, in the middle of which is a large pylom. This may be either covered or lacking a cover. The cover may be round and of one piece or divided radially into 2—4 segments. The polygonal side is slightly narrower than the equatorial diameter; the height is less than the diameter, and for this reason the vesicle generally, when prepared, sets between the sheets of glass of a slide parallel to the bottom place. Opposite the bottom plane on the spherical surface is generally a swelling or smaller aperture, the diameter of which is about 1/4 of the pylom at the bottom. Close to the periphery, a hexagon can be distinguished inside the circumference of the circle. The corners of this hexagon are situated half way between the angles of the bottom plane. The polygons appearing in the side view are pentagonal.

This type resembles *Cymatiosphaera* to some extent, especially if it is flattened.

Tranvikium polygonale n. species
(Fig. 19, Plate XV: 112—121, XVI: 122, XVII: 130, 131, XIX: 160).

HOLOTYPE: GSF prep. no. 111, plate XVI: 122.

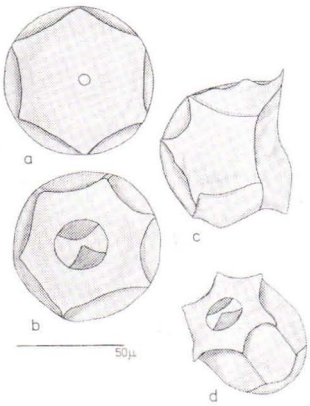


Fig. 19. Acritarch type *Tranvikium polygonale* found in borehole 4 in Lumparn: a. viewed from above, b. »bottom-level» view, c. side view, d. oblique view in relation to bottom level.

TYPE LOCATION AND TYPE STRATUM: Lumparn borehole n:o 4, 52.0—52.5 m, Middle Ordovician.

DERIVATION OF NAME: latin, polygonale, polygon shape of the vesicle.

DIAGNOSIS: As for genus and dimensions.

DIMENSIONS: The diameter of the equator of the bell-shaped vesicle is c. 70—35 μ, and the height c. 55—27 μ. The diameter of the aperture on the bottom plane is c. 13—8 μ, that of the aperture on the upper surface c. 3 μ.

OCCURRENCE: A fairly common species at the depth of 50—55.37 m.

Tylotopalla Loeblich 1970

Acritarchs of small size with circular to subcircular central vesicle as well as numerous short processes, the interior of which is connected with the interior of the central vesicle. Processes terminate in a point, or before the end is a rosette composed of tiny prickles.

Tylotopalla sp. 1. Plate XVI: 123—126.

DESCRIPTION: Contour of vesicle is fairly polygonal, with the angles formed by exceptionally broad-based, short processes. On the terminal portion of the processes are tiny prickles. Diameter of vesicle 35—40 μ, height of processes c. 3—5 μ. The form resembles the species *T. caelamenicutis* Loeblich 1970, but, among other things, the striations on the processes are lacking.

OCCURRENCE: Numerous individuals observed at the depth of 51 m.

Tylotopalla sp. 2. Fig. 20 a, plate XVI: 127.

DESCRIPTION: The vesicle has a square contour. Processes form the ridges of a polygon. The terminal portion of the processes is peg-shaped and covered with nodules. The main body is composed of undulant protuberances. The total diameter is c. 30 μ.

At the depth of 51 m, exceedingly rare.

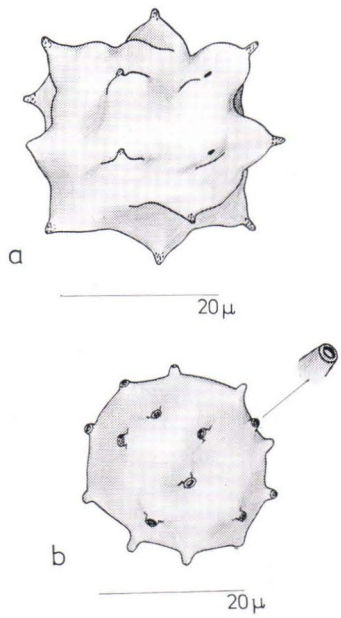


Fig. 20. *Tylotopalla* types from drilling site No. 4 in Lumparn: a. T. sp. 2, b. ?T. sp. 3, detail of process.

Tylotopalla sp. 3. Fig. 20 b, plate XVI: 128.

DESCRIPTION: The vesicle is circular, with a diameter of c. 25 μ. Short tubular processes, measuring c. 3 μ and numbering c. 23. The distal end of the processes is tubular and inside is a peg-shaped barrier.

Very rare occurrence at 51-m depth.

Veryhachium Deunff (1954) 1958, emend. Downie & Sarjeant 1963

In the polygonal or subpolygonal vesicle, there are 3—8 hollow, closed spines. The diameter of the vesicle generally measures 10—40 μ.

Cramer (1964) in his study combines many species into formgroups. For example: in the study just mentioned, included in the designation *V. trispinosum* (Eisenack 1938) also are *V. downiei* Stockmans et Williere, *V. geometricum* (Deflandre 1942), *V. reductum* (Deunff 1958) and *V. trisulcum* (Deunff 1951). In the original descriptions of these species, the distinctive features are not always characterized with unambiguous accuracy; hence the determination of these species is difficult. In the description of the triangular forms of Lumparn, therefore, as generalized a classification as possible has been observed, one based on structural and textural features. In the *V. trispinosum* type (Fig. 21), the distinguishing features are based mainly on the structure of the processes.

Veryhachium domasioides n. sp. Fig. 21 b, Plate XVII: 141

HOLOTYPE: GSF prep. no. 71, plate XVII: 141.

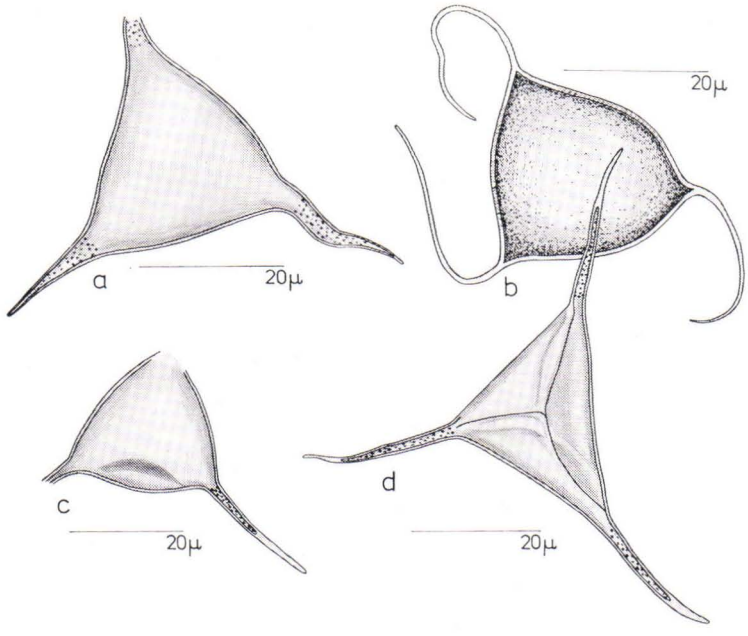


Fig. 21. *Veryhachium* types from drilling site No. 4 in Lumparn: a. *V. reductum*, b. *V. domasioides*, c. *V. trispinosum*, d. *V. geometricum*.

DIAGNOSIS: Two sides of the rounded triangular vesicle are equally long and longer than the third side. The processes are slender and curved, and the hollow interior of their basal portion is very short. The surface of the vesicle is granular. The dimensions of the vesicle are 23 × 28 μ, and the length of the processes is c. 25 μ.

OCCURRENCE: Only few occurrences met with at a depth of 45.34—46.34 m.

REMARKS: The species differs markedly from *Domasia trispinosa* Downie 1960, which is more oblong in shape.

Veryhachium estrellitae Cramer 1964

DESCRIPTION: Pentagonal, 7-pronged, diameter 50 (40 μ). Surface of vesicle rough and streaky. Streaks could not be distinguished on the thin walled form of Lumparn, perhaps on account of wear. Plate XVII: 133.

Veryhachium lairdi Deflandre 1946

DESCRIPTION: Vesicle rectangular, c. 18 × 15 μ, processes at angles c. 25 μ. Plate XVII: 137.

OCCURRENCE: Only one observation made at depth of 45.34—46.34.

Previously reported from e.g. the Silurian in Canada (Deunff 1954), and the Llanvirn deposit at Roche-au-Merle, France (Paris & Deunff 1970).

Veryhachium oligospinosum (Eisenack 1934)

Synonym: *Goniosphaeridium oligospinosum* Eisenack *et al.* 1973.

DESCRIPTION: The vesicle is more or less square in shape with the spines at the angles. In addition, there are 1 or 2 additional spines. The form occurring in core no. 4 is markedly smaller than the one of maximum size de-

scribed by Eisenack; the length of the sides is c. 25 μ, the length of the processes c. 25 μ. They are granular. Plate XVII: 134.

OCCURRENCE: Only a few individuals were observed at depth of 50.8—51.34.

Observations previously reported from, e.g., Ordovician deposits (Górka 1969, German 1974).

Veryhachium rhombispinosum n. sp.

HOLOTYPE: GSF prep. no. 109, plate XVII: 135.

DIAGNOSIS: The vesicle is polygonal, with the processes lying in two levels. Both levels are triangular. Number of processes 6. The lower-level processes are situated at the halfway point of the sides of the upper level. Length of sides averages 25 μ, that of processes c. 20 μ.

OCCURRENCE: Observations made at depth of 50.8—51.34 m.

REMARKS: The species differs from *V. rhomboidium* Downie 1959 owing to, among other things, its more regular geometric form. *V. bulbiferum* (Deflandre) Deunff 1954 resembles the new species in some degree but differs from it in size and structure.

Veryhachium stelligerum Deunff 1958

DESCRIPTION: The vesicle is composed of five prongs, which are all on the same plane. Plate XVII: 136.

OCCURRENCE: A few observations recorded from the depth of 50.80—51.34.

Previously observations have been reported from a.o. the Middle Ordovician deposit of Veryhach (Deunff 1958) and the Upper Arenigian of Poland (Górka 1969).

Veryhachium aff. *triangulatum* Konzalova

DESCRIPTION: The vesicle is fairly slender and triangular without prickly appendages. Sides are concave and c. 40 μ long. Plate XVII: 138.

OCCURRENCE: Rare occurrence at the depth of 53.0—55.37 m.

Veryhachium trispinosum (Eisenack 1938)

DESCRIPTION: The vesicle is nearly triangular, yellowish. Length of sides averages 27 μ. Over 1/3—1/2 the length of their main portion, the processes are hollow and covered with nodules, except for the distal portion where they are fairly smooth. Length of processes 20—30 μ. Fig. 21 c, Plate XVII: 139, 140.

REMARKS: In shape, it approaches *V. downie* Stockmans & Williére, but the *V.d.* holotype is substantially smaller: height 15—18 μ, length of processes 10—15 μ.

OCCURRENCE: Common form in Lumparn limestone.

Previously observed to occur in, among other places, the Llanvirn-Llandeilo deposit of Rennes (Le Corre & Deunff 1969), the Llanvirn deposit of Roche-au-Merle (Paris & Deunff 1970), aff. species in Sierra de Buçaco (Henry & Thadeu 1971).

V. trispinosum ssp. *geometricum* (Deflandre 1942, Deunff 1954)

DESCRIPTION: Delicate triangular vesicle, at the terminal portion of which are processes. The processes are relatively broad-based, hollow and granular over 2/3 their length, but the surface of the vesicle is smooth. From the center, a figure runs toward the tips, one likely to be quite clearly defined on both sides. Length of sides c. 25—28 μ, length of processes c. 20—25 μ. Fig. 21 d, Plate XVII: 142.

OCCURRENCE: Common especially at the depth of 49.34—49.70 m.

A species met with ordinarily in Devonian and Silurian deposits, but the occurrence of this, like many other triangular acritarch forms, would seem to cover a geologically wide time span.

V. trispinosum ssp. *granulatum* n. ssp.

HOLOTYPE: GSF prep. no. 111, plate XVIII: 144.

DIAGNOSIS: Central vesicle triangular, length of sides c. 30 μ, length of processes c. 20 μ. Fairly densely grown on the vesicle surface are tiny nodules.

Remarks: The type differs from the distinctly spiny-surfaced forms described by Cramer (1964) and also from the nodular-surfaced *V. irroratum* Loeblich & Tappan species described by Loeblich (1970).

OCCURRENCE: Rare at the depth of 52.0—52.5 m.

V. trispinosum ssp. *reductum* (Deunff 1958)

DESCRIPTION: The triangular vesicle is delicate, transparent, 20—25 μ in size. Spines short and tapering at the end, 10—20 μ long and covered with nodules. Fig. 21 a, Plate XVII: 132.

OCCURRENCE: Fairly common at the depth of 49.34—49.70 m.

Previous observations made in, for example, the Llanvirnian deposit of Roche-au-Merle (Henry & Thadeu 1971).

V. trispinosum ssp. *trisulcum* (Deunff 1951)

DESCRIPTION: Vesicle triangularly bulging, with a diameter of 35—40 μ. Processes straight or bent, length 75—100 μ. Color yellow or brown. The large form mentioned in the foregoing has not been observed in the present samples, though small forms with relatively long processes that resemble the *V. trispinosum* were observed (Plate XVII: 143). cf. Henry (1969).

Lower Cambrian acritarchs in the lower part of hole No. 4

The sample obtained for inspection from the reddish layer of fine sand underlying the limestone deposit comes from a depth of about 64 m. Analysis proved that the sample contains a relatively few acritarch species but nevertheless sufficient for dating. Among the species observed: some *Leiosphaeridia,* as well as a few *Granomarginata squamacae, Cymatiosphaera solfensis, Estiastra* sp. These are Lower Cambrian forms that to a large extent are the same as the ones observed in the Lower Cambrian sandstone dykes described previously as well as the shale and sandstone deposit of the Sulva region (Laurén *et al.* 1978).

PALYNOLOGICAL SUMMARY OF THE CLASTIC DYKES IN THE ÅLAND ISLANDS AND THE PALEOZOIC SERIES OF STRATA AT LUMPARN

The most important microfossils met with in the sandstone fissure fillings in the Åland Islands and the silt bed underlying the limestone of Lumparn are represented in Figure 22. The dykes and the silt bed have been classified on the basis of microfossil data into chronological categories. As it has been noted, most of the fissure fillings and

● abundant
▲ common
• rare
x very rare

locality	Acanthodiacrodium angustizonale	A. species	Aranidium sp.	Archaeodiscina umbonulata	Baltisphaeridium ciliosum-typ	B. compressum	B. ornatum-typ	B. species	Cymatiogalea sp.	Cymatiosphaera solvensis	C. sp.	Dasydiacrodium sp.	Eliasum sp.	Estiastra sp.	Granomarginata squamacea	Leiomarginata simplex	L. sp.	Leiovalia sp.	Leiosphaeridia species	Lophodiacrodium sp.	Lophosphaeridium sp.	Micrhystridium species	Ooidium rossicum	O. sp.	Ovulum punctatum	Stelliferidium ålandicum	S. sp.	Pirea sp.	Synsphaeridium sp.	Tasmanites bobrowskii	T. sp.	Trachysphaeridium sp.	Chitinozoa	
Nr 53 Långbergsöda - Öjen	●	▲						●				●	x						●							▲		x						Lower Ordovician
4 Östra Sundskär				x°		x											x		▲	x							x						x	
63 Loören galena vein					x			x											▲	x			x	x										
Loören galena vein (2-5 cm)			●					x							●°				▲			▲			x				●				x	
29 Stora Granskär								●		●					●	▲			⬤											x		●		Lower Cambrian
63 Loören								●	x		x								⬤								●				x			
76 Väderskär 160°									x										▲								x			●		▲		
76 Väderskär 20°					x										x				●											x				
20 Svartholmsöarna								x											▲		x	x								x	x			
53 C Långbergsöda-Öjen		x					●	●						x					▲															
Tranvik borehole 4										●				●	●				●															

°Lower Cambrian redeposited species

Fig. 22. Grouping of fissure fillings in the Åland Islands and the silt underlying the limestone at Lumparn done on the basis of the microfossils

the basal strata in Lumparn have been dated to the Lower Cambrian. All the fissure fillings classified as Lower Cambrian do not, however, correspond to a narrowly defined Lower Cambrian, for the age differences between some of them are likely to be considerable. A minority of the sandstone fissure fillings contain a lower Ordovician acritarch community.

In the Lumparn basin, located within the rapakivi massif sedimentation took place at the beginning of the Cambrian period. Before that, it had probably been exposed to continental erosion. The acritarch forms buried in connection with the sedimentation of the fine sand probably belong to the group of coastal micro-plankton organisms. The species are characteristic of clay and sand facies.

Evidently no sedimentation took place in the Åland area during the Middle and Upper Cambrian stages or the sedimentation that did take place war eroded prior to the onset of the Ordovician period. The latter possibility is not likely for no coarser sediments indicating erosion are found overlying the fine sand deposits in the Lumparn basin.

After the formation of the Lower Cambrian deposits, sedimentation was resumed during the later part of the Lower Ordovician or the beginning of the Middle Ordovician together with deposition of carbonates and a rising sea level. The rounded glauconite spheres commonly observed at the depth of about 61 m support a Lower Ordovician dating. The acritarch species, however, are younger than the typical Lower Ordovician occurring in the dyke, described by Tanner 1911. Conceivably, during the Lower Ordovician, the transgression began earlier in the northern part of the Åland Islands than in the Lumparn region.

The acritarchs in the depth zone of 40.80—61.67 m in the Lumparn drill-hole No. 4 are presented in Fig. 23, grouped into genera.

At the depths of 31—40 m, there are few acritarchs, and these are weathered and darkened to a sepia shade. The limestone is partly discolored by Fe_2O_3. The weathering of the microfossils might have been caused by the action of iron bacteria or other anaerobic bacteria in a sedimentation basin that had become fairly deep. Also this deposit dates probably to the end of the Middle Ordovician, for the few remaining forms do not include species identifiable as Upper Ordovician forms alone.

The number of preserved acritarchs at a depth of about 40—45 m is sufficient for dating. The majority consist of small *Leiosphaeridia* species with pyloms as well as *Baltisphaeridium* species. *Baltisphaeridium eisenackianum* occurs only in this upper part. It is more common in strata dating from the Upper Ordovician than from the Middle Ordovician (Eisenack *et al.* 1973). Possibly, the strata in question at Lumparo correspond to the upper part of the Middle Ordovician. An Upper Ordovician age can not be excluded. It is noteworthy that at the depth of 40.80—41.50 m the sediment contains exceptionally angular, worn algal cellular tissue.

During the carbonate deposition at the 47—48 m level, the depth of the water could have exceeded 100 m, for according to Playford *et al.* (1976) *Girvanella,* which also occurs in the Lumparn limestone, is classified among the algae that belong to the fore-reef and inter-reef facies. The sedimentation milieu close to the reef is characterized by relatively rich faunal life and rapid sedimentation, which nevertheless took place in clear water. The acritarch species are suggestive of a Middle Ordovician age.

Noteworthy is the large proportion of triangular *Veryhachium* forms, especially in the middle part of the diagram (Fig. 23). Corresponding occurrences have been pre-

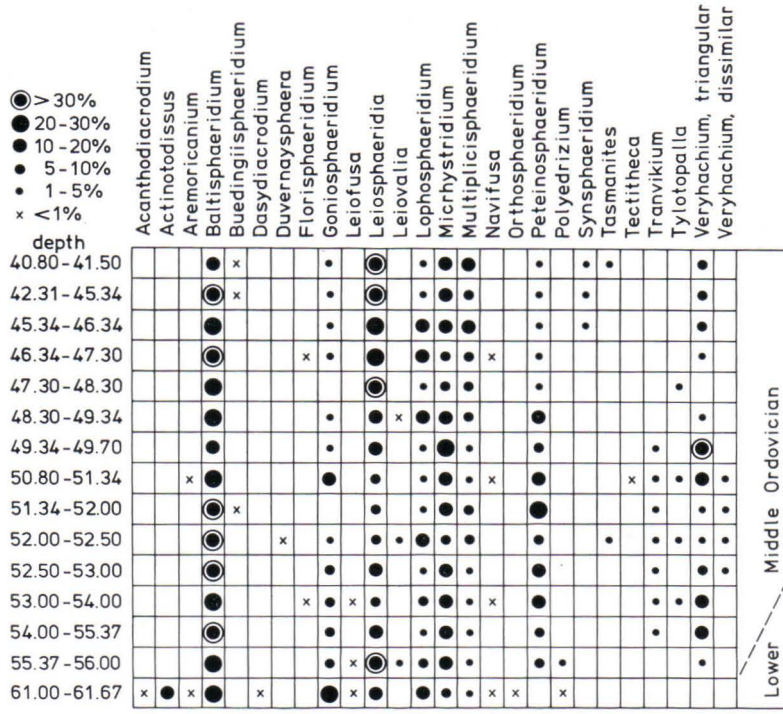


Fig. 23. Diagram of the acritarch genera contained in the limestone samples taken from drilling site No. 4 at Lumparn, together with dating based on estimates.

viously reported from the Upper Ordovician stratum of Veryhac and Kerglint (Deunff 1958, 1966, Henry 1969). *Veryhachium* and *Baltisphaeridium* (LeCorre & Deunff 1969) are main occurrences also in the Middle Ordovician schist of Rennes as well as in the Roche-au-Marle deposit (Paris & Deunff 1970) dating back to the Llanvirn (Middle Ordovician). In view of the evidence provided by other acritarch occurrences, the mid level of the Lumparn limestone bed has been interpreted as Middle Ordovician.

Acritarch species dating from the Middle Ordovician are most abundant at a depth of about 50—55 m in borehole 4. *Baltisphaeridium* species dominate, they are mainly the same species as those described by Kjellström (1971 a and b, 1976) and Górka (1969) from Middle Ordovician deposits. At the depth of 61.0—61.67 m, the deposit was probably formed during the Lower Ordovician. In addition to the lithological similarity with formerly dated deposits in the Baltic Sea area, the acritarch species also suggest such a conclusion. The rare *Acanthodiacrodium* Timofeev or *Priscotheca* Deunff and *Dasydiacrodium* Timofeev are Lower Ordovician forms. The *Actinotodissus baltica* occurring at this depth approaches the genus *Acanthodiacrodium*. The *Baltisphaeridium* and *Goniosphaeridium* species constituting the maximum are known from both the Lower and the Middle Ordovician.

Since in borehole 4, the depth zone 40.80—61.67 has been interpreted to represent the Middle Ordovician and the upper part of the Lower Ordovician, the probability is that there are gaps in the sedimentation. The

thickness of the Ordovician limestone in Lumparn is of the same order as the Finngrundet occurrence, but the latter represents an older Ordovician stage (Thorslund & Axberg 1979, Tjernvik & Johansson 1979). Represented in the Ordovician limestone of Gotland is, with the exception of a few gaps, the Ordovician System for the main part (Jaanusson 1973, Flodén 1980). It belongs to the so-called Estonian Zone (Männil 1966), which is characterized by gray calcareous sediments. The occurrence in the Åland Islands must also be classified as belonging to this zone rather than to the western Swedish-Latvian zone, which has been correlated to the deeper part of the Baltic Ordovician sea (Männil 1966, Flodén 1980).

The exceedingly fine-grained calcilutite met with in borehole 6 is unsuitable for dating with acritarchs. The stratigraphic position of this deposit in relation to the Ordovician microflora described in the foregoing is, however younger. Since with respect to its properties the sediment resembles to a large extent the limestone of the Wesenberg stage (Sauramo 1942) or the Rakvere stage, this estimate is in agreement with the palynological result obtained from the somewhat older portion of the deposit. No signs of any notable erosion at the transition level can be perceived. According to a more recent interpretation, the Rakvere corresponds to the upper part of the Middle Ordovician (Männil 1966). Merrill's (1979) study brings more exactitude to the dating of the upper part of the drill cores in Lumparn, giving an age corresponding to the Nabala stage (F 1 a) of the turn of the Middle and Upper Ordovician periods. The fine-grained sediment indicates that the depth of the water had been considerable. For the same reason, the acritarchs have probably been destroyed.

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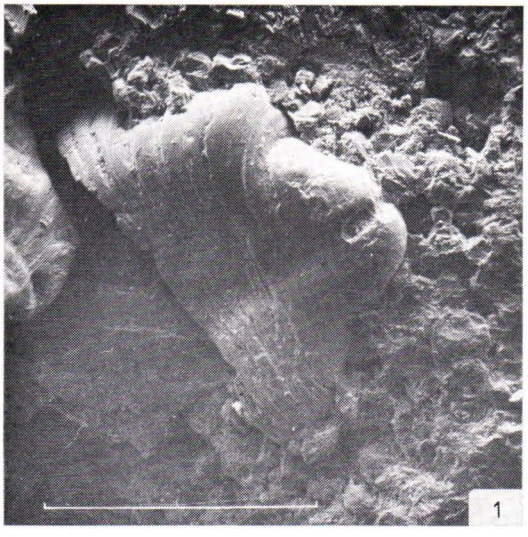
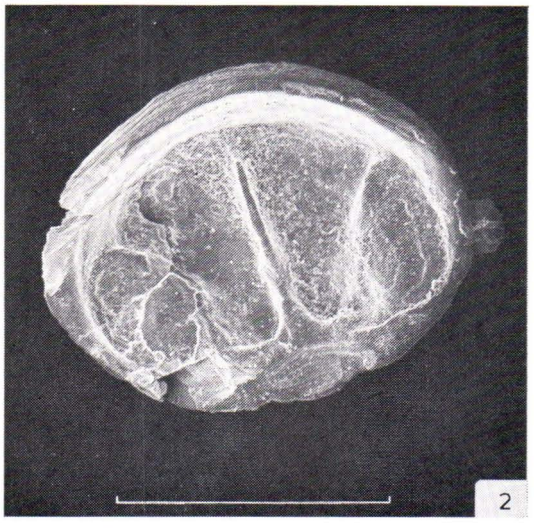
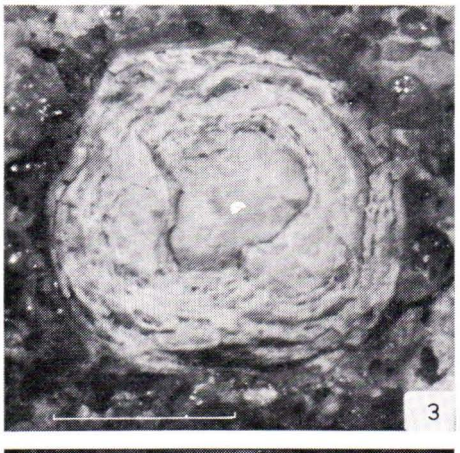
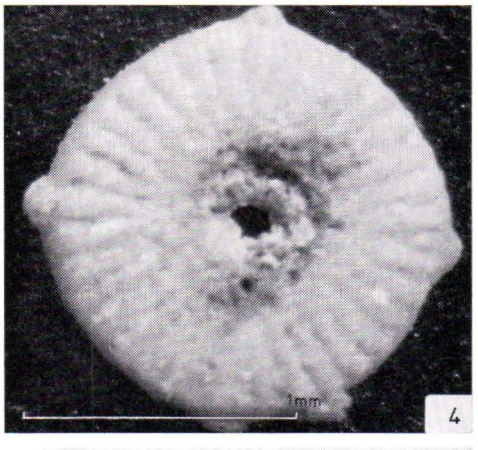
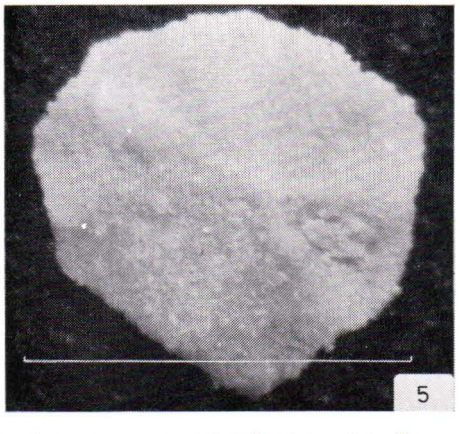
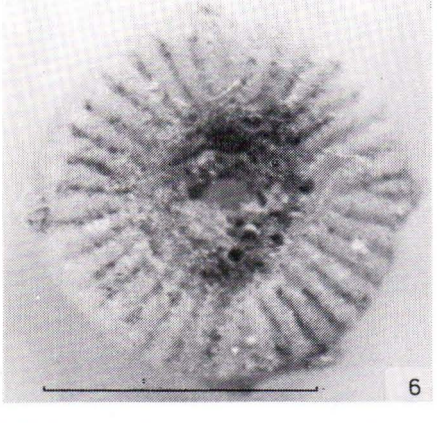




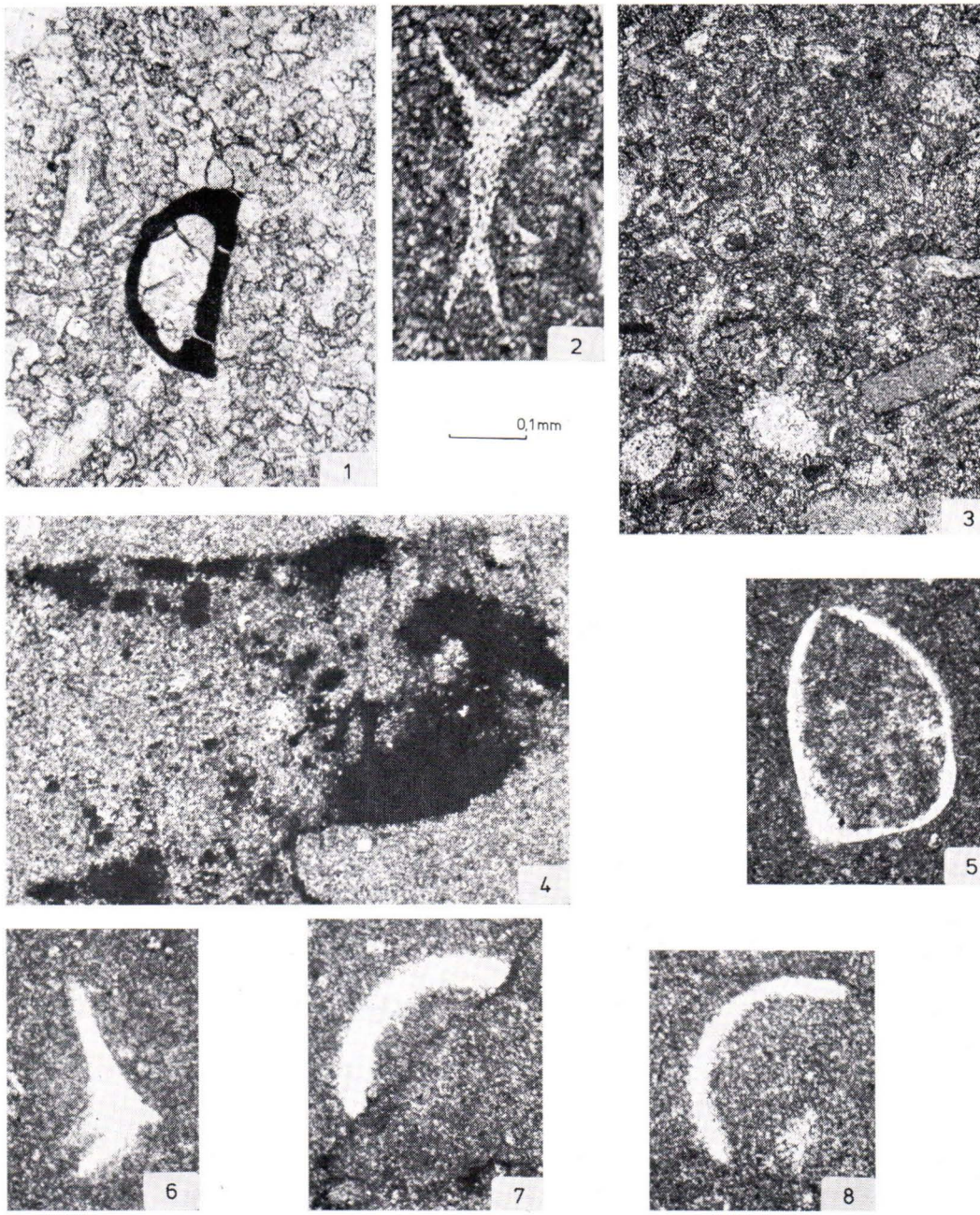




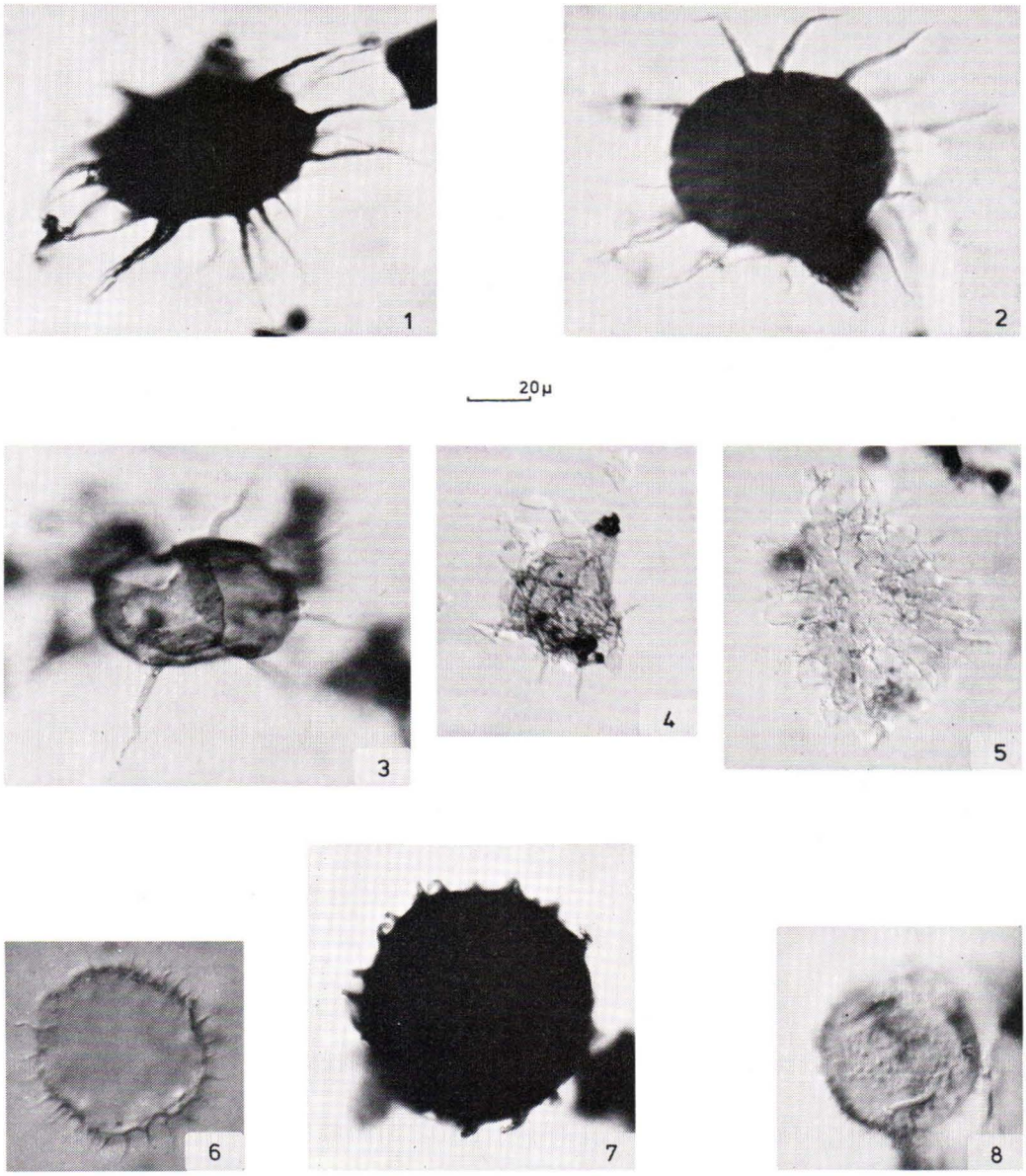




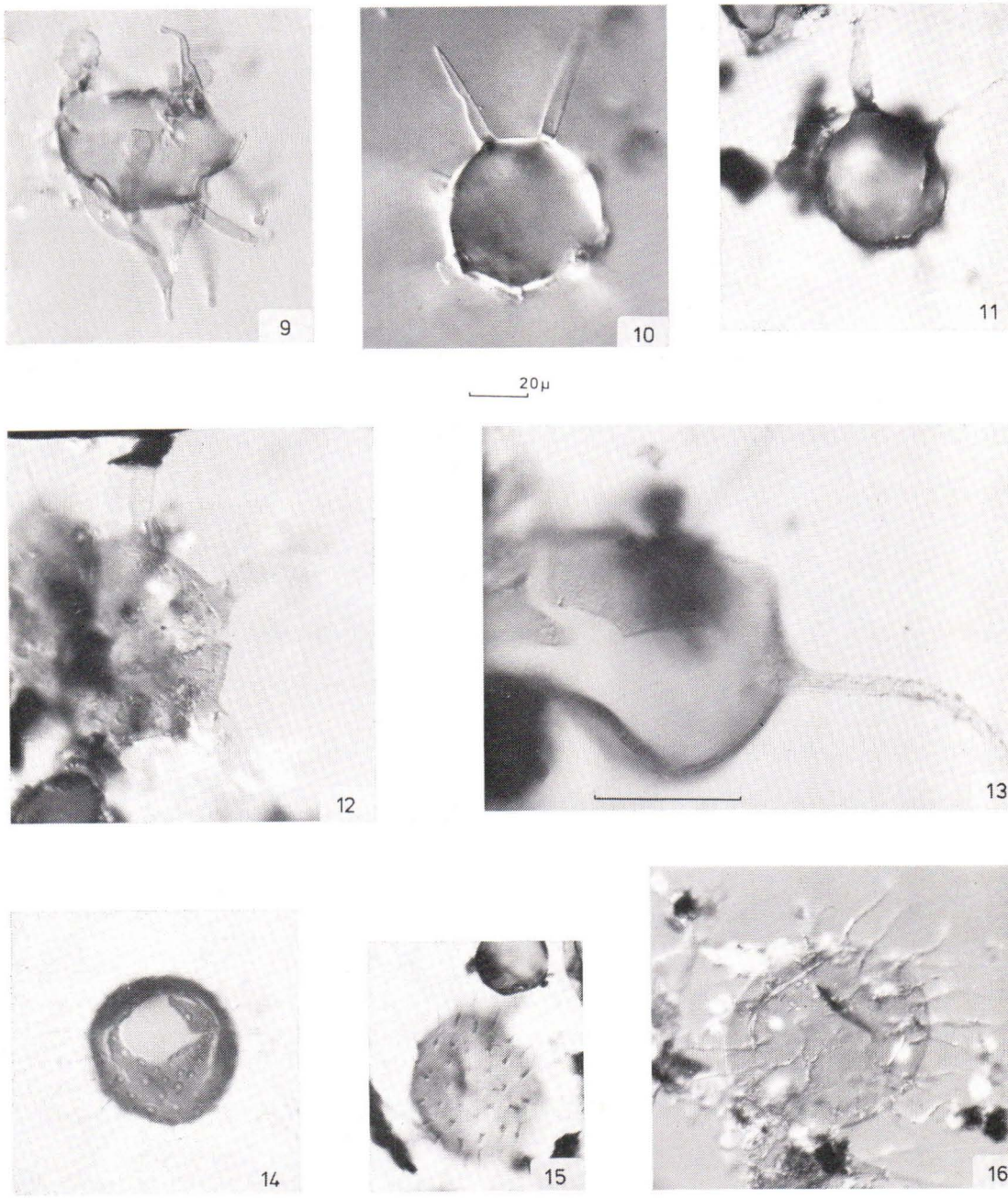
1, 2. *Ceratreta tanneri,* Långbergsöda-Öjen; 3. mollusc shell, Loören; 4, 6. crinoid stemjoint; 5. crinoid thecaplate?, 4—6. Lumparn drill core No. 6: —21.2 m.



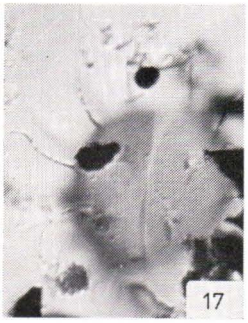
1—3. Thin sections of fine grained limestone, deep drilling No. 4: —52.0 m in Lumparn; 4—8. calcilutite in deep drilling No. 6: —4.3 m., 4. hematite spots, 5—8. fossil fragments.

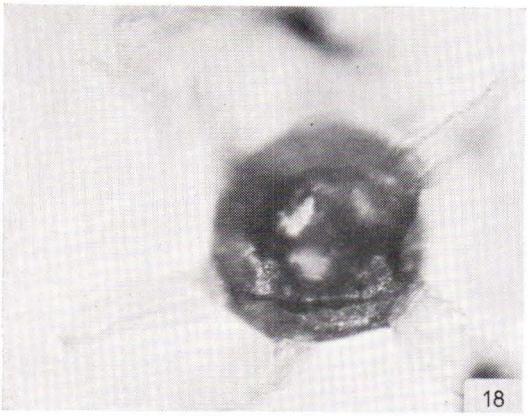


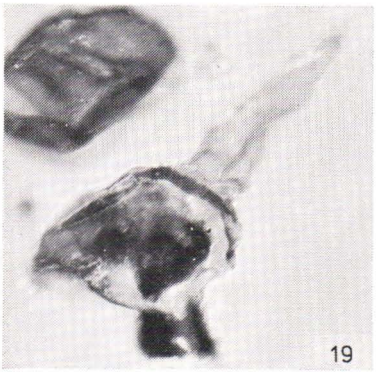
1—3. *Actinotodissus baltica*, 4. *Aremoricanium* sp., 5. *Baltisphaeridium anneliae*, 6. *B. brevifilicum*, 7. *B. brevispinosum*, 8. *B. brevituberculum*, Lumparn deep drilling No. 4.

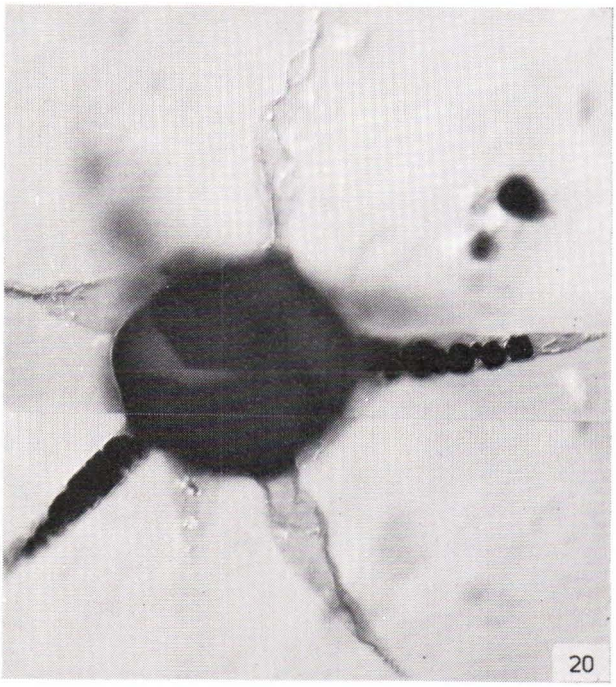


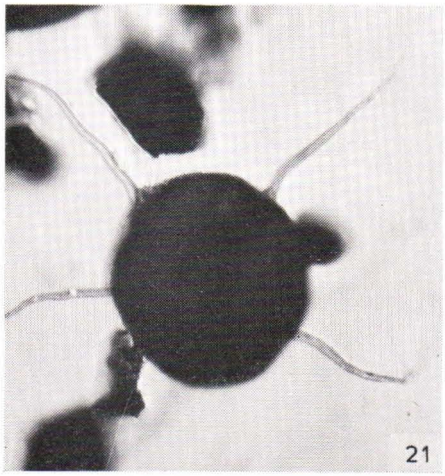
9. *Baltisphaeridium bulbosum*, 10. *B. calicispinae*, 11, 12. *B. constrictum*, 13. *B.* aff. *eisenackianum*, 14. *B. filosum*, 15. *B. hamatum*, 16. *B. hirsutoides*, Lumbarn deep drilling No. 4.











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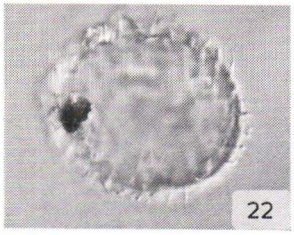
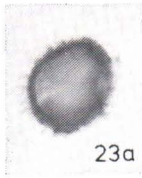
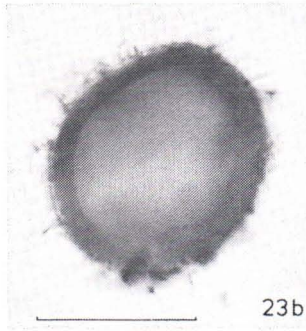
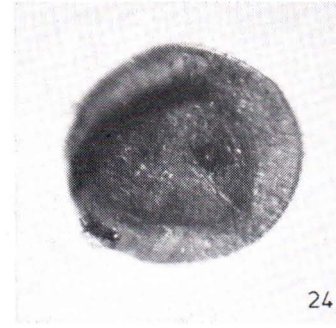


17. *Baltisphaeridium ingerae*, 18, 19. *B. lancettispinae*, 20. *B. latiradiatum*, 21. *B. longispinosum*, 22. *B. microspinosum*, Lumparn deep drilling No. 4.







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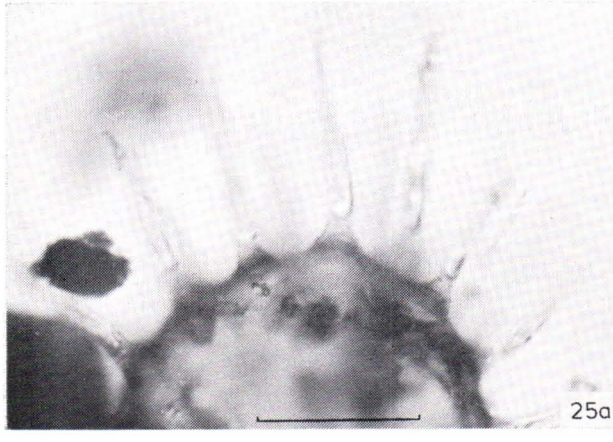
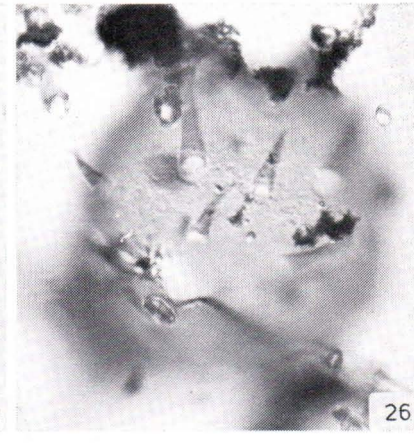
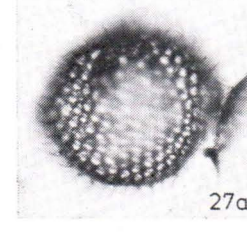
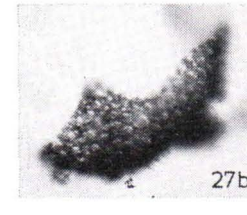
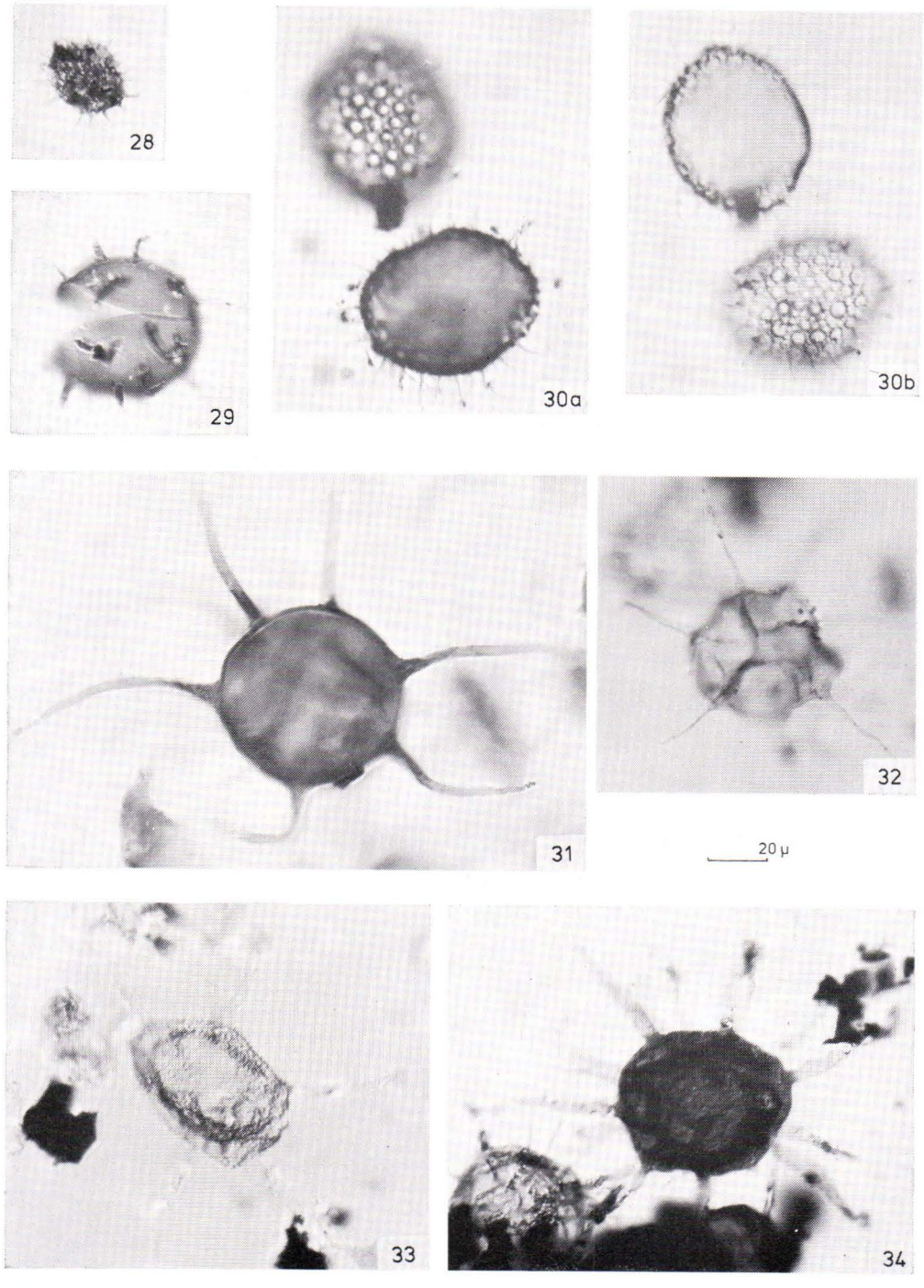




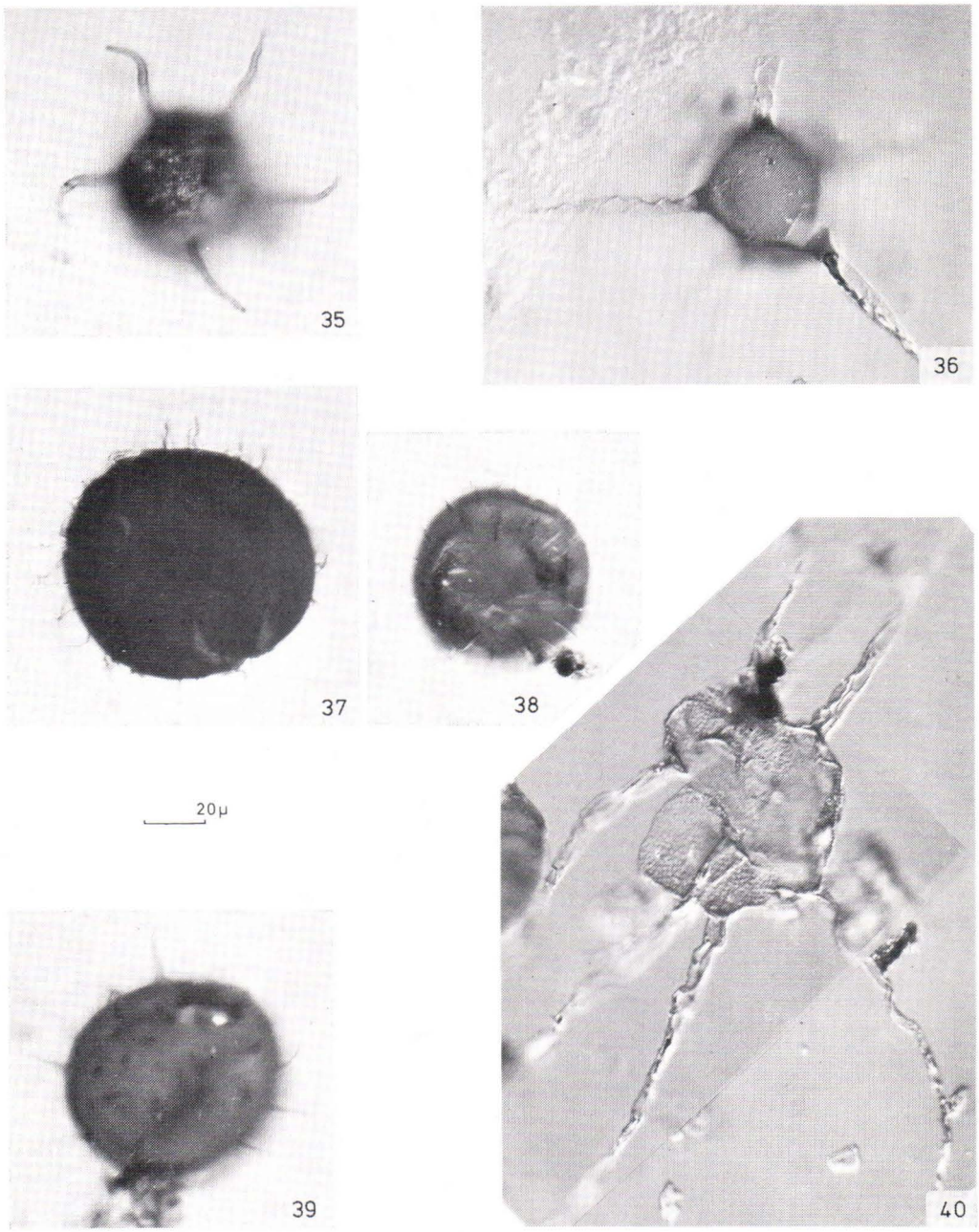




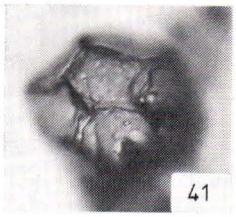
23 a, b. *Baltisphaeridium multipilosum* var. *minor*, 24. *B. nannium*, 25 a, b. *B. oligopsakium*, 26. *B. psilatum?*, 27 a, b. *B. regnelli* var. *densespinosa*, Lumparn deep drilling No. 4.



28. *Baltisphaeridium simplex*, 29. *B. spinigerum*, 30 a, b. *B. tranvikensis*, 31. *B. longispinosum*, 32. *B. longispinosum*, angular vesicle, 33. *B. pustulatum*, 34. *B. oligopsakium*, Lumparn deep drilling No. 4.



35. *Baltisphaeridium bulbosum*, 36. *B. calicispinae*, 37, 38. *B. filosum*, 39. *B. psilatum*, 40. *B.* sp., Lumparn deep drilling No. 4.



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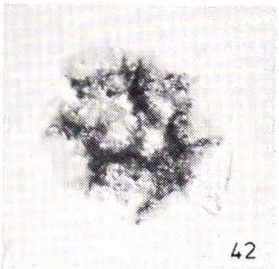
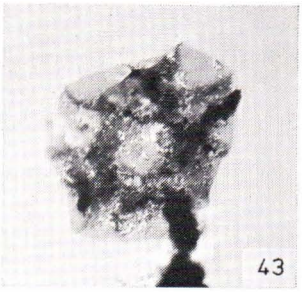
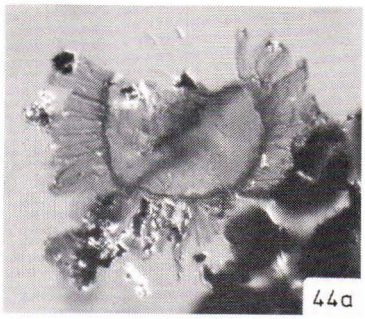
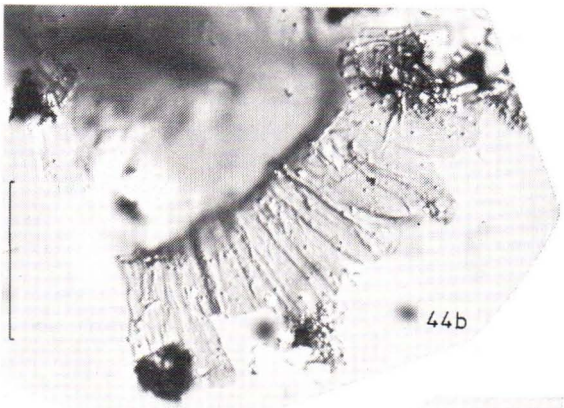
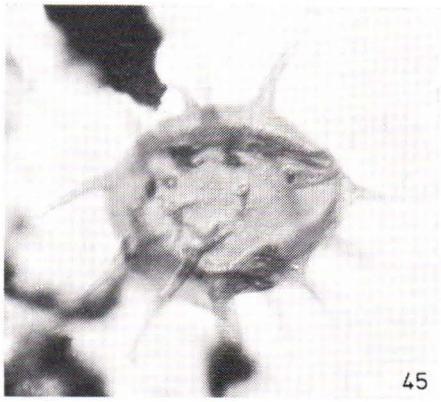
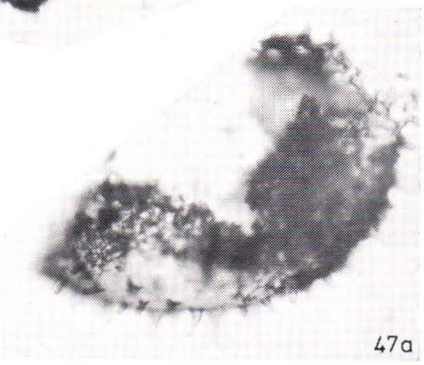


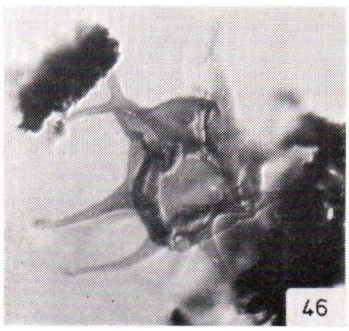


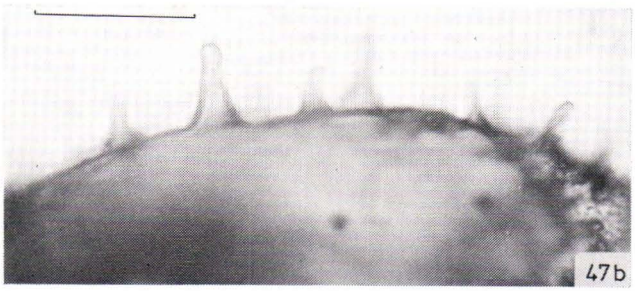




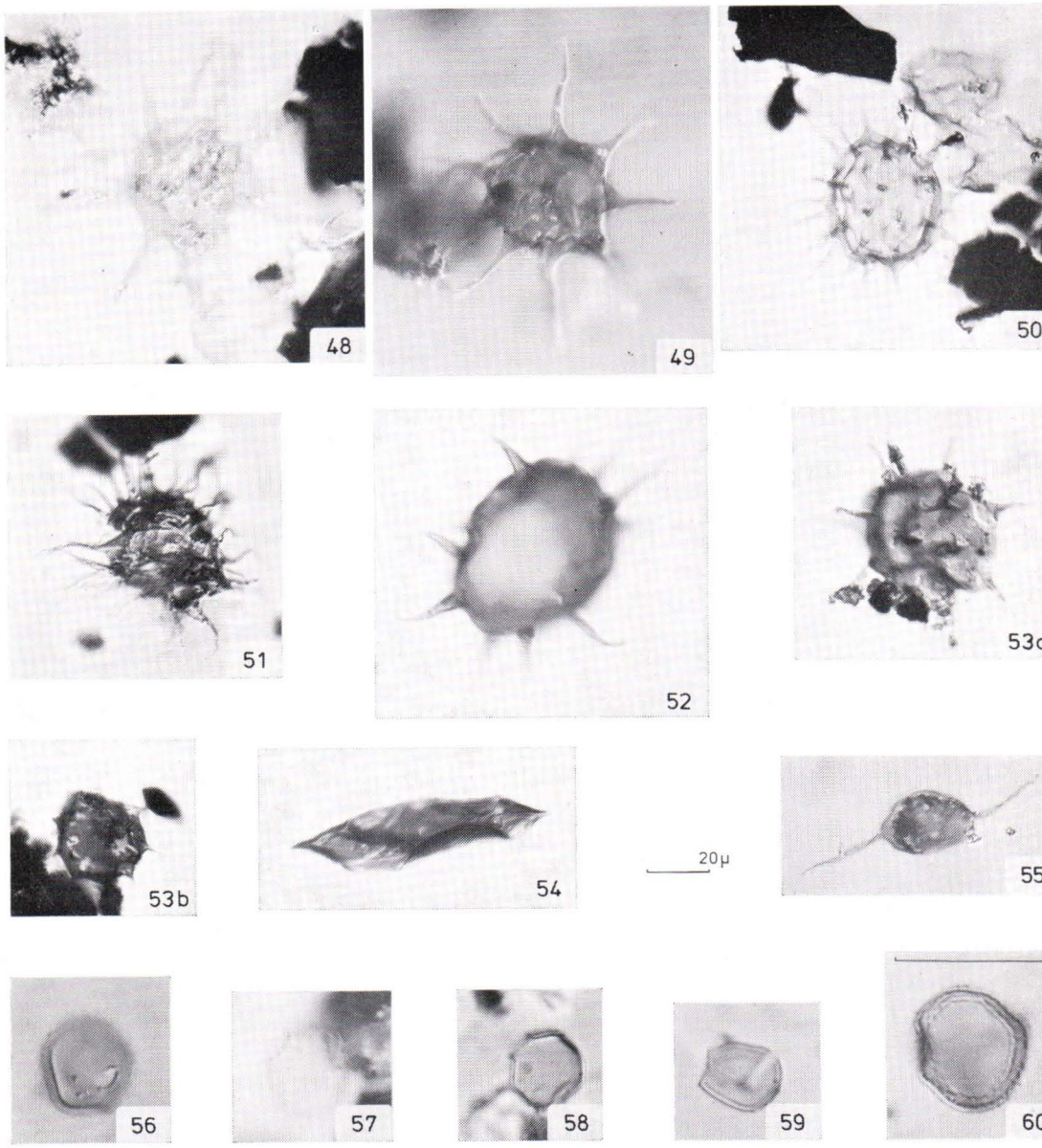




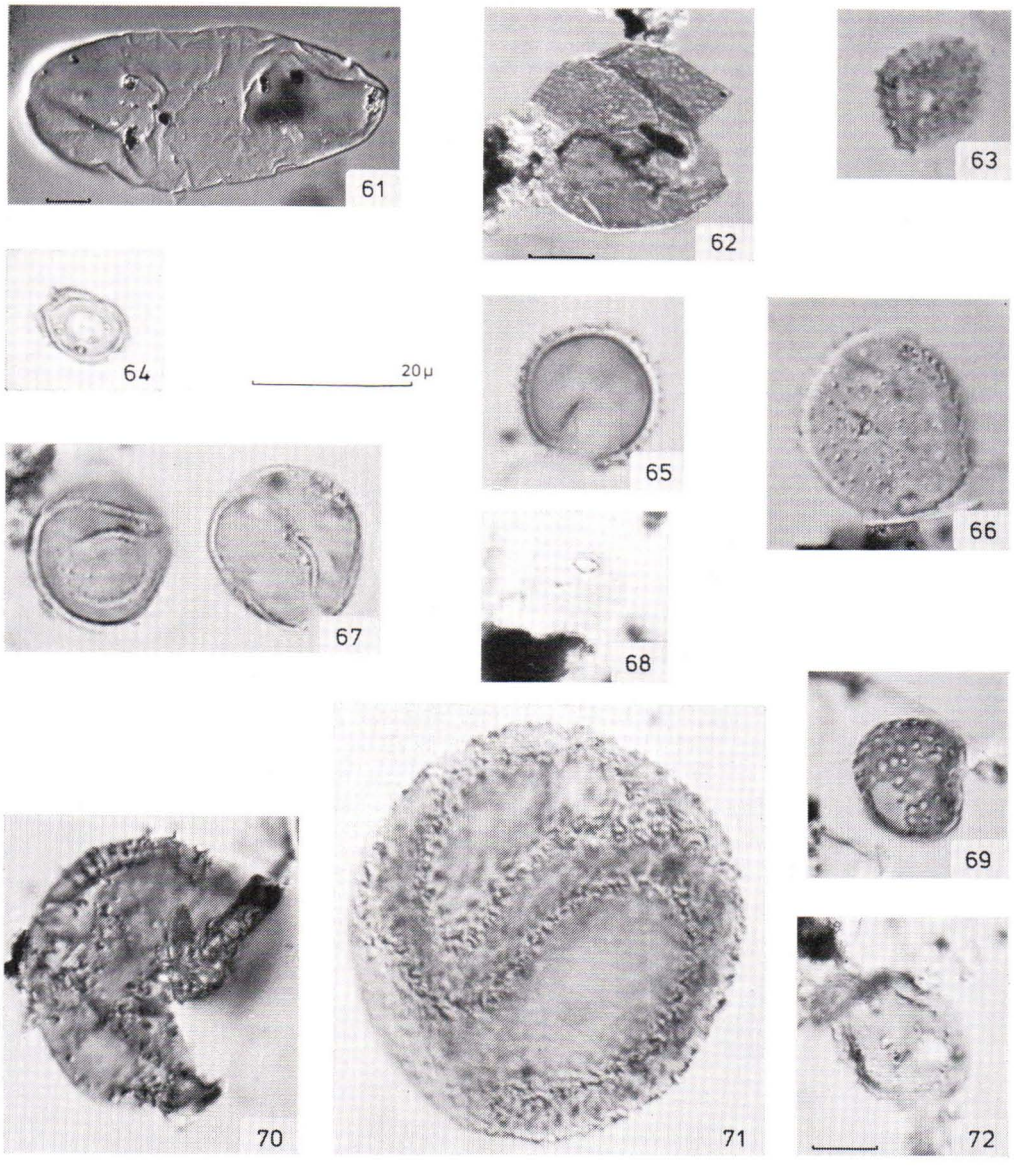




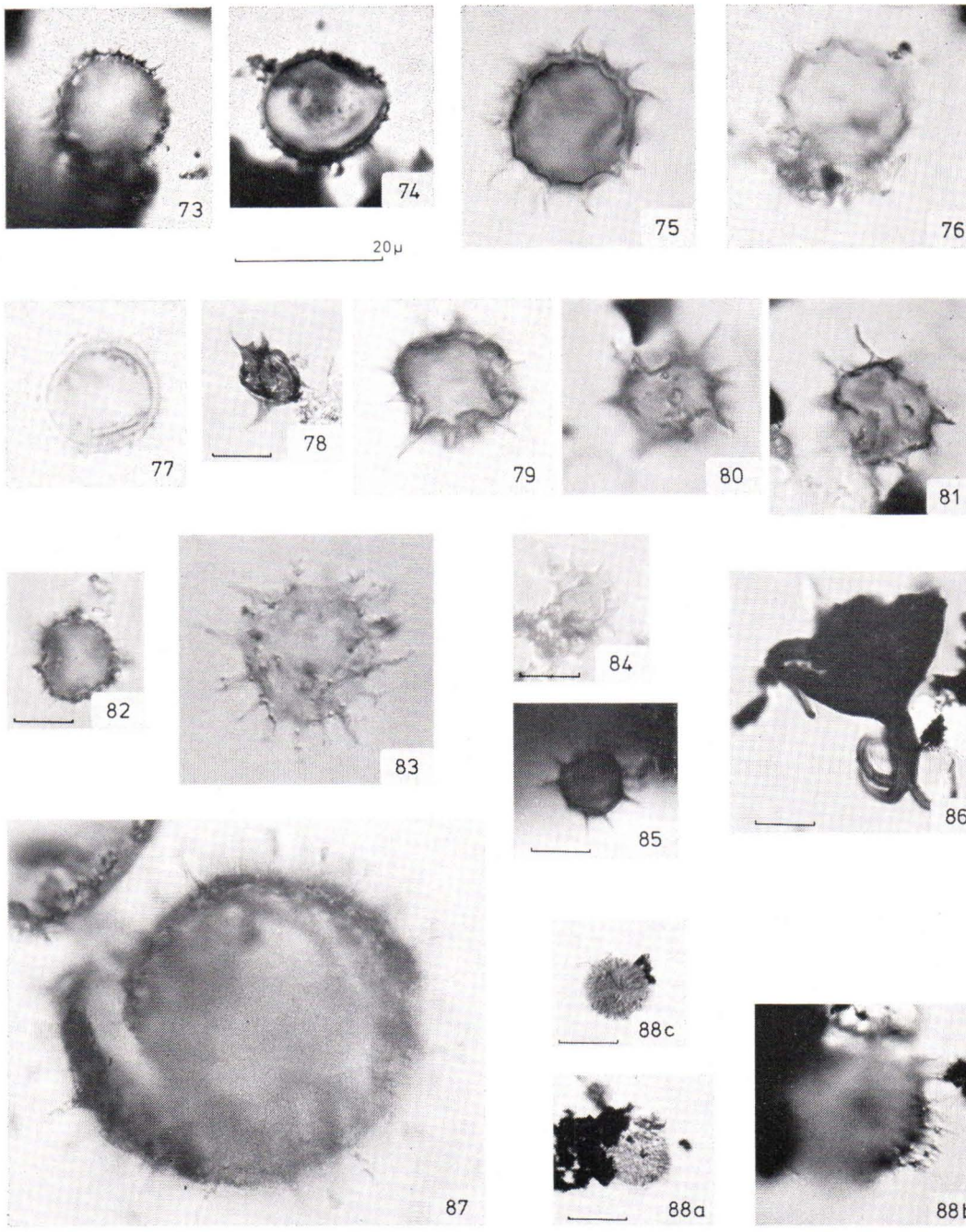
41. *Cymatiosphaera* aff. *canadensis*, 42, 43. *C. solfensis*, 44 a, b. *Pterospermella tranvikensis*, 45. *Goniosphaeridium christiani*, 46. *G. mochtiensis*, 47 a, b. *G. peregrina*, Lumparn deep drilling No. 4.



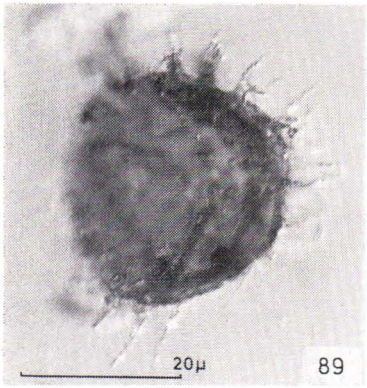
48. *Goniosphaeridium polygonale* subsp. *conjunctum*, 49. *G. polygonale* subsp. *pellicidium*, 50. *G. polygonale*, 51. *G. polygonale* ssp. *polyacanthum*, 52. *G. polygonale* ssp. *uncinatum*, 53 a, b. *G. pungens* (Tim.) Raus., 54. *Leiofusa* sp., 55. *L. granulacutis*, 56—58. *Leiosphaeridia granulatopylum*, 59. *L.* sp., 60. *L.* sp., Lumparn deep drilling No. 4.

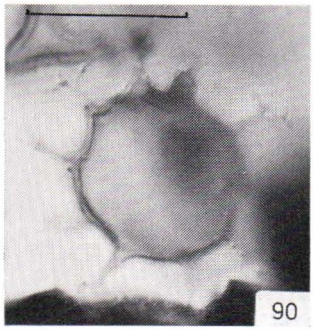


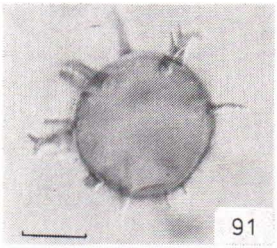
61. *Leiovalia similis*, 62. *Lophosphaeridium citrinipeltatum*, 63. *L.* aff. *diplicativum*, 64. *L.* sp. 1, 65—67. *L.* sp. 2, 68. *L.* sp., 69. *L.* sp., 70. *L.* sp., 71. *L.* sp., 72. *Buedingiisphaeridium* sp., Lumparn deep drilling No. 4.

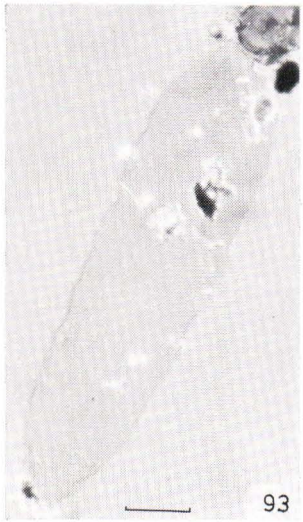


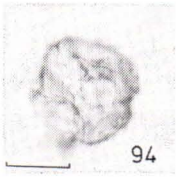
73, 74. *Micrhystridium campoae*, 75, 76. *M. pseudocoronatum* n. sp., 77. *M. nannacanthum*, 78. *M.* aff. *stellatum*, 79—81. *M.* sp., 82. *Multiplicisphaeridium alloteaui*, 83. *M. raspa* (Cramer) Eis. & al., 84, 85. *M. bifurcatum*, 86. *M. sartbernardense*, 87. *M. gotlandicum*, 88 a, b, c. *M.* sp. 1, Lumparn deep drilling No. 4.

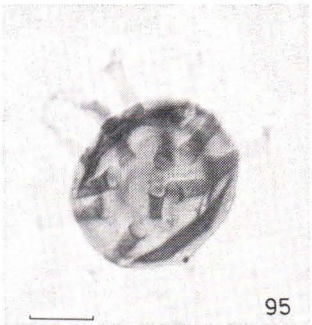


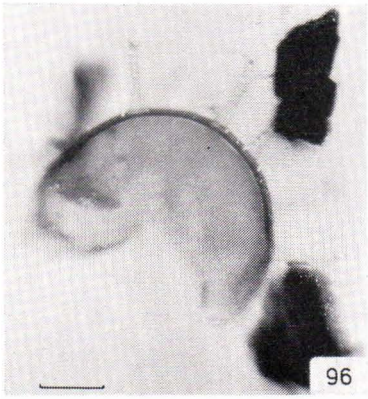




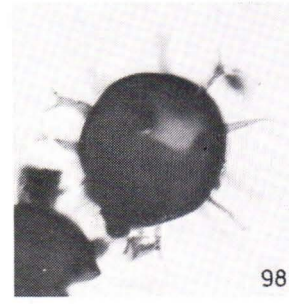


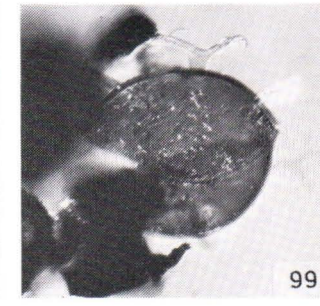




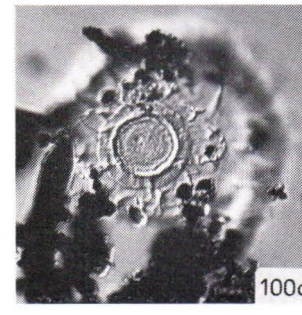


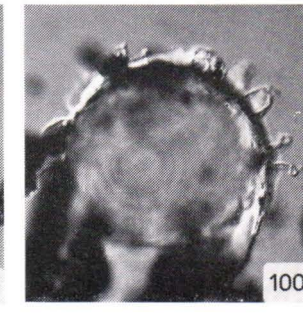
89. *Multiplicisphaeridium* sp. 2, 90. *M.* sp., 91. ?*Peteinosphaeridium* sp., 92. *Navifusa tenuis*, 93. *N. navicula*, 94. *Peteinosphaeridium breviradiatum*, small form, 95. *P. elegantulum*, 96. *P. heteromorphicum* subsp. *granulataspinosa*, Lumparn deep drilling No. 4.

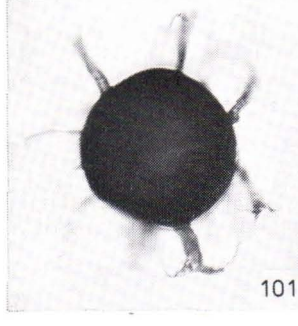


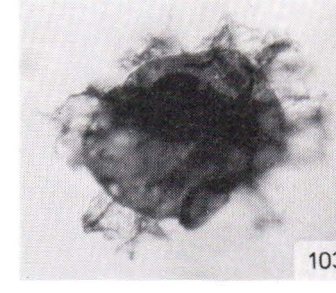


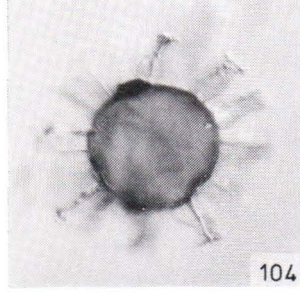
20 µ

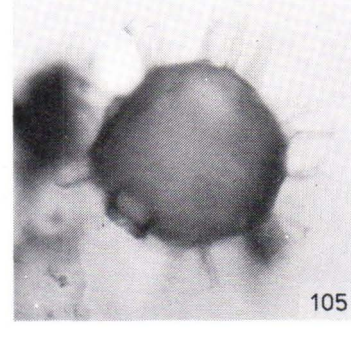


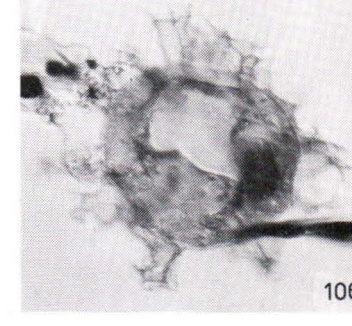




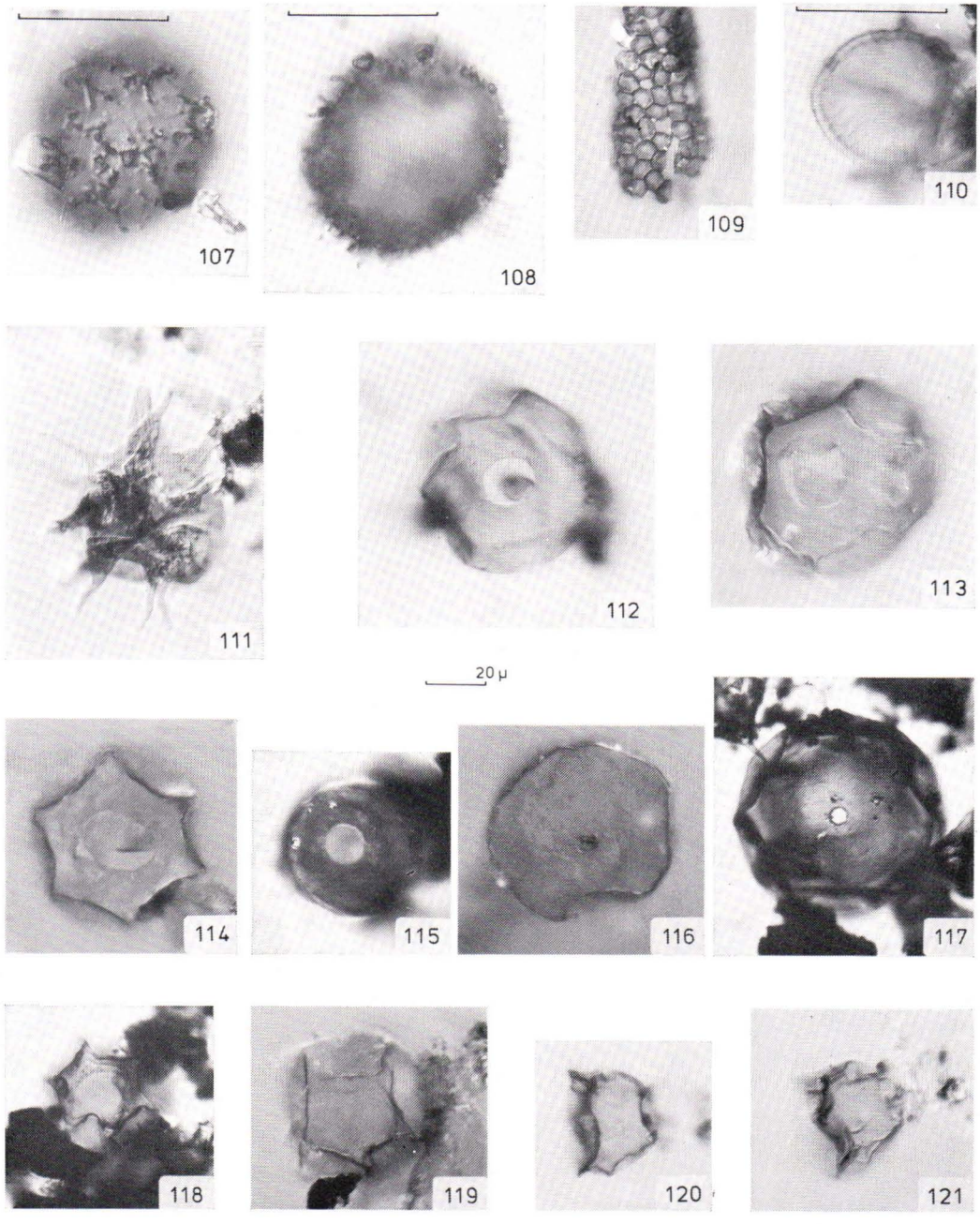




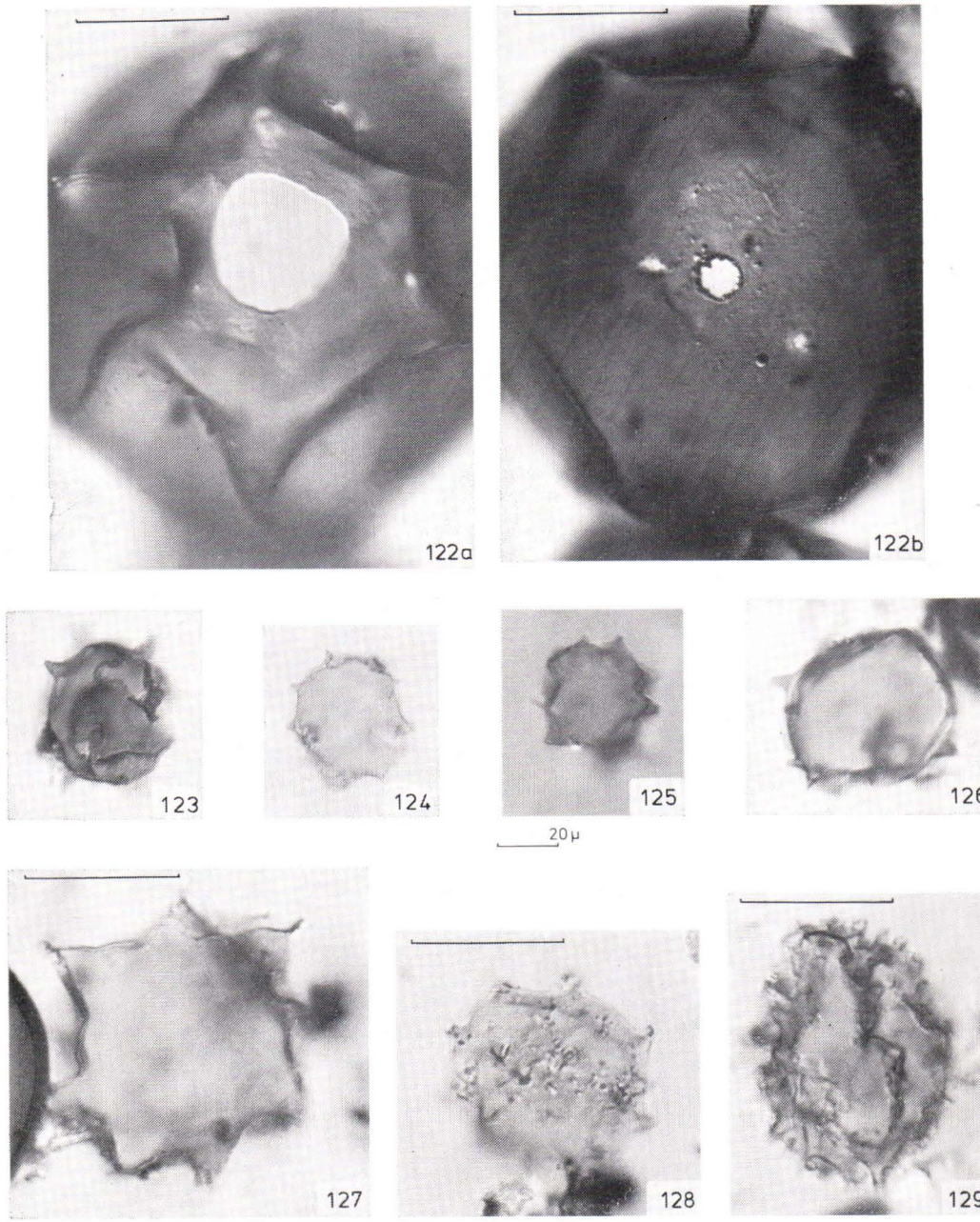




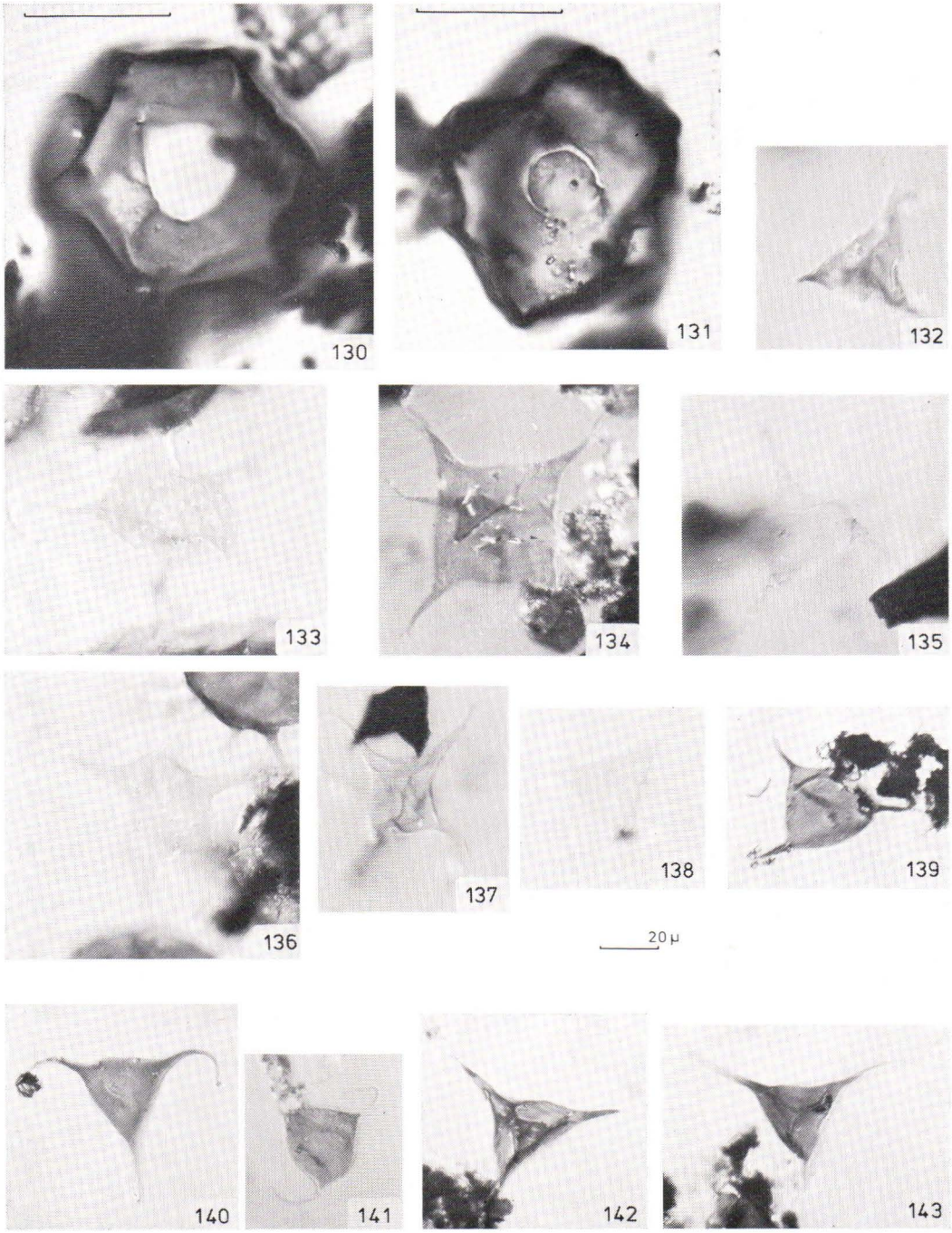
97, 98. *P. heteromorphicum,* 99. *P. majorfurcatum,* 100 a, b. *P. macropylum* f. *coronata,* 101. *P. nudum,* 102. *P. nudum,* short appendages, 103. *P. polyfurcatum* n. sp., 104, 105. *P. trifurcatum* subsp. *cylindroferum,* 106. *P. trifurcatum* ssp. *hypertroficum;* fig. 100 in boulder from Segelskär, the rest are from Lumparn, deep drilling No. 4.



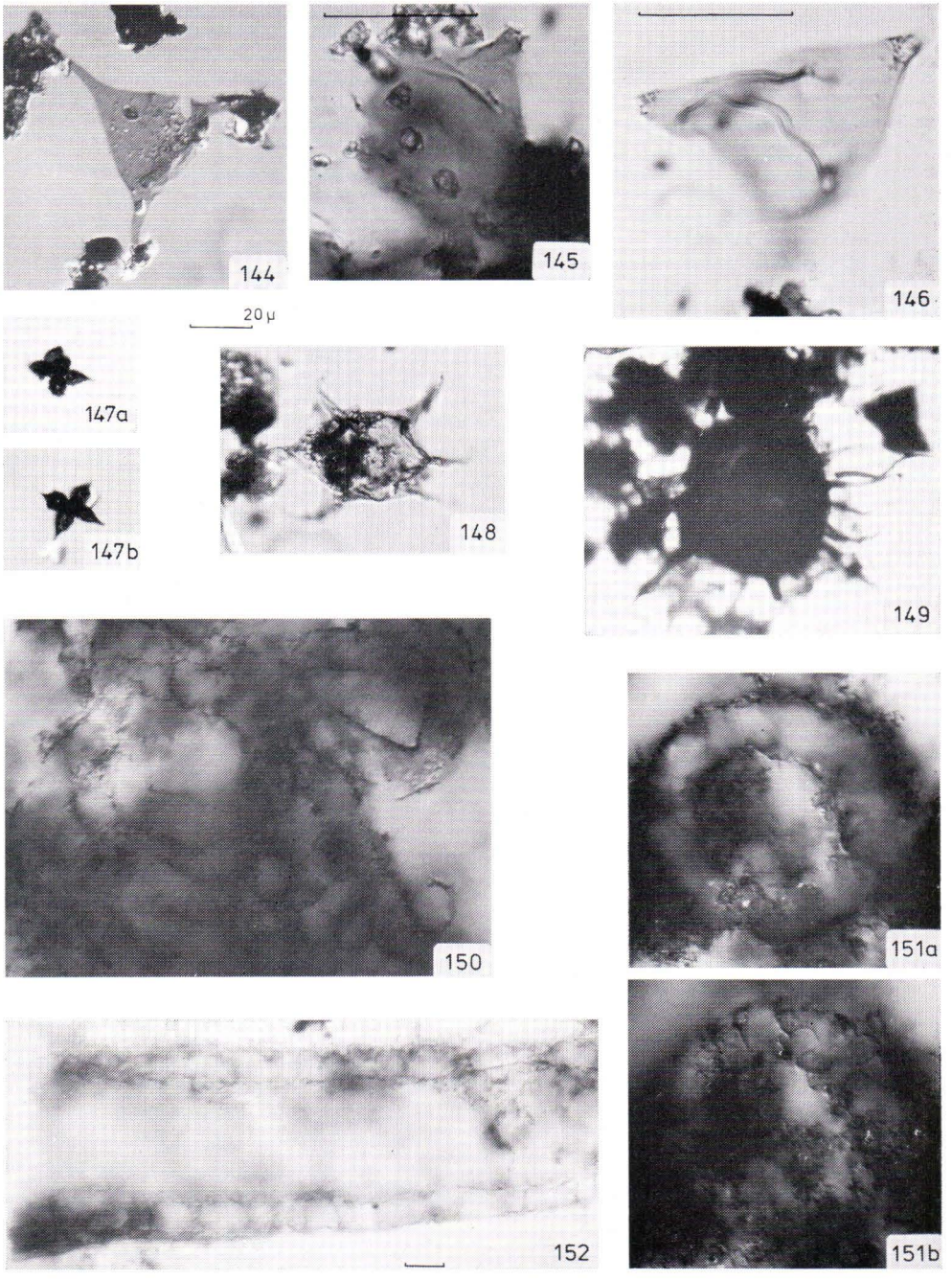
107, 108. ?*Peteinosphaeridium* aff. *hystrichoreticulatum*, 109. *Synsphaeridium* sp., 110. *Tasmanites nanus*, 111. *Tectitheca complicata*, 112—115. *Tranvikium polygonale*, hexagonal side, 116, 117. *T. polygonale*, spherical side, 118—121. *T. polygonale*, oblique and side view, Lumparn deep drilling No. 4.



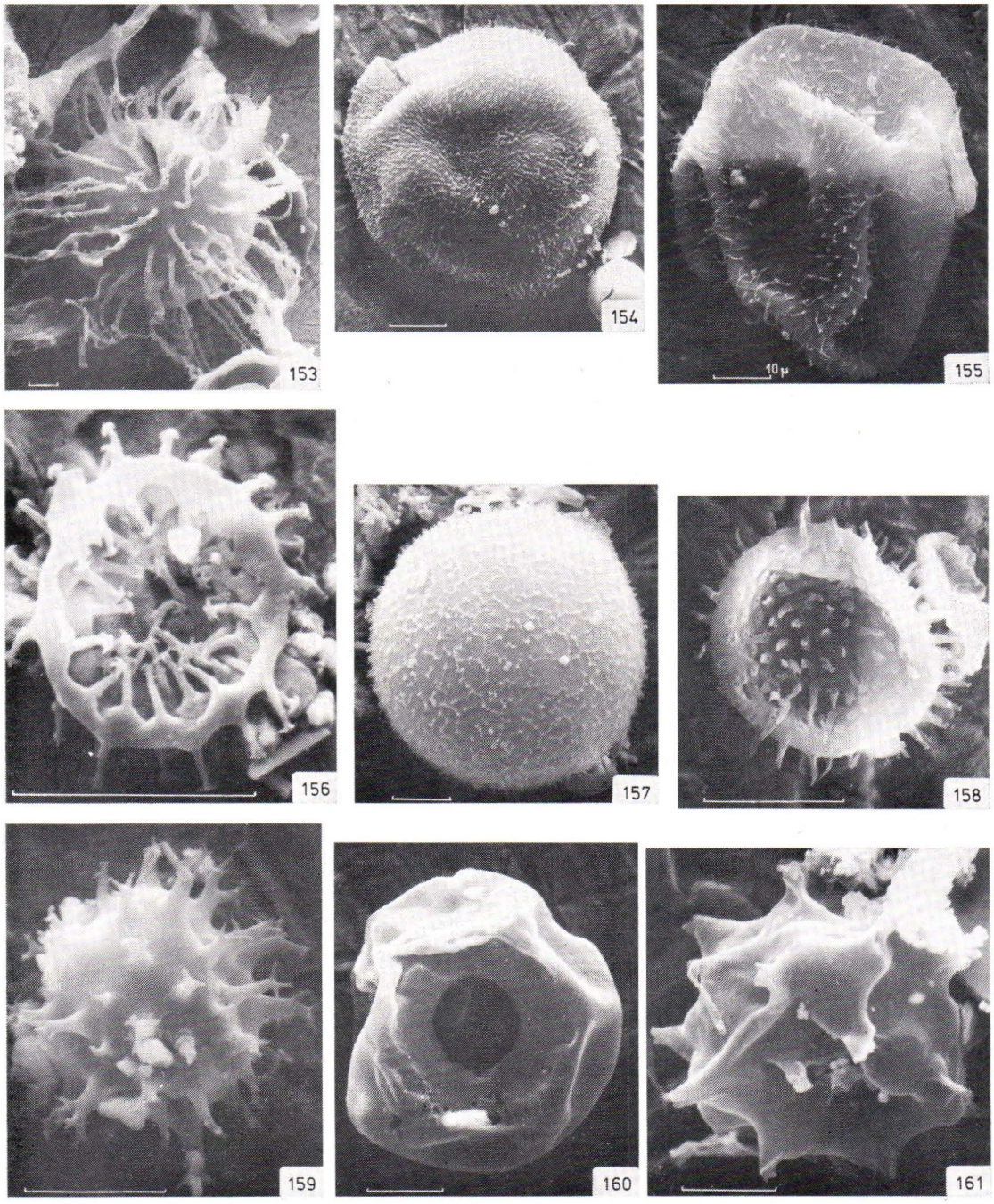
122 a, b. *Tranvikium polygonale*, hexagonal and spherical sides, 123—126. *Tylotopalla* sp. 1, 127. *T.* sp. 2, 128. *T.* sp. 3, 129. ? *Tylotopalla* sp., Lumparn deep drilling No. 4.



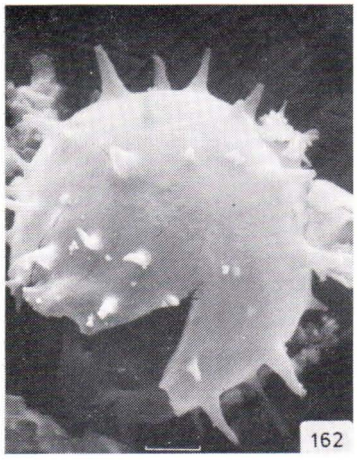
130, 131. *Tranvikium polygonale,* 132. *Veryhachium trispinosum* subsp. *reductum,* 133. *V. estrellitae,* 134. *V.* aff. *oligospinosum,* 135. *V. rhombispinosum,* 136. *V. stelligerum,* 137. *V. lairdi,* 138. *V.* aff. *triangulatum,* 139, 140. *V. trispinosum,* 141. *V. domasioides,* 142. *V. trispinosum* subsp. *geometricum,* 143. *V. trispinosum* aff. subsp. *trisulcum,* Lumparn deep drilling No. 4.

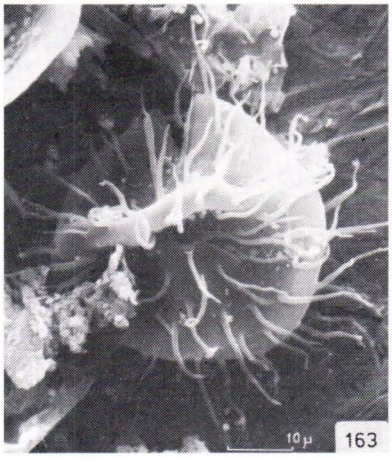


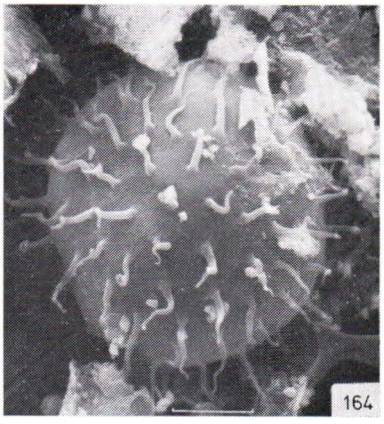
144. *Veryhachium trispinosum* subsp. *granulatum*, 145, 146. *Florisphaeridium* sp., 147 a, b. *Estiastra* aff. *minima*, 148. *Acanthodiacrodium* sp., 149. *Dasydiacrodium* sp., 150. *Girvanella problematica* var. *lumbricalis*, 151 a, b. *G. rotaeformis*, 152. *Dasycladacea*-algae, Lumparn deep drilling No. 4.

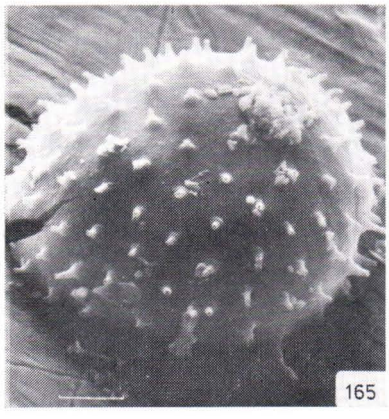


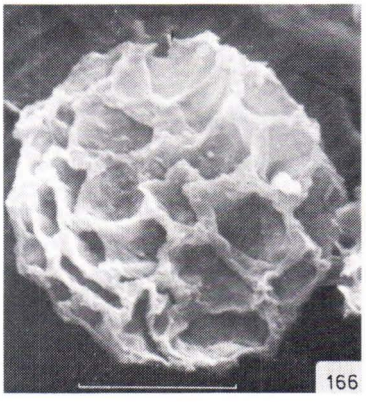
153. *Baltisphaeridium anneliae*, 154. B. *nanninium*, 155. *B. microspinosum*, 156. *Multiplicisphaeridium* ? sp., diameter about 12 µ, 157. *Cymatiosphaera* sp., 158. *Micrhystridium* sp., 159. *Multiplicisphaeridium* aff. raspa, 160. *Tranvikium polygonale*, 161. *Tylotopalla* sp., Lumparn deep drilling No. 4.

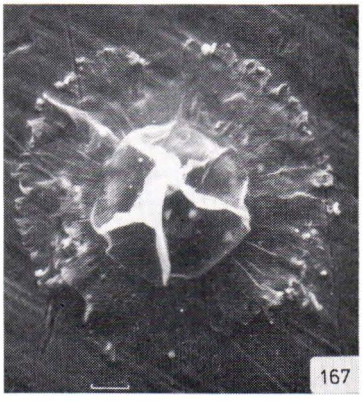


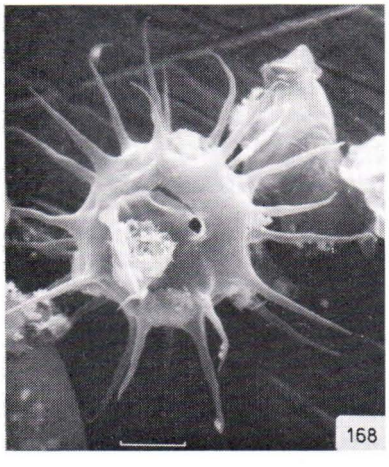


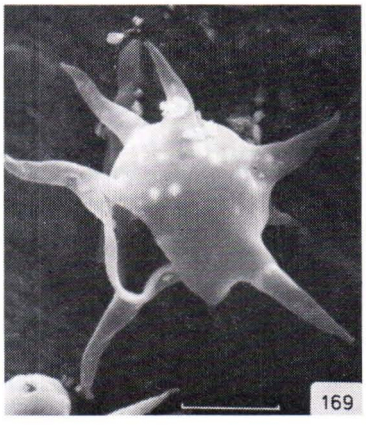


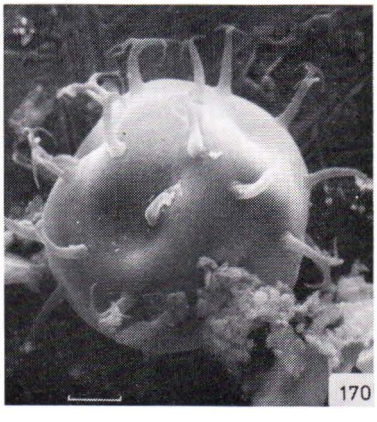












162. *Baltisphaeridium brevispinosum*, 163. *B. filosum*, 164. *B. flagellaticum* Kj. ?, 165. *B. regnellii*, 166. *Cymatiosphaera* sp., 167. *Pterospermella tranvikensis*, 168. *Goniosphaeridium polygonale*, 169. *G.* sp., 170. *Peteinosphaeridium nudum*, Lumparn deep drilling No. 4.

THE BEDROCK GEOLOGY OF LUMPARN BAY, ÅLAND

by

B. Winterhalter

CONTENTS

INTRODUCTION

Most of the bedrock in the Åland Islands, southwest of the Finnish mainland, consists of rapakivi-granite (Hausen, 1964), a not too common intrusive, postorogenic type of rock exhibiting several peculiarities. One is its susceptibility to chemical weathering, although not very obvious on Åland, and the other is its tendency to perpendicular jointing. Both factors have played a significant role in the past geological evolution of the area, and they are responsible, together with subsequent crustal movements, for the present topography of the crystalline basement.

Erratics of late Proterozoic and early Paleozoic sediments are found abundantly in various parts of the area. Especially the erratics of Ordovician limestone are quite conspicuous when found exposed on the shores, owing to their exceedingly light color and characteristic surface texture. They have commonly been assigned an origin involving glacial transport from the marine area north of the islands, although there has also been speculation about a local source. In 1926, a group of geologists on excursion (Kulling 1926) discovered Ordovician limestone cropping out at sea-level, forming a shoal (Kalkskär) some 300 meters south of Tranvik point, in the northern part of Lumparn Bay (Fig. 1). This discovery dramatically verified the previous assumptions of *in situ* sedimentary rocks in the Lumparn basin as deduced from the high frequency of erratics, especially along the southeastern shores of the bay.

Encouraged by this find, necessary funds were allocated by the Finnish Ministry of Education for drilling into the formation (shoal). Considerable difficulty was encountered in the drilling which had to be terminated at a depth of 58 meters (Sauramo 1942). After penetration of 31 meters of hard calcilutite, mostly light grayish with occasional reddish stains, the drill collected samples of clayey intercalations in limestone. These lower and middle Ordovician limestones, totaling 32 meters in thickness, were found to be underlain by Cambrian claystones and siltstones, the clay being so soft that the drill string finally jammed at the depth of 58 meters.

The extent of the submarine Paleozoic formation was and is, in fact, even today a question needing further investigation. The Pargas Kalk Company — now Oy Partek Ab — tried to resolve the question of the extent of the limestone sequence by carrying out a series of drillings. Although the number of drill holes was, according to Mr. Rolf Boström (pers. comm.), considerable, all the holes were located in the vicinity of the shoal and thus did not succed in delimiting the extent of the formation, except north of the shoal. In 1979, Partek drilled five additional holes in the central parts of the basin. The drill cores indicated that the limestone (Ordovician) is limited in extent to the northeastern part of the basin, i.e., to the shoal area and its extension south and southeast.

Cambrian siltstones and, especially, basal conglomerates of possible Proterozoic age seemed to occupy large parts of the bay bottom. The basal conglomerate, as it occurs on,

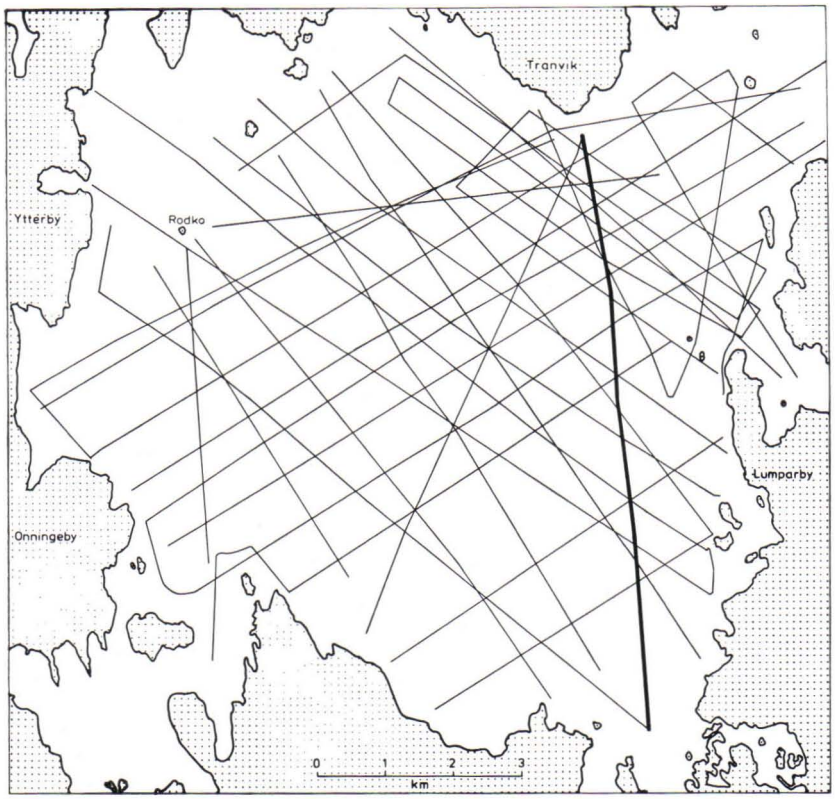


Fig. 1. Outline map of Lumparn Bay, (cf. Fig. 1, p. 8, and Fig. 2, p. 9) with tracklines showing the location of the continuous seismic reflection profiles. The hold line denotes the location of profile in Fig. 8.

e.g., the small island of Rödko in the west-northwestern part of the bay, was assigned by Asklund and Kulling (1926) a Jotnian age. Basal conglomerates were also observed to occur in some of the Partek drill cores. The underlying rapakivi basement was deeply weathered and partly brecciated in most of the cores that penetrated the sedimentary sequence.

Regarding the origin of the Lumparn basin, most authors advocate a tectonic depression. In a recent study on the conodonts in the Ordovician limestone from Lumparn, Merrill (1979) proposes a meteoritic hypervelocity impact to be responsible for the present form of the basin. Previous marine geological work done in the area by the Geological Survey of Finland indicated that the bathymetric map (Fig. 2) of the bay could not provide a very reliable basis for an analysis of the bedrock morphology toward determining a possible meteoritic origin. The Quaternary sediments were found to be of considerable thickness and capable of masking possible signs of an astrobleme. Thus a number of new seismic reflection profiles were made in the bay, together with sonobuoy measurements, in an attempt to gain a better understanding of the geology and tectonics of the submarine area.

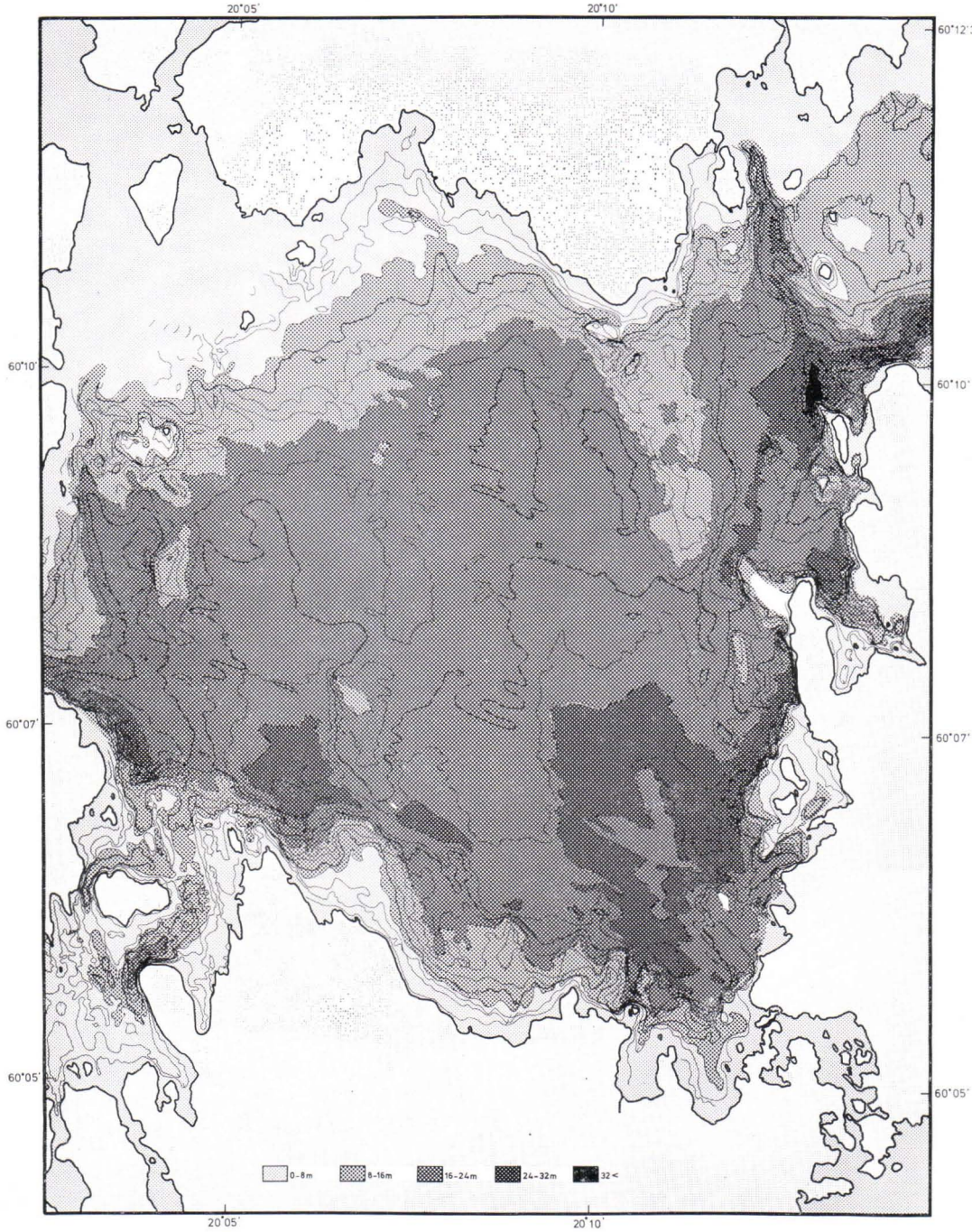


Fig. 2. The bathymetry of Lumparn Bay, redrawn from a bathymetric map prepared at the Oy Partek Ab company.

SEISMIC PROFILING

During the years 1974, 1976 and 1978, a total of 350 km of single channel reflection profiles were run across the Lumparn Bay (Fig. 1). In the majority of the profiles, a 1 cu. in. Bolt Air Gun was used as a sound source. Larger chamber sizes (20 and 40 cu. in.) were used in sonobuoy refraction shooting.

The conditions for high resolution profiling are very adverse, owing to the rather shallow depth of the water, with the inevitable multiple reflections coinciding with the subbottom reflectors. Furthermore, the great thickness (20—40 meters) of late- and, especially, postglacial silt containing gas bubbles formed from decomposing organic matter in the upper part of the sediment caused strong reverberation of the acoustic pulse (Fig. 3), effectively scattering all but the lowest frequencies to be registered on seismic profiles. Thus to achieve penetration, low-frequency band-pass filtering had to be resorted to, inherently sacrificing resolution.

The drill cores obtained by Partek suggested that the limestone strata in the Kalkskär area are rather inconsistent and anomalous to the assumed deposition under quiet conditions. Post-depositional dislocations are evident in the reflection profiles (Fig. 4) run across the part of the limestone formation es-

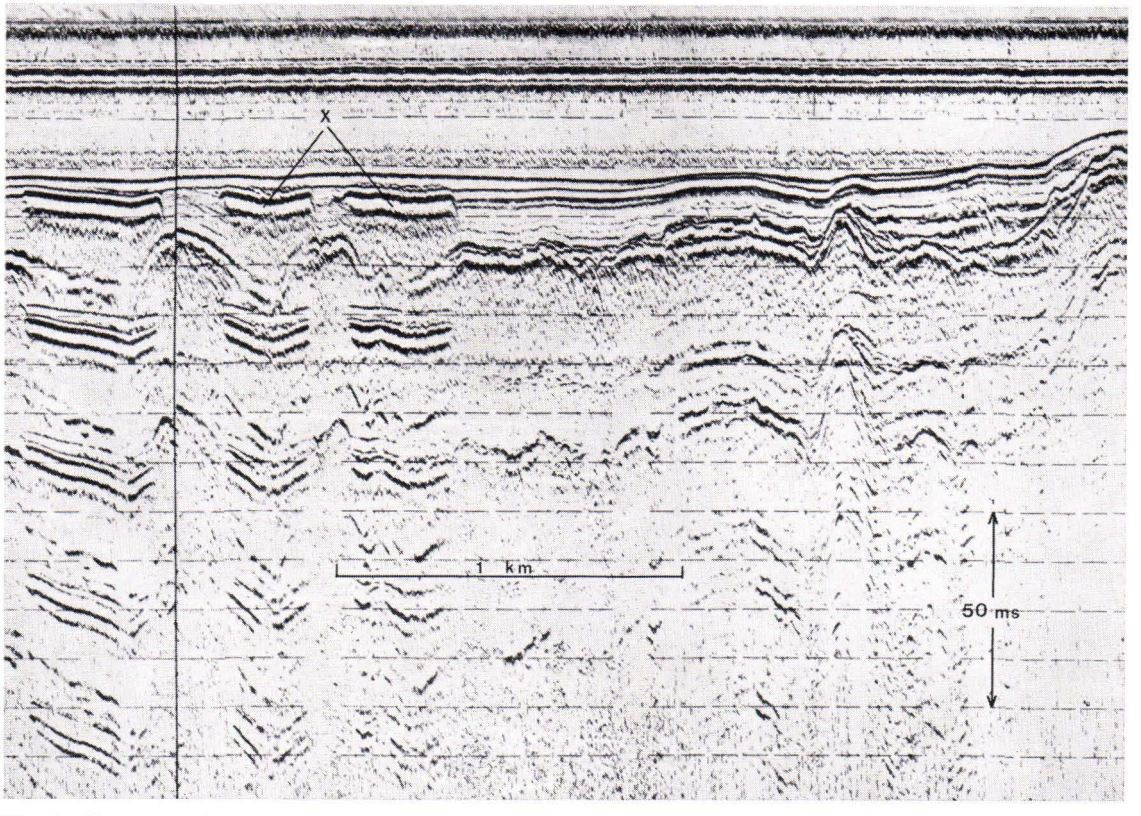


Fig. 3. Example of a reflection profile exhibiting multiples and the »basin effect» — reverberations — e.g. (x) in the figure.

tablished by the drillcore data (Oy Partek Ab). The upper surface of the limestone, which is partly covered by Quaternary sediments, is very rugged, a feature typically assigned to tectonized rocks. Due to the rugged limestone topography no acceptable sonobuoy refraction results were acquired from the shoal area. However, the high seismic velocity (3500 m/s), measured in limestone of similar quality and age in the Bothnian Sea (Winterhalter 1972) less than 100 km north-northwest of Lumparn, can probably also be assigned to the present deposit. The more or less poorly consolidated sandy and silty sediments, of Lower Ordovician and Cambrian age, which underlie the limestone, exhibit a seismic velocity considerably lower than that of the limestone. This leads to a situation where a high-velocity layer, in shallow water, and with a rugged top surface, is underlain by a low-velocity layer. The numerous multiples effectively masking the possible weak internal reflections make the acquired reflection profiles quite difficult to interpret. Although there is a definite analogy between the lithology of the sediments in the Lumparn Bay and that of the equivalent deposit in the Bothnian Sea, where the Cambrian sediments are clearly discernible on the reflection profiles (Winterhalter 1972, Axberg 1980), the lower boundary of the Cambrian in Lumparn Bay can be detected but very vaguely. This must be due to the similarity of the acoustic impedances (products of seismic velocity and specific gravity) of the Cambrian sandy and silty sediments and the subjacent, deeply weathered granitic basement and/or aforementioned Proterozoic sediments (p. 116). The sonobuoy refraction profiles are likewise and on the same grounds rather difficult to interpret. In most cases, the T/D sonograms showed a more or less uniform increase in velocity with increasing depth. These were originally interpreted to indicate the existence of sedimentary rocks down to a depth of 100 to 200 meters u.s.l. However, the few drill core data later made available by Partek from the central part of the basin suggests that the increase in velocity observed on the refraction profiles could be due to the inverse effect of a diminishing degree of weathering with depth in the rapakivi-granite forming the crystalline basement.

Despite poor penetration into the limestone, the reflection profiles do indicate the existence of a substantial formation in the northeastern part of the bay. Although internal sedimentary structures (bedding planes) were observed only in a few profiles from the northwestern edge of the formation (Fig. 4), the »high-velocity» limestone of the Tranvik area seems to produce a rather special signature on the reflection profiles owing to its high reflectivity and the existence of internal reflectors despite their weakness. No similar signature is to be found in profiles from other parts of the bay, indicating the limited extent of this rock type.

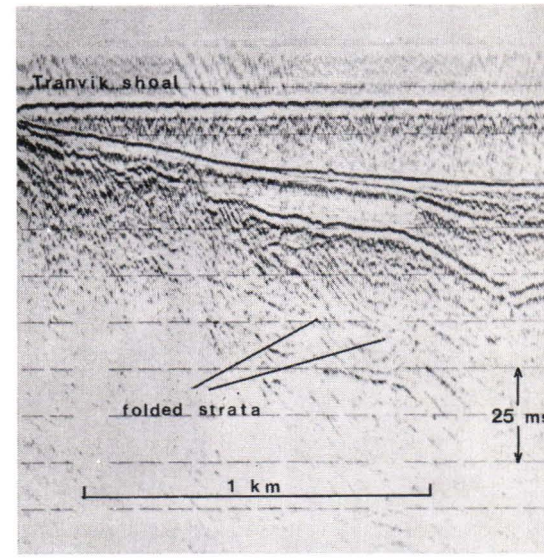


Fig. 4. Continuous seismic reflection profile across part of the limestone outcrop south of Tranvik point showing the limestone shoal area and gently folded strata (Cambrian ?) dipping west.

Likewise, the profiles from the other parts of the bay exhibit slightly varying signatures, distinguishable from the kind caused by typical crystalline bedrock. This characteristic of signatures has provided an opportunity to delineate the extent of both weathered granite and the assumed Proterozoic sediments (cf. p. 00).

THE BEDROCK OF LUMPARN BAY

The fortunate availability of drill-core data from Lumparn Bay, although scarce, still has provided sufficient background information to aid in preparing a schematic bedrock map (Fig. 5), based on the interpretation of seismic reflection and refraction data.

The crystalline basement

As stated in the introduction, Lumparn Bay is located within a large massif of post-orogenic granite, which, in accordance with its mineralogical composition and texture, (cf., e.g., Vorma 1976) is classified as rapakivi granite. The texture and structure of the granite exhibit considerable local variations (Hausen 1964, Bergman 1981), ranging from typical rapakivi (wiborgite) with orthoclase ovoids mantled by oligoclase, to pyterlites (unmantled ovoids), and granites without ovoids including aplites and quartz porphyries. The eastern shore of the bay consists, for example, of a wiborgite and pyterlite, the southern and western shore of pyterlite together with quartz porphyritic rapakivi. According to the map of the rapakivi-granites of the Mariehamn area prepared by Bergman (1979), it is obvious that Lumparn Bay is located in the contact junction of various types of granites originally representing either different stages in the emplacement of the granite or different levels of the assumed batholith dislodged by tectonic activity and subsequently degraded to a common level.

The contacts between the various types of granite are too vague to be followed under water on geophysical grounds. Also the limited number of drill holes from the marine area prevents such an attempt. These drill cores do, however, indicate the rapakivi to be deeply weathered. Also brecciated rapakivi is encountered in the drill cores, indicating crustal movements.

On the continuous seismic reflection profiles, the pre-Quaternary basement, originally interpreted as consisting of a sedimentary bedrock, owing to its gently undulating surface, and indications of internal structural features can and does in many instances represent deeply weathered granite surface, as revealed by the drill-core data. This interpretation is not inconsistent with the results of the sonobuoy refraction measurements, which show a gradual increase in seismic velocity with depth starting from a velocity typical of sand and gravel (2000—2300 m/s) and, for that matter, also of an unconsolidated breccia, to that of intact granite (around 5500 m/s).

The sedimentary bedrock

It is obvious from what is known of the granitic surroundings and the drill-core data that the ultimate basement under the bay consists of rapakivi granite. Owing to the marked perpendicular jointing and the susceptibility to chemical weathering, possibly

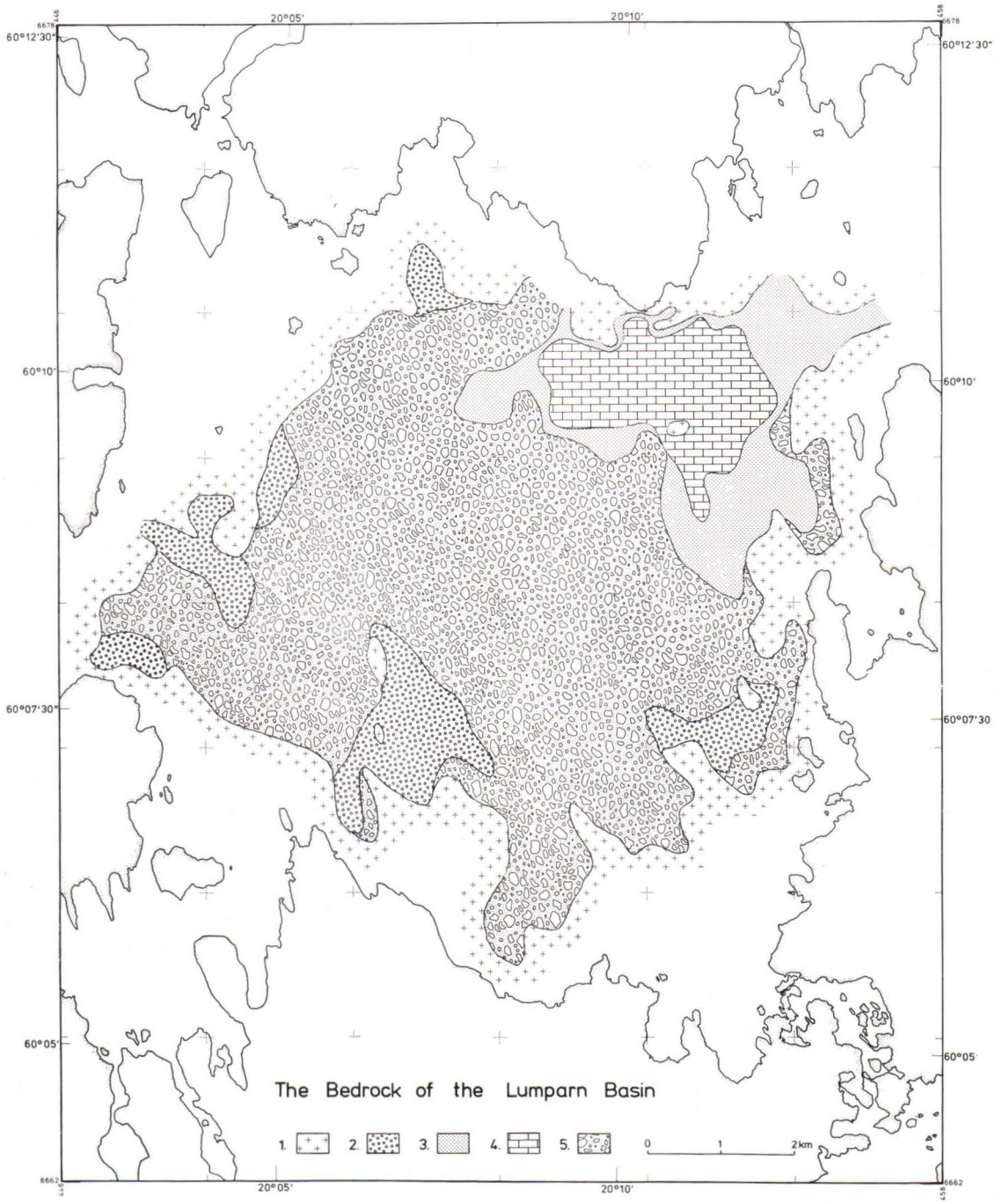


Fig. 5. Outline map of the bedrock of the Lumparn basin: 1. granite (rapakivi), 2. undifferentiated sedimentary rock, 3. Cambrian sandstone and siltsstone, 4. Ordovician limestone, 5. deeply weathered, granite, possibly erosional remains of sedimentary rock.

promoted by tectonic activity, the granitic material formed basal breccias and conglomerates in Proterozoic times. Remains of an *in situ* occurrence of such an arkosic basal breccia (conglomerate) is still visible, e.g. on Rödko island (Asklund & Kulling, 1926) and in some of the drill cores acquired by Partek. Similar rocks have been found as erratics along the southern shoreline. This arkose has been assigned a Jotnian age (op. cit), mainly based on a close textural and mineralogical resemblance to similar deposits elsewhere in Fennoscandia. A further argument in favour of a Jotnian age is the proximity to other well established occurrences in the Baltic Sea (Winterhalter *et al.* 1981). The distribution of these proposed Jotnian sediments, conglomerates and sandstones, as shown in the petrological map (Fig. 5), should be considered as highly tentative, owing to the difficulties encountered in the interpretation of the seismic profiles.

The Ordovician limestone outcrop, the Kalkskär Shoal, south of Tranvik point, first described by Kulling (1926), was sampled by drilling in 1931. The drill core (cf., p. 116) was later studied by Sauramo (1942), who failed to date the core material, owing to absence of dateable fossils. Later on, Oy Partek Ab drilled several holes both in the shoal area and somewhat south of it with the intent of establishing the extent of the limestone deposit. The sediments encountered in the drill cores varied considerably even between adjacent cores drilled only a few hundred meters apart. It became evident that substantial dislocations have occurred both during deposition and more probably later. Some of the drill-core material has been studied by Merrill (1979) and Tynni (1982). Merrill dates the limestone from the shoal to late Caradocian, Upper Ordovician. This is verified by Tynni's work on microfossils. The limestone sequence consists of biomicritic and various calcilutitic and dolomitic layers. The bottom of the Paleozoic sequence at Kalkskär consists of Lower Ordovician and Lower Cambrian sandstones and siltstones (Tynni 1982).

As mentioned previously, the reflection profiles from the limestone area are extremely difficult to interpret, owing to the scarcity of detectable internal features; the acoustic signature of the limestone can, by some exercise of the imagination, be used to eliminate those sections of the reflection profiles where the existence of limestone is improbable. Consequently, the distribution of the limestone in the map (Fig. 5) can be assumed to be fairly reliable. The distribution of the Cambrian sandstones and siltstones is, however, not necessarily limited to the single formation in the northeastern part of the bay. Thin deposits (erosional remains) of Cambrian sediments can easily be overlooked because of their close resemblance to compact Quaternary sediments and/or weathered older sediments or even weathered bedrock, when occurring as small talus formations. This is also the reason why, in the legend for the bedrock map, the term undifferentiated sedimentary rock has been applied to denote this uncertainty.

MORPHOLOGY OF THE LUMPARN BASIN

In the aerial view, Lumparn Bay gives the impression of a somewhat distorted square, sharply outlined by two major fracture lines, one running almost N-S along the eastern side of the bay and the other running along the S-SW side coinciding with one of the most pronounced fracture systems in the Åland region, i.e., manifested in the many ob-

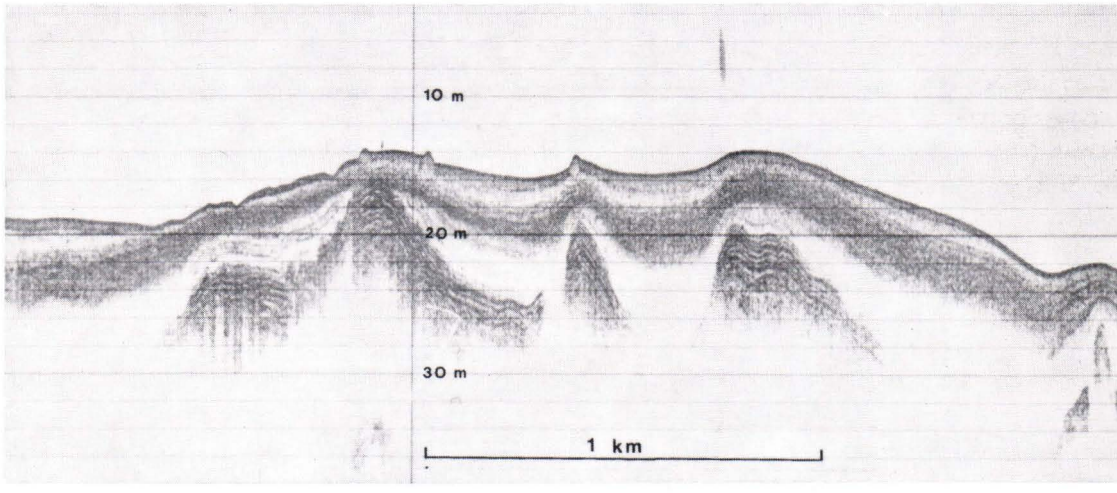


Fig. 6. Echosounding profile showing lateglacial silty sediments covered by »basin fill» type of postglacial mud.

served lineaments trending 120/300° (Hausen 1964, fig. 11, Bergman, 1981, fig. 24).

Except for the few islands located along the periphery of the bay, the absence of islands does make the bay an anomalous area in the Åland region, which is renowned for its multitude of islands and skerries.

The bay as a whole is rather shallow (Fig. 2), with a mean depth of close to 20 meters. The bottom morphology is gently undulating except for the few elongated deeps accentuating the eastern submarine slope. The flatness of the bay bottom can be ascribed to the existence of rather thick deposits of late- and postglacial silts and clays (muds). The postglacial muds, in particular, generally exhibit a tendency to be deposited as »basin fill», i.e., they tend to flatten out existing irregularities in the subbottom (Fig. 3 and 6).

To obtain an idea of the morphology of the pre-Quaternary basement, the available continuous seismic reflection profiles were used to compile the map in Fig. 7 showing the depth of the pre-Quaternary basement. The contour intervals are in 10 ms increments. The depth in milliseconds denotes the two-way travel time required by an acoustic pulse to travel from the surface to the subbottom reflector and back to the surface for recording. At a sound velocity of 1500 m/s (= sound velocity in water), the 10 ms interval is equivalent to a depth of 7.5 meters. The sound velocity in postglacial muds, forming the bulk of the Quaternary sediments in the bay, ranges from less than 1000 m/s in the topmost sediments to 1600—1800 m/s for the mud and silt deeper down. The low velocity registered for recent sediments is attributable to decomposing organic matter that causes the formation of micro-gas-bubbles, producing a phenomenon known as »basin effect». The till beds underlying the late-glacial silts are generally rather inconspicuous, being often only a few meters thick.

The limited number of reflection profiles makes it obvious that the map of the pre-Quaternary morphology cannot be correct in every detail; it does, however, definitely prove that the topography of the bedrock surface is quite different from the bathymetry of the bay. It is clear that tectonic processes, together with the perpendicular jointing of

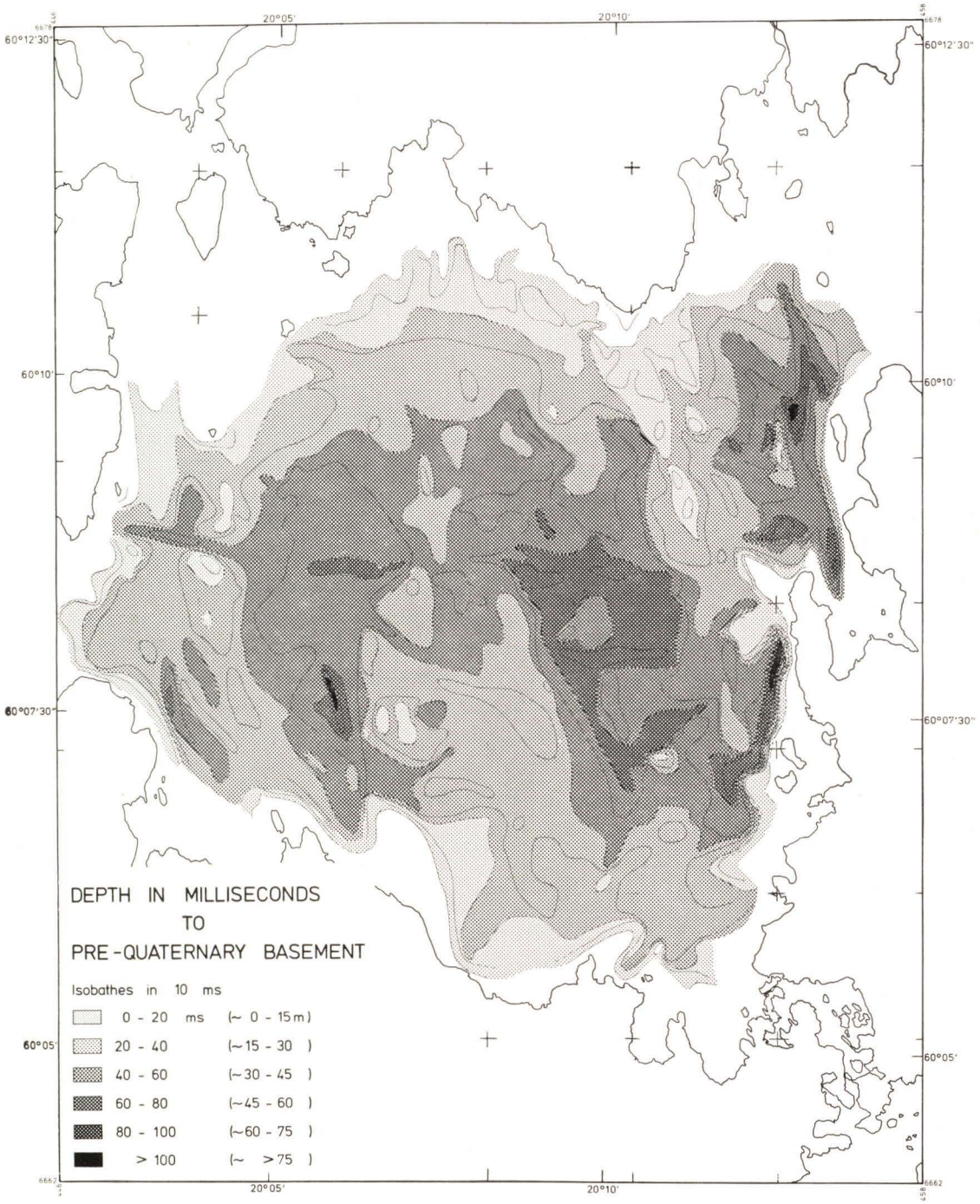


Fig. 7. Map showing the depth of the pre-Quaternary basement, i.e. topography of the bedrock underlying the Quaternary sediments. See text.

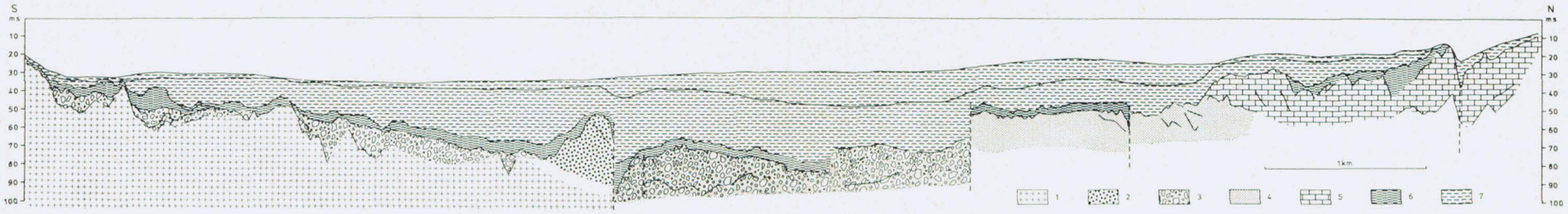


Fig. 8. A schematic interpretation of a reflection profile running S-N across the deepest part of Lumparn. Faults and fractures could be seen on the original profile. The vertical scale is in milliseconds for a two-way travel time. Legend: 1. crystalline basement (rapakivi), 2. undifferentiated sedimentary rock, 3. weathered granite, possibly erosional remains of sedimentary rock, 4. Cambrian sandstone and siltstone, 5. Ordovician limestone, 6. glacial marine sediments, 7. late- and postglacial clay and silt.

the rapagivi-granite, have been major factors affecting the bedrock morphology of the bay. The fact that deeply weathered granite is well preserved on the bottom, as observed in the drill-core material, is a clear sign that glacial erosion had not been very effective in the area, this actually being the case within most parts of the Baltic Sea region. The small-scale features in the bedrock topography can be ascribed to lithological differences in the sedimentary rocks deposited on top of the Precambrian granitic basement and to subsequent denudation, which has left the odd remains of Proterozoic and Early Paleozoic sediments shown in Fig. 5.

The analysis of the reflection profiles provided also sufficient data to delineate the major fractures occurring in the bedrock. Most of the fractures coincide well with the trends of the tectonic lineaments observed on land (e.g., Hausen 1964, Bergman 1981). Although morphological features, scarps, etc., quite often indicate the existence of a tectonic lineament, only those fractures (Fig. 8) that represent either faults or crush zones, actually detectable on the reflection profiles, have been incorporated in the map. In reality, the lineaments are probably far more persistent than suggested in Fig. 9.

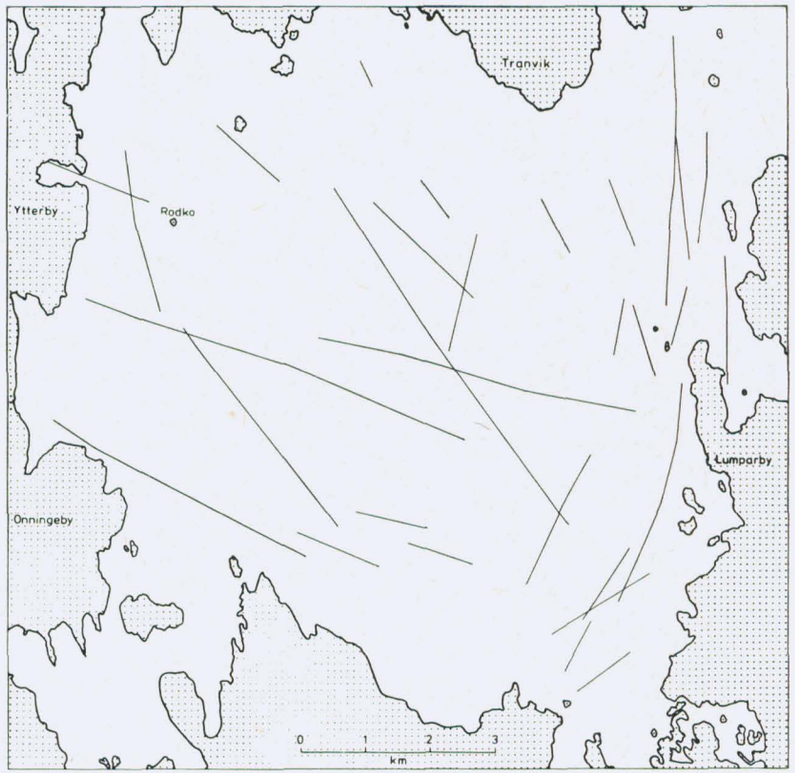


Fig. 9. The main faults and fractures in the Lumparn basin, as interpreted from the reflection profiles.

THE ORIGIN OF THE LUMPARN BASIN

Being an anomalous feature in the Åland area and the only known locality in Finland exhibiting an exposed outcrop of Ordovician limestone, Lumparn Bay has attracted the interest of geologists, past and present. The basin has been generally considered to have formed through tectonic processes representing a graben-like feature in the horst-like rapakivi massif of Åland (Kulling 1926, Metzger 1927, Hausen 1964 and others). Recently, however, Merrill (1979), in a study on Ordovician conodonts from the Åland Islands, proposes a meteoritic impact origin for the basin.

The fact that meteor impact craters have been identified in various parts of our planet has triggered off a hectic race to identify all likely and unlikely »dents» in the Earth's crust as impact structures. There are several candidates within the Baltic Sea qualifiable as impact structures. Of these, especially Lappajärvi has been studied in great detail by, among others, Lehtinen (1976). His evidence for an impact origin of the lake is quite impressive. A more controversial locality is the Söderfjärden depression, described by Laurén *et al.* (1978). The Paasivesi basin in southeastern Finland has the form and size of depressions easily assigned a meteoritic origin; but definite indicators typical of astroblemes, e.g., impact melts and shock structures, have

not been observed (Elo *et al.* 1982). It is understandable that the temptation is very strong to assign an impact origin to all circular, non-volcanic depressions in the Earth's crust. Even Merrill, who is known as a scrupulous researcher, has yielded to this temptation. He denounces the tectonic origin proposed for the Lumparn Basin by earlier geologists and presents a long line of »evidence» in favor of his own theory.

As mentioned in the foregoing, the present study is based on a considerable number of seismic reflection profiles running across Lumparn Bay (Fig. 1) and on drillhole data provided by Mr. Boström of Oy Partek Ab. Although this material seems to favor a tectonic origin, an impact origin cannot be catagorically denied.

As his first argument in favor of an astrobleme, Merrill calls attention to the shape of the basin. He finds the basin to be »markedly circular in map view». It does not really matter whether it is circular or »squarish», unless the present shoreline is the only acceptable datumline. The isostatic uplift in the area is at present approximately 5 mm per annum (Winterhalter 1981); it was very much greater following the deglaciation some 10.000 years ago. Thus the map view would be quite different if the shoreline were drawn to picture the situation some thousand years pre- or postdating the present (cf., Fig. 7 and Bergman 1979 b).

If the absence of islands, which characterizes Lumparn, is indicative of an astrobleme, as maintained by Merrill, then the most likely impact crater in Finland, Lappajärvi, cannot be one, for there we find a most pronounced central island, with many smaller ones scattered around. The central island, Kärnäsaari, exhibits several outcrops of lava-like bedrock having the typical features of an impact melt (Lehtinen 1976).

Merrill finds the »circularity» of the basin to be »distinctly at odds with the grain introduced into the topography by Pleistocene glaciation». How this argument favors an impact origin is difficult to comprehend, especially since glacially induced landforms are very scarce in the area; virtually all the topographic elevations on land consist of barren bedrock.

As a further argument in favor of an impact origin, Merrill points to the northward dip of the limestone outcropping at the shoal (Kalkskär), just south of Tranvik, as being »exactly opposite from what would be expected if the structure were produced by drag associated with large-scale block faulting». Actually the steep dip of 40° NE, mentioned by Kulling (1926), which has intrigued Merrill, seems to belong to a large block of limestone probably glacially detached from its original location. According to the observations I have made in the area using SCUBA equipment, the part of the shoal that is in all probability located *in situ* exhibits a varying strike and dip typical of a hummocky reef formation similar to the Sylen Shoal in the Bothnian Sea (Winterhalter 1967, 1972, p. 33). The fact that the limestone occurrence in the Lumparn Bay has been severely tectonized or shocked, for that matter, is quite evident from the reflection profiles and drill-core data. The preservation of the limestone from denudation can be explained by the fact that it was down-faulted at a sufficiently early stage to withstand the erosive forces that removed similar deposits from the more elevated surrounding areas. This preservation of the »remains of a ring of Paleozoic rocks» within the Precambrian terrain of the shield was stated by Merrill to be »a characteristic that Lumparn shares with a number of Canadian impact sites and with Siljan» in Sweden; but this is a statement difficult to accept on the grounds of the data available at present. Fig. 5 shows the extent of the Paleozoic sediments as deduced from several hundred kilometers of continuous seismic reflec-

tion profiles, and I personally cannot see a circular trend in the occurrence of the preserved Paleozoic sediments.

Merrill suggests that the »large limestone masses west of Lumparn represent ejecta and/or portions of an overturned rim». Considering the general distribution of limestone erratics in the Åland region (e.g., Metzger 1927, Fig. 1) and what is known of the distribution of the Paleozoic sediments in the Bothnian Sea, north of Åland (Winterhalter 1972, Axberg 1980), an impact origin for the erratics seems to be rather far-fetched. A glacial transport seems to be more plausible. I agree with Merrill that the conglomerates and, especially, breccias found as erratics along the southern shore as well as in some of the drill cores acquired by Oy Partek Ab should be studied in detail for possible clues as to their origin. I do not, however, see that the existence of breccias is as such indicative of a possible impact origin, as suggested by Merrill.

Although there is insufficient evidence definitively to contradict Merrill's proposition of an impact origin for the Lumparn basin, I hope that I have succeeded in showing up some of the weaknesses I find most obvious in his claims. Personally, I find a tectonic origin, as envisaged by earlier researchers, such as Kulling (1926) and Metzger (1927), far more plausible.

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