Geological Survey of Finland

Bulletin 297

On the geology and the Cambrian sediments of the circular depression at Söderfjärden, western Finland

by Lennart Laurén, Jyrki Lehtovaara and Rolf Boström and Risto Tynni

Geologinen tutkimuslaitos . Espoo 1978

Geological Survey of Finland, Bulletin 297

ON THE GEOLOGY AND THE CAMBRIAN SEDIMENTS OF THE CIRCULAR DEPRESSION AT SÖDERFJÄRDEN, WESTERN FINLAND

BY

LENNART LAURÉN, JYRKI LEHTOVAARA AND ROLF BOSTRÖM
AND RISTO TYNNI

WITH 21 FIGURES, 5 TABLES IN TEXT AND 9 PLATES

GEOLOGINEN TUTKIMUSLAITOS
ESPOO 1978

Laurén, L., Lehtovaara, J. and Boström, R. 1978: On the geology of the circular depression at Söderfjärden, western Finland. *Geological Survey of Finland, Bulletin, 297*, p. 5—38. 20 figures and 4 tables.

The conspicuous circular structure of Söderfjärden was studied by geological observations, gravity and seismic surveys and by diamond drillings. The results reveal a depression in the Precambrian basement, some hundred meters deep and partly filled with sandstones and siltstones, which have been micropaleontologically dated to Lower Cambrian.

The occurence of a tuffaceous breccia indicates that the structure formed either by a metoritic impact or by forceful magmatic activity.

Lennart Laurén, Paraisten Kalkki Oy, SF-21600 PARAINEN

Tynni, R. 1978: Lower Cambrian fossils and acritarchs in the sedimentary rocks of Söderfjärden. *Geological Survey of Finland, Bulletin 297*, p. 39—81. 1 figure, 1 table and 9 plates.

Some fossils, especially *Volborthella tenuis*, and several microfossils (acritarchs) from the lower Cambrian sedimentary strata from Söderfjärden are discussed. The microfossils are classified according to acritarch-systematics into 18 formgenera. A detailed study of the fossils has revealed new species, although, the bulk of the microfossils consists of the same species as those described from Baltic lower Cambrian deposits.

Risto Tynni, Geological Survey of Finland, SF-2150 ESPOO 15

ISBN 951-690-089-5

Helsinki 1978. Valtion painatuskeskus

CONTENTS

ON THE GEOLOGY OF THE CIRCULAR DEPRESSION AT SÖDERFJÄRDEN, WESTERN FINLAND

by

Lennart Laurén, Jyrki Lehtovaara and Rolf Boström

CONTENTS

INTRODUCTION

The Söderfjärden structure is situated about 8 km south of the town of Vaasa in western Finland (Fig. 1). It forms a very conspicuous circular feature with a diameter of 5.5 km.

The interest of Paraisten Kalkki Oy for a closer examination of the structure was aroused when company geologists studying Landsat-1 (ERTS-1) images from western Finland spotted the circular feature on the images. Actually, the structure as it appears on satellite images as well as aerial photographs is not completely circular, but somewhat hexagonal (Fig. 2).

Morphologically the Söderfjärden structure forms a circular plain lying barely above sea level. It is circled by hills rising 20—40 m above sea level. Only a century ago the Söderfjärden plain was a bay connected with the sea, but the rapid land uplift in this region has elevated it to the present level. Drainage work has transformed the area into an important agricultural district. There are no rock outcrops within the basin.

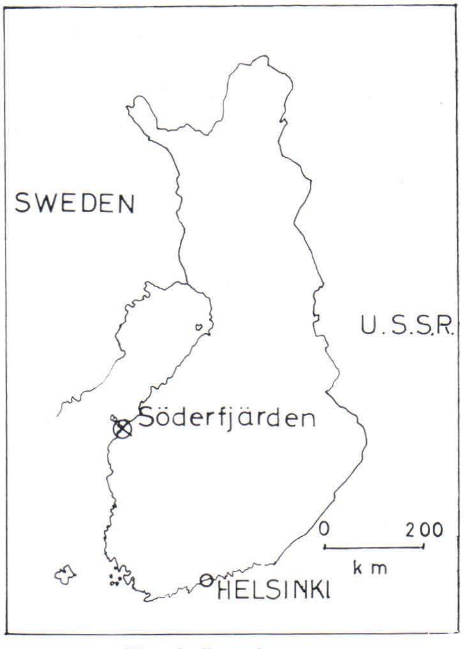


Fig. 1. Location map

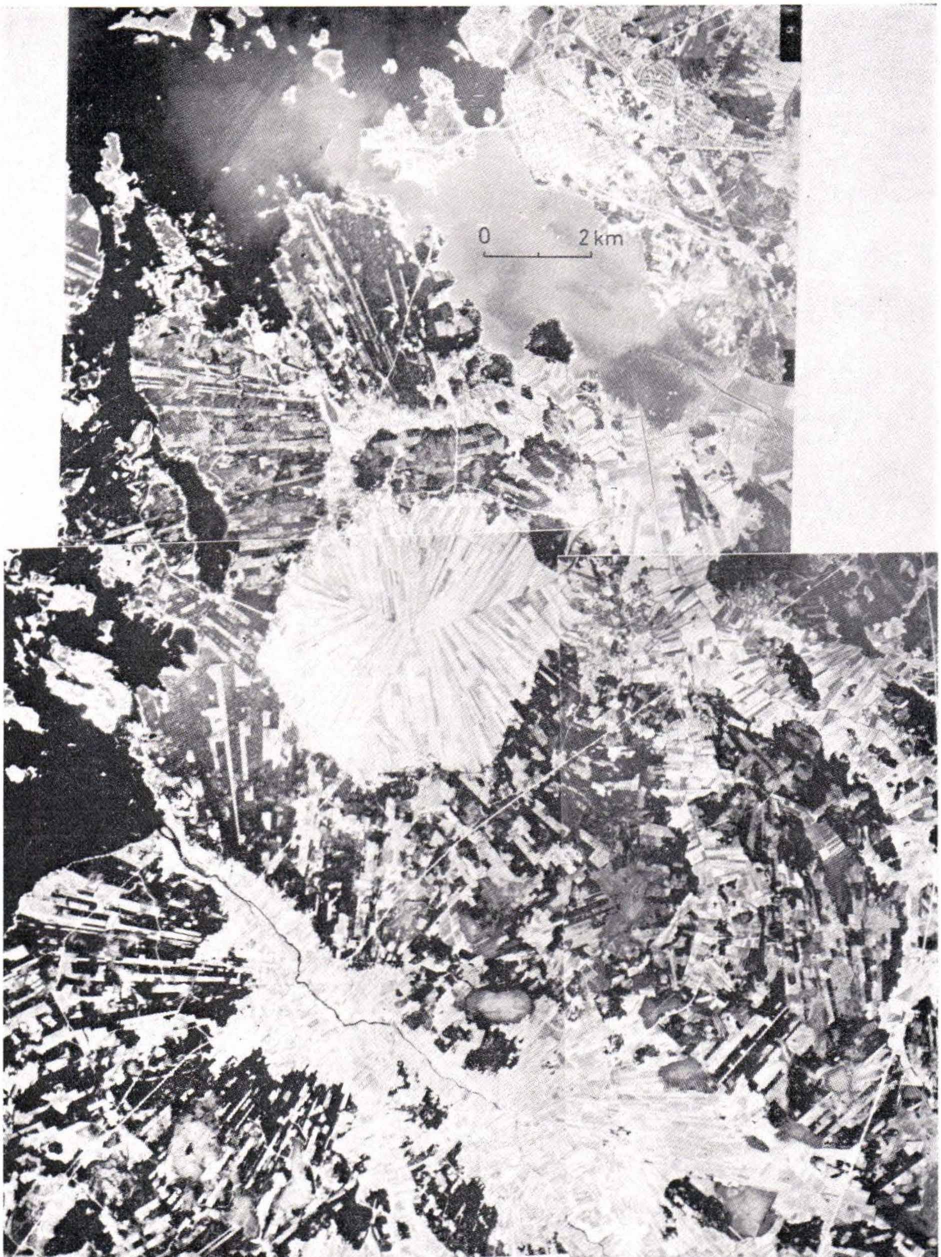


Fig. 2. Aerial photograph of the Söderfjärden structure.

GENERAL GEOLOGY

The country rock of the Söderfjärden circular structure belongs to the southern reaches of the Vaasa granite, a vast granitic pluton, the bulk of which is situated north of the direction Vaasa—Lappajärvi in southern East Bothnia (Saksela 1935, Laitakari 1942). Towards the south the rocks of the pluton gradually intermingle with and change into schists.

In the Söderfjärden area the Vaasa granite is gneissose in general appearance. It has also a migmatitic character showing both clear-cut and nebulous remnants of mica gneiss and, more scarcely, amphibolite and calcareous layers and concretions. Pegmatites are not frequent and occur in clearly migmatitic portions of the rock.

Any local rock types possibly related genetically to the circular structure were first sought in the local drift. Those were well exposed in the municipal sand pits of Solf and Malax, just southeast of the Söderfjärden structure. Besides the bulk of boulders consisting of the omnipresent Vaasa granite and Jotnian sandstone, a few more exceptional rock types were encountered (Fig. 3). Among those were cobbles of very heterogeneous tuffaceous material, in some cases seemingly brecciating the gneissose country rock, and pieces of the country rock looking strongly weathered and very brittle. Thereupon, rather soft boulders of whitish sandstone were met with.

Last mentioned rock types were found nowhere else on the rim about the circular structure. In the outcrops along the rim only inhomogeneous varieties of gneissose Vaasa granite were exposed. The tectonic orientation of the country rock was seemingly unaffected by the circular structure itself.

GEOPHYSICAL INVESTIGATIONS

Gravity survey

The gravity measurements were performed with a Worden gravimeter and the structure was at first covered with an irregular network of measuring points, the distance between the points being 200—300 m. The survey revealed a significant negative gravity anomaly and part of the area was measured with a regular grid of 100 × 200 m (Fig. 3).

The magnitude of the negative gravity anomaly is 5—6 mgal and the shape of the anomaly clearly outlines the circular (and hexagonal) character of the Söderfjärden structure.

A preliminary interpretation of the gravity measurements indicated that a thick soil cover could not be the sole cause of the anomaly. This would imply an overburden thickness of more than 100 m. As such an alternative seemed rather improbable, the anomaly was interpreted to be caused mainly by low-density rocks underlying the

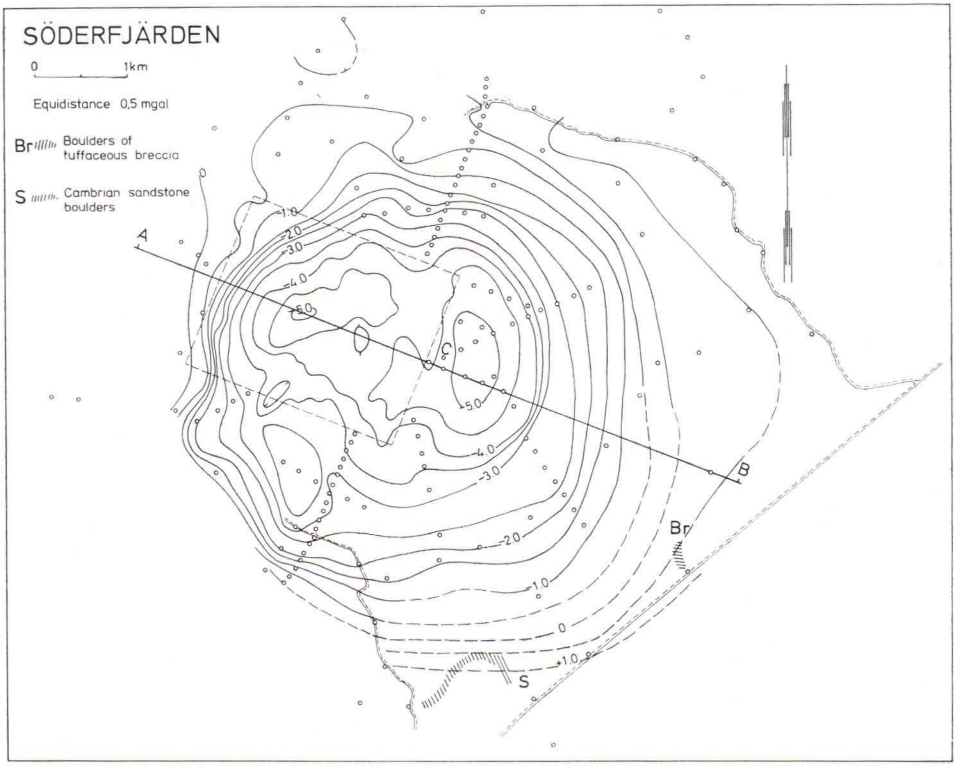


Fig. 3. Gravity map of the Söderfjärden area.

soil cover. These rocks should have a density considerably less than the surrounding granitic rocks. The conclusion clearly pointed to the existence of younger sedimentary rocks beneath the overburden. The occurence of boulders of Cambrian sandstone southeast of the structure also supported this assumption. In order to confirm the conclusion reached a seismic survey was performed.

Seismic survey

Two perpendicular seismic refraction profiles were measured across the Söderfjärden structure (Fig. 4, profiles A—C, D—E and F). The survey was performed by Geotek Oy using an ABEM Trio 12 channel seismograph.

Beneath the soil cover the seismic velocity ranges from 2 300 to 4 200 m/s i.e. it is distinctly lower than the normal velocities of Precambrian rocks. The distribution of the velocities measured is shown in the frequency histogram of Fig. 5.

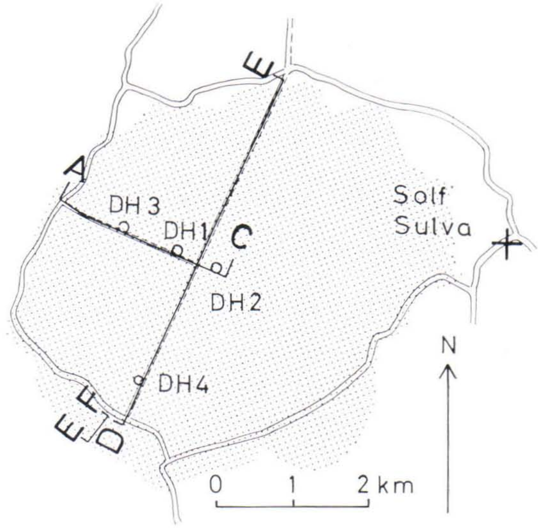


Fig. 4. Location of the seismic profiles and diamond drill holes.

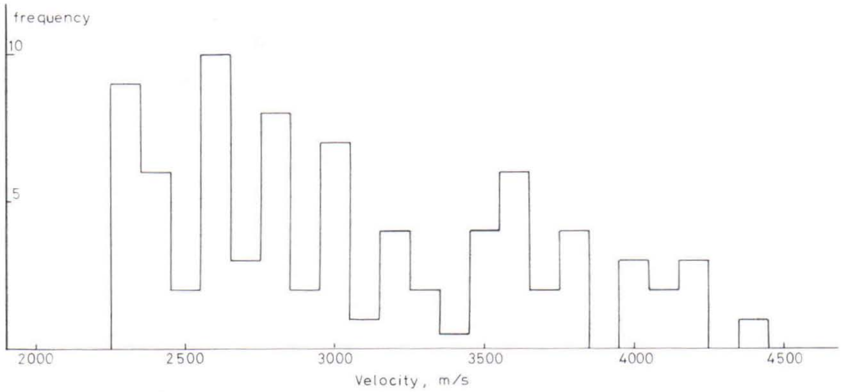


Fig. 5. Distribution of the seismic velocities.

The distribution pattern is rather indistinct. There is a certain shift towards the lower velocities with several peaks in the range of 2 300—3 000 m/s compared with only one distinct peak around 3 600 m/s in the higher range. When comparing these velocities with those measured at different sedimentary formations it appears that both the velocities of the Jotnian shales and sandstones at Muhos and Hailuoto (Lanne *et al.* 1974, Veltheim 1969) and those of Paleozoic sedimentary rocks (Winterhalter 1972, Clark 1966) lie within the same range as the velocities measured at Söderfjärden. The velocity of the Jotnian sandstone of Satakunta, at 4 000—5 000 m/s (Winterhalter 1972), is somewhat higher than the Söderfjärden velocities.

The seismic survey confirmed that the soil cover at Söderfjärden has a considerable thickness (Fig. 6).

According to the seismic results the upper part of the overburden consists of a 20—40 m thick clayey layer which is rather mud-like for the uppermost meters. The mud layer, which is indicated by very low velocities (240—300 m/s), absorbs the seismic energy quite strongly and thus reduces the depth penetration of the survey. The low velocity is probably due to a substantial amount of organic material in the soil. Swampgas has also been reported by the local population and it was encountered in one of the drill holes. The lower part of the overburden has a seismic velocity varying from 1 600 to 2 200 m/s in the deepest parts. The thickness of this layer is 20—70 m and it consists mainly of till being quite compact in the basal parts.The total thickness of the overburden is normally about 40 m but in the deepest parts it reaches about 100 m.

The seismic refraction survey was not able to penetrate the low-velocity formation in its thickest parts and could consequently give only minimum depths for these parts. This was due partly to the considerable depths and partly to the absorption of the seismic energy in the soft surface layers. The greatest depths were recorded in the western part of profile A—C where the seismic thickness of the sedimentary (low-velocity) formation is more than 320 m. The location of the thickest part of the seismic model coincides with the center of the gravity low. For the N—S running profile D—E the depth values are lower, but still over 170 m at the deepest parts. The seismic velocity of the deep parts is 2 300—3 000 m/s.

Steep contacts between the different velocity units and rather large lateral variation are characteristic features of the seismic profiles. Some form of block faulting within the basin is indicated. Especially in the N—S running profile blocks with velocities in the range of 2 300—2 800 m/s seem to be downfaulted between »horsts» of higher velocity (3 200—3 600 m/s). The outer contacts against the country rock also have a steplike character.

DRILLING RESULTS

Three diamond drill holes were drilled along the E—W running profile A—C (Fig. 4). Drill hole 3 was designated to intersect the depression at its thickest part, drill hole 1 where the rock surface is closest to the surface and drill hole 2 was placed in an intermediate position.

Drill hole 3 struck siltstone at a depthe of 72 m while (Fig. 7) drill hole 1 encountered altered gneissose granite (Vaasa granite) at a depth of 31 m. Drill hole 2 struck a peculiar rock, rich in fragments and showing both tuffaceous and breccia-like characteristics, at a depth of 49 m. The rock is in the following called tuffaceous breccia.

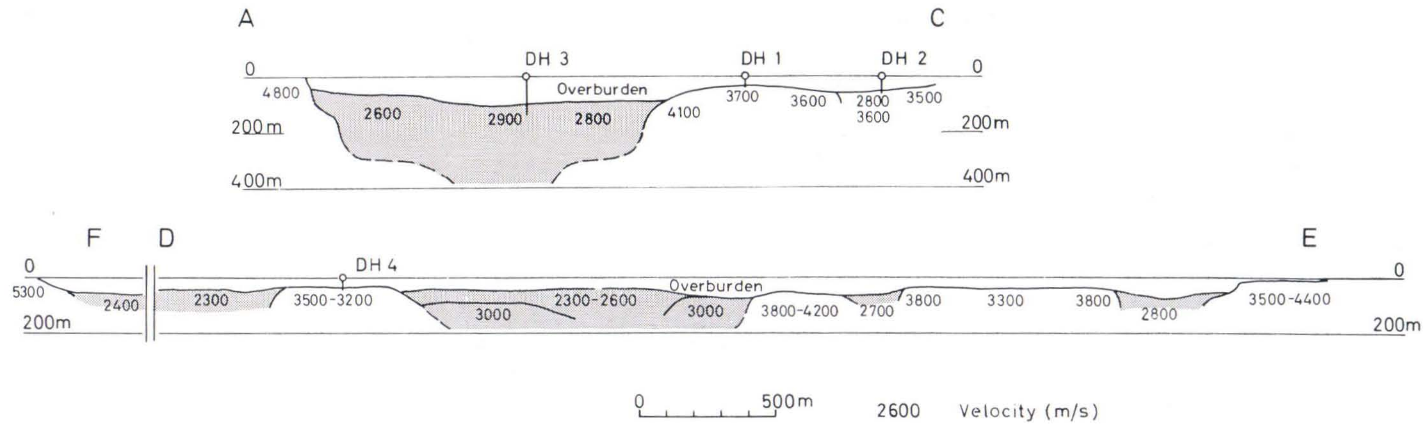


Fig. 6. Seismic profiles from the Söderfjärden structure

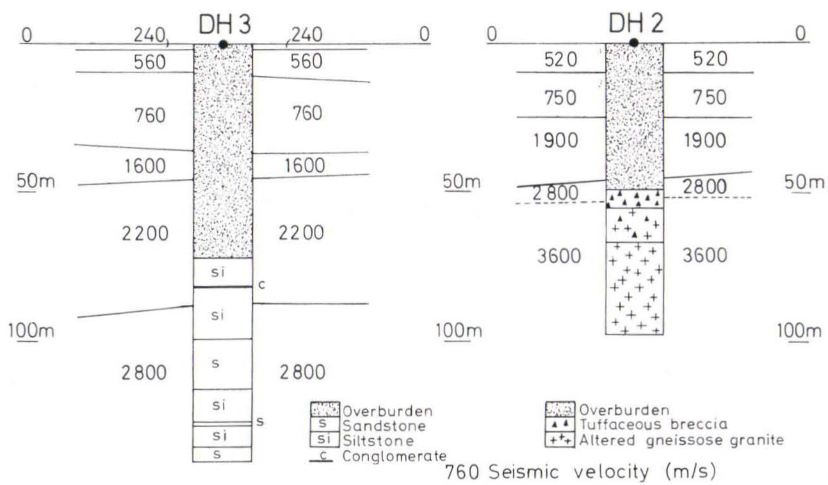


Fig. 7. Drilling results from drill holes 2 and 3

The breccia is underlain by more or less altered country rock (Fig. 7). A fourth hole was drilled in the »high-velocity horst» (3 200—3 500 m/s) in the southern end of the N—S running profile D—E. It struck altered gneissose granite containing veinlets of tuffaceous breccia. Drill cores of the different rock types are shown in Fig. 8.

The intention was to penetrate the sedimentary formation with drill hole 3, but due to technical difficulties the drilling had to be stopped at a depth of 140 m while still in sandstone. Anyway, the drillings clearly show that the deeper parts of the depression consist of sedimentary rocks. According to micropaleontological studies by Tynni (see p. 39) the age of the sediments is Lower Cambrian. It is also evident from the drillings that the bottom topography of the depression is rather undulating, in places the crystalline besement rises to only some tens of meters from the surface and is directly overlain by Quaternary deposits. The tuffaceous breccia is probably the clue to the origin of the depression, indicating either a meteorite impact or forceful magmatic activity.

Fig. 8. Drill cores of the Söderfjärden rock types (from left to right): shale, siltstone, sandstone, conglomerate, tuffaceous breccia, altered Vaasa granite.

INTERPRETATION OF THE GEOPHYSICAL MEASUREMENTS UTILIZING DRILLING DATA

Gravity

The drill cores received from the diamond drilling made it possible to measure the densities of the rocks within the Söderfjärden basin enabling a more detailed interpretation of the gravity anomaly (table 1, p. 21). The density data naturally represent a quite limited sampling of the structure but justify anyway some simplified model computations. The model was computed for the E—W running profile A—B (Fig. 9).

The accurate density distribution for the sedimentary pile cannot be determined due both to scarce density data on the siltstone and the uncertainty regarding the ratio of sandstone to siltstone in the sedimentary pile. A simplified model with a uniform density contrast of -0.35 g/cm^3 was employed. The density contrast used is probably somewhat larger than the actual difference which means that the resulting model should give minimum thickness values of the sedimentary formation. An overburden layer with the seismically determined thickness and a density contrast of -0.70 g/cm^3 was included in the computations.

The resulting model shows three basins separated by uplifts of the bottom. The basins reach a maximum depth of about 500 m. This result can be compared with the seismic study which gave a depth of more than 320 m for the westernmost basin. The geophysical methods employed thus establish a depth range for the depression of 350—500 m.

An interesting discrepancy can be observed between the middle basin of the gravity model and the other investigation results. No such basin is indicated in the seismic profile and the drillings did not encounter any sedimentary rocks in this area. Drillhole 1 struck altered country rock and drillhole 2 encountered tuffaceous breccia underlain by altered country rock, both at shallow depths.

One explanation to the discrepancy could be that the gneissose granite is underlain by low-density material. The material could conceivably be the tuffaceous breccia or some related material. This could mean that the middle basin is the location of some kind of magmatic vent.

Another possibility would be that the rock in the indicated middle basin is country rock, fractured and altered to a depth of several hundred meters. This could be explained as the central uplift forming by a meteorite impact, although it seems somewhat inexplicable that the deeply fractured center of the uplift would be surrounded by a rim of less fractured country rock.

The mass deficit in the Söderfjärden area was also calculated from the gravity anomaly. Using the same density values as in the model computation the anomalous mass causing the anomaly was calculated:

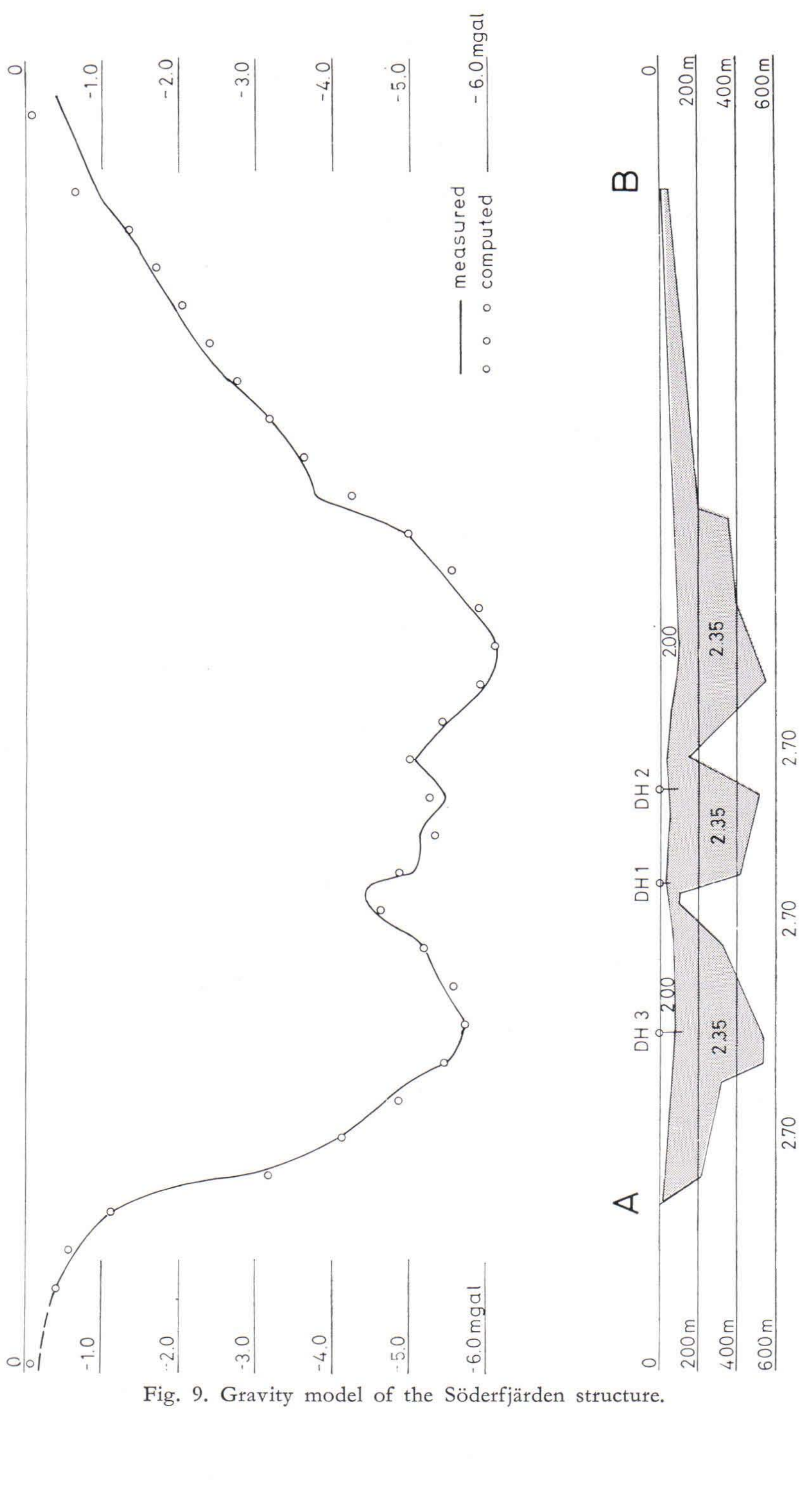


Fig. 9. Gravity model of the Söderfjärden structure.

Mass deficit	1.66×10^9 ton
Anomalous mass	11.0×10^9 »
Volume of anomalous mass	4.7×10^9 m^3

The received values for the anomalous mass and its volume must be regarded as a very rough estimate giving the magnitude of these quantities. Their importance for the interpretation is marginal as they constitute some kind of average values for the whole low-density complex.

Seismics

The drillings, although very limited in extent, enabled a rough correlation of lithological units with the seismic velocities. There seems to be a marked division of the velocities so that the lower end of the velocity range corresponds to sedimentary rocks and the higher end to more or less altered country rock:

Sediments	2 300—3 000 m/s
Tuffaceous breccia	around 2 800 m/s
Gneissose granite (more or less altered)	3 200—4 200 m/s

Using this rather tentative classification the surface distribution of the rocks along the seismic profiles can be outlined as shown in Fig. 10.

Fig. 10. Sesimically determined distribution of the rocks within part of the Söderfjärden depression

Magnetism

The aeromagnetic map of the area shows that Söderfjärden is magnetically a quite undisturbed area. A groundmagnetic profile crossing the structure in N—S direction confirmed the magnetically neutral character of the area.

Because impactite rocks often exhibit strong remanent magnetism, some magnetic measurements were made on drill core samples of the tuffaceous breccia. The results show besides a low magnetic suscpetibility a very low remanent magnetism (Q-values near 0).

PETROGRAPHY

Igneous rocks

Gneissose granite

The Vaasa granite is quite inhomogeneous in this region. The grain size is uneven and coarse, up to 2—5 mm in diameter. The color of the rock is greyish. Vaasa granite is typically porphyritic, the length of feldspar up to 3—5 cm, but its porphyritic character is subdued in the Söderfjärden area. The rock is also slightly garnetiferous.

The gneissose granite on the rim of the depression is sometimes broken into microscopically fine, cracky pieces. It is also locally rusty. In relation to these features the rock does not yet essentially deviate from what can be seen in outcrops elsewhere. Instead, the gneissose granite met with in the drillings seems to be always altered to some degree either by mechanical effects or by chemical changes.

The common gneissose granite on the rim consists of plagioclase, microcline, quartz, biotite, and muscovite. As alteration products occur chlorite, calcite, and fine saussuritic material. Accessorily occur almandine garnet, also more abundantly, and zircon, apatite, pyrite, and graphite. On the mineral basis the rock can be classified as a granodiorite in Streckeisen's (1972) system (plagioclase 65—90 % of the total feldspars), only rarely corresponding to a granite still relatively poor in alkali feldspars. Also chemically the schistose Vaasa granite (table 2, analysis 1) is granodioritic *e.g.* in comparison with an average composition of rhyodacites, the extrusive counterparts of granodiorites, in analysis 4.

Both plagioclase and potassium feldspar occur also as phenocrysts. Plagioclase is somewhat euhedric in the ground mass and fairly altered secondarily by saussuritization. Quartz is undulating, but other products of mechanical alteration are not met with. Both biotite and muscovite exhibit in a few cases bent flakes but no clear-cut kink bands.

3 1278012532

Altered gneissose granite

This name is used collectively for all altered variations of the gneissose granite that have undergone any macroscopically or microscopically visible mechanical or chemical changes. There are, expectedly, gradational variation from fresh rock to relatively strongly affected rock. However, the grade of alteration is only an average and the different grains of one sample display quite different degrees of alteration. The gneissose granite of altered variations in drill holes 1, 2, and 4 is elsewhere met with in a few erratic boulders.

In drill hole 1 a minute decrease of the degree of alteration can be detected downwards the core. Also this may be apparent and due to the fact that the upper portions of drill cores 1 and 2 are overwhelmingly made up of the tuffaceous breccia. Its thinnest veinlets in the altered country rock are macroscopically almost invisible, but make the country rock look more altered.

Plagioclase gives the hand specimen a greenish hue, when a fine-grained felt of alteration products obliterates the original grain. Plagioclase can be almost completely affected by saussuritization, sericitization and the like or be fully replaced by calcite. The alterations let the plagioclase remnant be extinguished according to its original optical orientation. However, in some areas surrounded by the altered plagioclase or, more rarely, as complete grains the plagioclase material consists of almost submicroscopic disoriented pieces. Such areas look almost isotropic. These could originate from a devitrification of maskelynite, but, in any case, show that plagioclase has been strongly affected.

Potassium feldspar is not farther sericitized than it is in the fresh country rock. Instead, it is in some places mechanically cracked more than is common. Cracking has created curved surfaces, partitioned sometimes secondarily.

Quartz is more broken than usually, having a scarce tendency towards a mortar structure. Also it often together with feldspar has been cracked mechanically into a mosaic-like pattern. Further, there exist fairly often rows, curved and straight, of very small-sized bubbly, often decorated, material. These are commonly similar to Böhm striations. From these there is a seemingly continuous change towards true multiple sets of closely spaced planar elements (Fig. 11). In the optical orientation those mainly follow the position of Böhm striations as given *e.g.* by Hietanen (1938) from metamorphic quartzites. Planar elements are not very rare at Söderfjärden. They have an obvious tendency to occur in large-sized quartz grains. In general the planar elements are concentrated in the close vicinity of the tuffaceous breccia. Further, there are also many grains with only single sets of lamellae of lowered birefringence.

Biotite is in some cases completely chloritized when situating close to the contact with the tuffaceous breccia. Biotite on the side of the breccia may have no sign of chloritization. This behavior is no standing rule and can be reversed. Kink bands in biotite are common (Fig. 12). In books of biotite and muscovite kinking affects both

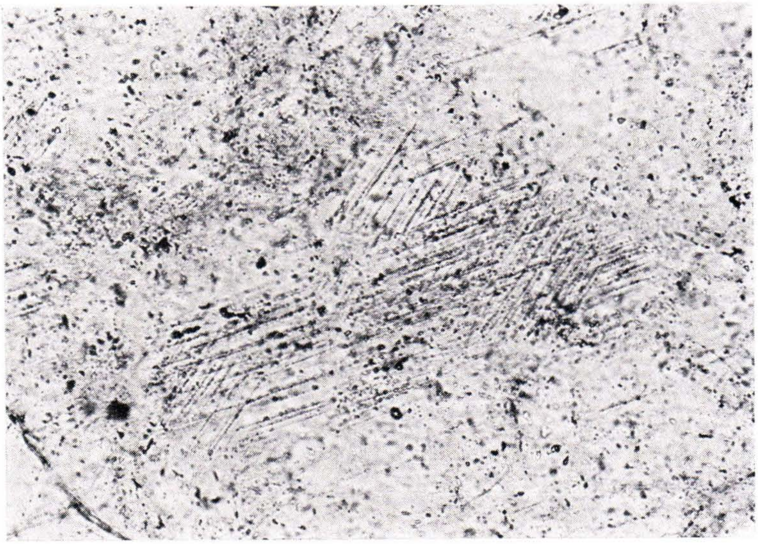


Fig. 11. Multiple sets of planar elements in quartz of a quartz vein, surrounded now by tuffaceous breccia. One nicol, 350 X.

minerals in the same way. Kink bands are found in chlorite, but they are not common. In the granitized mica gneiss of the paleosome, chloritization is far advenced, the flakes having no kink bands but abundant segregation of magnetite. In the accessory minerals no special alterations are observed besides breaking.

Fig. 12. Kink bands of biotite in altered country rock, close to the contact of a breccia vein. One nicol, 56 X.

Fig. 13. A dyke of fine grained tuffaceous breccia in altered country rock. Contacts are sharp and the grain size of the breccia diminishes towards them. One nicol, 56 X.

Tuffaceous breccia

In hand specimen this rock is distinguished by its tuffaceous inhomogeneous material consisting of very angular grains (Figs. 8, 13 and 14). These characteristics gave reason to call the rock by its present name. The color is greenish gray of varying shades, becoming darker towards finer grain sizes. The mean grain size is finer than in the country rock, but single fragments are from fist-sized pieces of gneissose granite to almost aphanitic powder. In the latter case the rock gains a lava-like outlook, especially when larger fragments, often single crystals, have a common orientation of their length axes. The rock is slightly porous as is also indicated by the average density (table 1).

Tuffaceous breccia is met with most extensively in the upper 20 m of drill hole 2 (Fig. 7). Also in holes 1 and 4 the breccia is more abundant in the upper part. The drillings confirmed that the tuffaceous breccia forms dykes[1]) of intrusive manner much like described as tuffisite from Schwaben by Cloos (1941) or pseudotachylites from several cryptoexplosions sites of the world (Freeberg 1966).

[1]) note added in proof:

Thin dykes and cavity fillings consisting of fine-grained chert-like material were found recently in the country rock boulders in connection with breccia dykes.

Fig. 14. Tuffaceous breccia containing fragments of finer grained material of same composition. One nicol, 56 X.

Table 1

Density values of the Söderfjärden rocks.

	Mean density	Range	SD	Number of samples
Sandstone	2.25	2.16—2.29	0.04	15
Siltstone	2.46			1*)
Tuffaceous breccia	2.45	2.41—2.50	0.02	10
Country rock	2.68	2.61—2.71	0.03	9
Fractured and altered country rock		2.42—2.63		9

*) during storage the siltstone samples had dried up, causing their disintegration when immersed in water. One measurement was performed on a sample saturated with steam.

Contacts between the tuffaceous breccia and country rock are normally well defined, and often in the finer grades the grain size still decreases towards contacts (Fig. 12). A distinction from the country rock becomes ephemeral only when the size of fragments grows very large.

Microscopically, any flow structure in the broken breccia material is either lacking or weak, shown by biotite flakes tending to parallel larger fragments in a preferred direction.

A rather common order of the grain size is 0.01—0.1 mm in the matrix that still has fragments of 1—2 mm in diameter. There seems to be some diminishing of the grain size upwards regarding the relative frequency of aphanitic breccias of even submicroscopically fine material in the upper levels of the original breccia.

Table 2

Chemical compositions of the Söderfjärden and similar rock types

	1	2	3	4	5	6	7
SiO_2	68.74	66.98	65.32	66.27	98.3	62.95	67.1
TiO_2	0.43	0.53	0.59	0.66			
Al_2O_3	16.32	14.00	13.09	15.39	0.50	18.21	2.3
Fe_2O_3	0.21	0.67	1.73	2.14	0.15[a]	2.72	1.0[a]
FeO	2.44	3.4	3.16	2.23		3.4	
MnO	0.03	0.06	0,06	0.07		0.03	
MgO	0.81	3.00	4.00	1.57		2.10	0.18
CaO	4.89	1.11	0.67	3.68	0.46	0.45	16.5
Na_2O	3.22	2.17	2.02	4.13	0.01	0.21	0.04
K_2O	1.76	4.28	3.96	3.01	0.11	4.25	0.44
P_2O_5	0.21	0.012	0.24	0.17		0.08	8.9
H_2O+	0.63	3.10[b]	4.34[b]	0.68		4.98[b]	3.8[b]
H_2O-	0.06						
S		0.26	0.05			0.40	
total	99.85	99.31	99.2		99.5	99.8	100.1

1. Schistose Vaasa granite. Äystö, Teuva, anal. L. Lokka (Saksela 1935).
2. Altered gneissose granite. Söderfjärden, drill hole 1, 71.8 m, anal. Partek lab.
3. Tuffaceous breccia. Söderfjärden, drill hole 1, 54.1 m, anal. Partek lab.
4. Effusive rhyodacite, average. Nockolds (1954).
5. Whitish sandstone. Block 59-e, Malax, anal. Partek lab.
6. Fine siltstone. Söderfjärden, drill hole 3, 73.35 m, anal. Partek lab.
7. Conglomerate. Söderfjärden, drill hole 3, 81.70 m, anal. Partek lab.

a. Total iron

b. Ignition loss at 1 000 °C

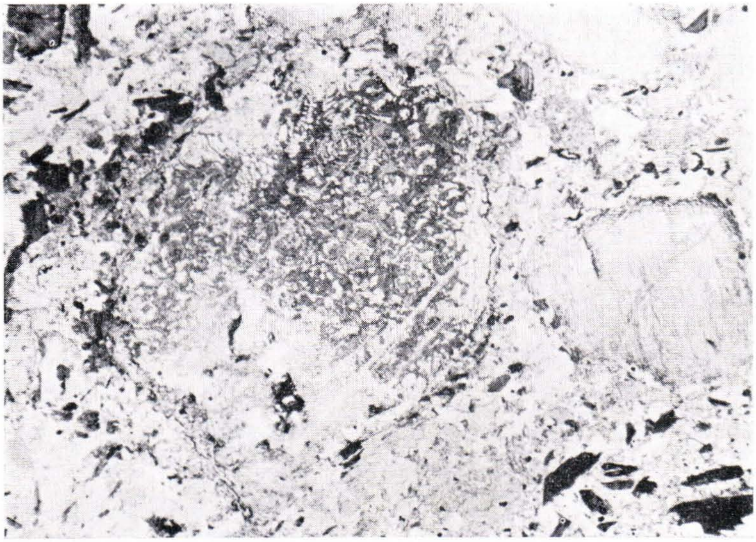


Fig. 15. A fleck of recrystallized material (filling the center). The darker areas show a perlitic manner of recrystallization. One nicol, 14 X.

Minerals of the breccia are the same as in the country rock. This is also substantiated by a comparison of the chemical compositions of the tuffaceous breccia and the gneissose granite of the core (table 2, analyses 2 and 3). They come very close to each other. The breccia is also fairly similar to the average of effusive rhyodasites (analysis 4).

As fragments in the breccia occur, besides the country rock and single minerals, also broken pieces of similar tuffaceous breccias, of smaller grain sizes (Fig. 14). There are a few schlieren-like flecks of brownish isotropic material having microcrystalline spots of lighter material or fully microcrystalline blurs with brown-rimmed perlitic forms (Fig. 15). These can be of (re)melted or at least devitrified origin, either from once shocked or melt glass or of from material precipitated into cavities of the breccia.

The minerals of the breccia have altered at least as strongly as those in the altered country rock, and also unevenly. Among the strongest altered plagioclase are some isotropic patches besides the other alterations. Potassium feldspar is relatively fresh as before. Sericitization occurs more frequently. Planar elements occur in quartz rather often, but, perhaps due to the generally smaller grain size, tightly located planes are fairly scarce. Micas are strongly kinked and quite undeformed flakes are rare. Also chlorite is often kinked. Biotite shows decomposition and segregation of magnetite. The clean chlorite flakes might have been recrystallized from affected biotite. The open cavities of the rock have often a zeolitic hemming.

Sedimentary rocks

General characteristics

Besides the outwash boulders of whitish sandstone, poorly indurated sedimentary rock is so far met with only in drill hole 3, in an interval of 67.5 m (Figs. 7 and 8). This hole did, however, not completely penetrate the sedimentary pile, as the drilling was stopped in the sandstone. These rocks are characterized by distinct colors and an average hardness much weaker than generally encountered in the Jotnian sandstone. In these sedimentary rocks there is a continuous gradation of the grain size from conglomerate balls of c. 30 mm in diameter to almost submicroscopic clay flakes that are under the upper limit of true clay particles in common grade scales (Pettijohn 1975).

When the Atterbergian classification is used in the microscopic grain size examination, the macroscopic rock types of conglomerate (grain diameter exceeding 2 mm) and sandstone (0.2—2 mm) will mainly stay unaltered. Only the finest fractions of the macroscopically determined sandstone then appear to pass below the upper limit of the next category of diameter 0.002—0.2 mm, which rock has been here called siltstone True shale (diameter less than 0.002 mm) is rare as a rock type of any larger volyme.

The color of the conglomeratic rock is brownish green. The sandstone is whitish in different shades. Rocks of finer grain sizes are greenish grey altering in hue.

A macroscopic classification into three main rock types was based upon the differences in color and grain size. A generalized succession of so defined rock types in drill hole 3 is displayed in the following set-up (see also Fig. 7):

(top)

greenish gray siltstone, soft, partly mixed with marly and glauconitic material and layers	4 m
siltstone and glauconitic sandstone, intercalated layers	5 m
polymictic conglomerate, phosphoritic	0,5 m
siltstone and glauconitic sandstone, intercalated layers	7 m
greenish gray siltstone, soft	10 m
whitish sandstone, inhomogeneous, minor faults and slumping structures in thin siltstone intercalations	17 m
greenish gray siltstone, soft	11 m
greyish white sandstone, clayey	1 m
greenish gray siltstone, soft	7 m
whitish sandstone, thin siltstone intercalations, some minor faults (core loss 3.5 m)	5 m
	total 68 m

(bottom)

Conglomerate

The conglomerate layer rests upon a layer of glauconitic silty sandstone of about one meter in thickness. It is overlain by a bed of siltstone of equal thickness. The conglomerate layer measures 39 cm along the drill core. As the inclination of the beds here is 40—50° from the horizontal position, the true thickness is less than 30 cm. The contacts of the conglomerate layer are rather sharp. Another conglomerate layer of only one conglomerate ball in thickness intercalates siltstone 5 m higher at the depth of 76.64 m.

The polymictic balls make a framework of pebbles of 5—20 mm in diameter, occupying 60 % of the total volume of the conglomerate (Figs. 8 and 16). Pebbles are well rounded and somewhat elongate. The sandy matrix between the pebbles makes 30 % of the rock. Its grain size maximum is between 0.2—1.0 mm. The degree of roundness is less than in the framework and varies more strongly, from subangular to rounded. This unevenly distributed matrix is cemented by carbonate and rarely by glauconite, also by some regrowth of the quartz grains.

The balls are brownish of different intensities in color, caused by an isotropic brown cement in them. The existence of apatite in that material was shown by means of x-ray diffraction. The gross analysis of a conglomerate sample reveals a high

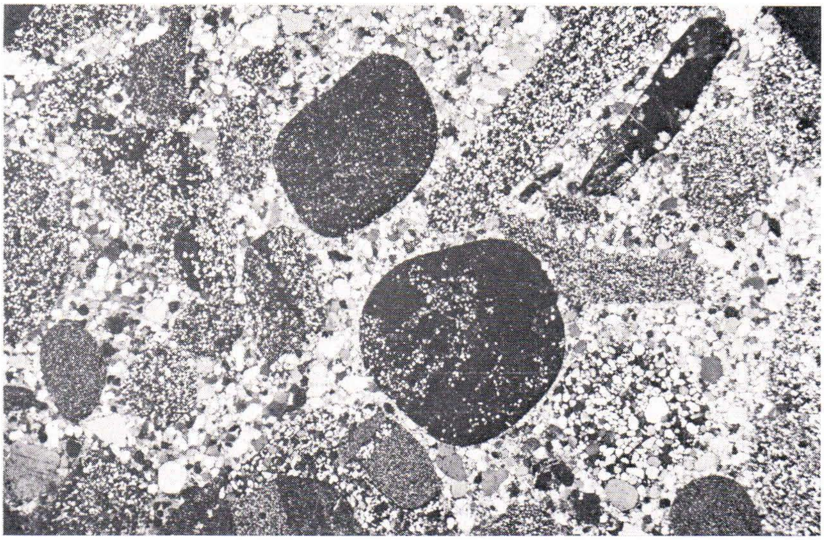


Fig. 16. Polymictic conglomerate, a composite ball at the bottom. One nicol, 4 X. Photo E. Halme.

P_2O_5 value of 8.9 % (table 2, analysis 7) and that of a conglomerate ball gives 11.0 % P_2O_5. Thus the brown material is here collectively called collophane and is due to an obvious phosphoritization of the balls.

The rock types of the balls are heterogenous; there are practically no two balls of exactly the same variation of rock type. According to the grain size most balls consist of different siltstones, both fine and coarse. Some stratification can be seen in siltstone. Sandstone is more rare. A possible fossil remain of ball size is composed only of dark brown collophane, replaced by minor carbonate.

Some composite balls exhibit well rounded fragments of earlier conglomerates (Fig. 17). Those conglomerates were broken and abraded into new balls of the present conglomerate independent of the ball contacts in the old conglomerates. The rock types of the primary balls are also many and of same variations as met with in the simple balls.

The matrix of the conglomerate proper consists mainly of quartz, less of feldspars — some fresh microcline grains are up to 2 mm in diameter. A few glauconite, garnet, and carbonaceous collophane grains are also found. These minerals also occur in the siltstones and sandstones of the balls, where they are often far less rounded, from angular to subrounded, and smaller than in the matrix around the balls. The amount of micaceous and chloritic minerals in the balls increases towards finer siltstones grades. Detrital heavy minerals zircon, apatite, epidote, and ore minerals are scarce in the balls. In one coarse siltstone there are stripes of enriched zircon, tourmaline, and magnetite in an environment otherwise rich in quartz.

4 1278012532

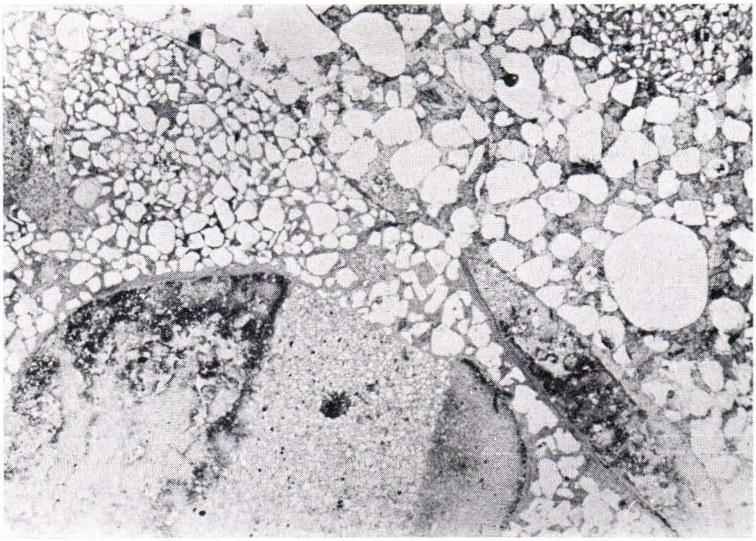


Fig. 17. A complex conglomerate ball fills the lower left half. Inside it is a ball of stratified siltstone. Both are cemented by collophane. One nicol, 14 X.

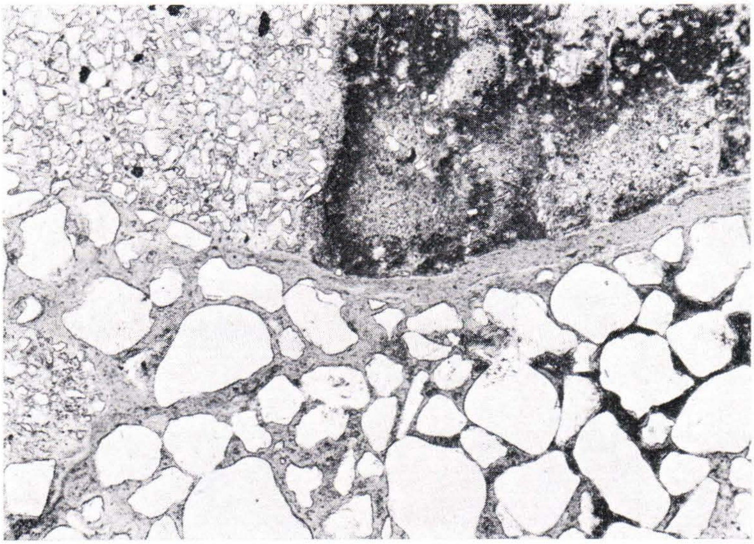


Fig. 18. A detail of the previous figure. The collophane armor around a primary siltstone ball (upper side) inside a composite ball where collophane also is the cement. 56 X, one nicol.

The matrices in the primary balls of the composite conglomerate are fine grained to dense, cemented partly and often fully by colloidal-looking cryptocristalline collophane. Other authigenic cements (pyrite, glauconite, and quartz) are more rare Besides being cemented by glaucophane, the primary balls often have an armor of glaucophane (Fig. 18).

On the surface of the collophaneous fine grained balls are lengthy embayments of up to 1.2 mm. Such features are possibly caused by burrowing animals (Mens and Pirrus 1975). In the embayments are some grains of glauconite that also occurs with carbonate in cracks of the same balls. The possible fossil grains are ovale or tabular in shape, of sand grain size. They consist of pale brown isotropic collophane and in one case of radially fibrous chalcedonic silica, now partly replaced by carbonate. The carbonaceous pigment of some oval collophane grains thus may be of organic origin.

Kinked mica flakes are not met with. They can easily have opened along kink boundaries into smaller flakes during erosion, if the provenance of any conglomerate material has been in the tuffaceous breccia. Few quartz grains have some planar lamellae-like features whereas Böhm striations are frequently met with.

Sandstone

The first boulders of whitish sandstone found in the sand pits were noticeably brittle (Fig. 8). Thereupon, more strongly indurated sandstone boulders were also recognized. Both kinds are again encountered in the drilled sequence. There are several aberrations from the whitish main color, due to the amount of glauconite, carbonate, and clayey material.

The grain size limits for sandstone as defined above (p. 23) called would, strictly taken, let only part of the rock macroscopically dubbed sandstone be accepted as coarse grained enough. But if the lower limit of the Wentworth scale of 1/16 mm will be used at this point, the demarcation will more closely follow local conditions. On the other hand, when studied under the microscope, the mineralogical composition does not change at this particular limit any faster.

The typical whitish sandstone is often pure enough to be called a *quartz sandstone* (quartz arenite or orthoquartzite according to Pettijohn, 1975) containing quartz no less than 95 %. This can also be seen from the analysis of a sandstone boulder (table 2, analysis 5). However, the amount of feldspars in many cases increases making the rock a *subarkose* (feldspar limits 5—25 %). The voids of sandstone may be partly open, up to 10—20 % of the total rock volume, and partly or fully filled with matrix grains and diagenetically regrown quartz in crystallographic continuity with the framework grains. When the cement is carbonate or glauconite exceeding 5 %, the rock can be called a *calcareous sandstone* and a *glauconitic sandstone*, respectively. Such a cement locally occupies 40 % of the sandstone.

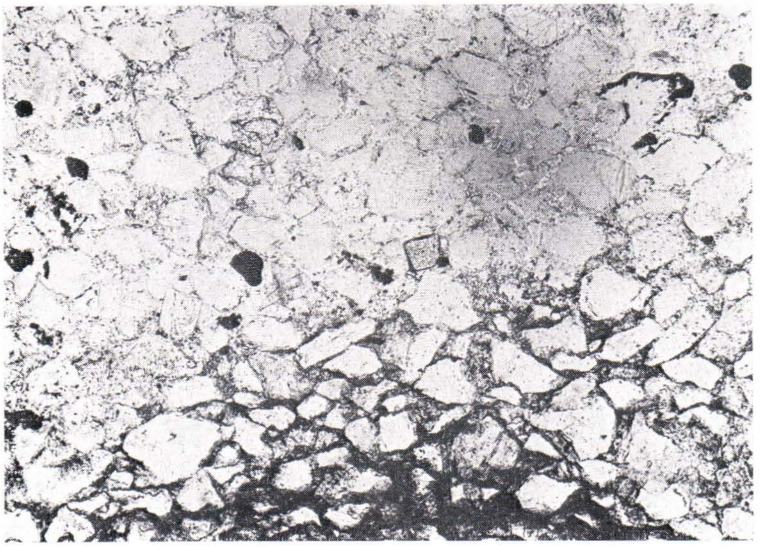


Fig. 19. Impure sandstone from a boulder. The sub-angular grains are weakly cemented. A tourmaline grain at center, limonitic cement close to bottom. One nicol, 88 X.

The roundness of the framework grains is from subangular to rounded. The degree of roundness increases in general with the growth of the grain size. The sorting of sand has often been good, but not too rarely a mixture of a far unsorted *silty* or even *clayey sandstone* has formed.

In the quartz grains no unequivocal multiple sets of lamellar elements have been verified, but plenty of other striations. The feldspar grains are relatively fresh. This is obviously due to the wearing off of the more strongly altered feldspars of the source rocks during disintegration and transportation.

Sometimes glauconite forms an essential mineral, as it occurs in the framework. Glauconite is normally an aggregate of fine grained crystals of deep green color. Only rarely it exists as larger single grains. Normal sized grains of siltstone having collophane as cement show local small accumulations, together with grains made up entirely of collophane. Only accessorily occur muscovite, biotite, possibly clay minerals, tourmaline, zircon, sphene, epidote, garnet, magnetite, ilmenite, pyrite — even cementing — and limonite.

The changes in grain size and mineral composition are frequent and often gradual. Clear-cut contacts also occur between beds of sandstone and fine siltstone. There is an average inclination of beds around 30—40° from the horizontal when the drill hole is used as a vertical reference. Small faults and minor folds of the order of one centimeter occur and are best visible in connection of thin siltstone intercalations. Together with these exist miniature slumping structures. Rusty surfaces with heavy mineral enrichments (Fig. 19) can be discerned.

It may be of interest to mention here of an unintentional later find of similar quartz sandstone with minor glauconite among common beach pebbles on the eastern shore of Attu island, Archipelago of SW Finland.

Siltstone and shale

In the finest mixtures, when 0.002 mm is used as the demarcation line against shale grains, it seems as if the proportion of fine silt grains were still dominant. This suggests to defining the rock as a *clayey silstone*, but an optical study in these minute grain sizes can be suggestive only.

The macroscopic as well as microscopic color of the siltstone and shale is grayish green, becoming darker when the grain size decreases. Chemically (table 1, analysis 6) the largest differences from the gneissose granite and tuffaceous breccia are a decrease of 3—4 per cent points in the amount of silica and a like increase of alumina. This is not a very large change. Also it can be noticed that the color of the tuffaceous breccia is rather close to that of siltstones. The green hue of siltstone is in any case caused to some degree by the presence of glauconite.

The fine siltstones and shales are mechanically soft, almost non-indurated, becoming hard and brittle when drying. The color also becomes paler.

Varieties of coarser siltstone are mainly same as those occurring in sandstones, only containing some more micaceous meterial. Towards finer sized siltstone and shale the proportion of quartz and feldspars to mica-like minerals further changes in favor of the latter ones. The quality of the finest minerals and presence of clay minerals stay unsolved by means of optical microscopy. Some solitary larger grains of rounded quartz and glauconite occur in the finest grained varieties of siltstone. Besides the common decrease in sorting of material, there is a rather steady average lowering of the degree of roundness in the clastic grains from conglomerate through sandstone to siltstone. Rusty staining exists as small spots in some siltstones as well as in sandstones. This probably is of rather secondary origin.

Small faults together with slumping structures occur in some siltstones and shales as in sandstones. They have arisen at the latest during the compaction of the sedimentary pile.

REGIONAL SETTING OF THE SEDIMENTARY ROCKS

The microfossils found in the Söderfjärden sedimentary rocks correlate with those of the Lower Cambrian Series of Estonia and other Baltic areas, as explained in detail on pp. 39—81.

Also lithostratigraphically a similar correlation can be made: the phosphorus-rich conglomerate of Söderfjärden with its composite balls and collophanic armor is fairly similar to the wide-spread phosphoritic conglomerate horizon separating the Lontova and Lükati Stages of the Lower Cambrian in Estonia (Mens and Pirrus 1975). In Estonia the conglomerate is underlain by the »blue clay» whereas it in Söderfjärden is underlain by siltstones and shales of similar composition.

Phosphoritic conglomerates also occur in the Brantevik and Norretorp sandstones of the Lower Cambrian in Scania, southern Sweden (Lindström and Staude 1971).

Boulders of sandstone and conglomerates, in many ways similar to the rock varieties occuring at Söderfjärden, are described from several localities in western Finland (e.g. Marmo and Laitakari 1952, Simonen and Kouvo 1955, Lonka and Papunen 1968, and p. 29 of this work). These provide some evidence for the Söderfjärden rocks belonging to the once more continuous Cambrian sedimentary cover. It can still be found *in situ* in the Bothnian Sea (Veltheim 1962, Winterhalter 1972) and, apparently, upon dry land at Lauhavuori (Simonen and Kouvo 1955), c. 100 km south of Söderfjärden.

The 50 to 100 meters of clayey overburden above the Cambrian sedimentary rocks in the Söderfjärden basin can be interpreted as having deposited postglacially into an empty depression excavated into the softer sedimentary rocks by the Pleistocene glaciations. Thus the sedimentary rock strata at Söderfjärden may have originally consisted of also younger sediments that now have been removed from the depression.

The Lower Cambrian of Scania measures about 120 m at Simrishamn (Lindström and Staude 1971) whereas the thickness of the Lower Cambrian in western Latvia is at most about 110 m (Jankauskas 1974). The thickness of at least 70 m of the inclined sedimentary strata at Söderfjärden is already considerable and the geophysically indicated thickness is at least 320 m. To gain this may necessitate an exceptionally abundant and rapid sedimentation rate, which could account for the slumping and faulting observed in minor scale. This would indicate either a subsiding or a primarily deep sedimentation basin.

DISCUSSION

The geophysical investigations have confirmed that the Söderfjärden structure is a more or less circular depression in the Precambrian bedrock. The interpreted minimum depth of the depression is 400—500 m. Drillings and micropaleontological investigations (see p. 39) have revealed the existence of Early Cambrian sediments in the deeper parts of the depression while in the shallow parts the rocks underlying the soil cover consist of a tuffaceous breccia and weathered bedrock.

The origin of the Söderfjärden depression could be the result of:

1. Meteorite impact
2. Igneous activity
3. Block subsidence

In the following, data which have some bearing on the origin of the structure will be discussed.

Shape and depth

The overall circular shape is in agreement with a meteoritic origin as well as with a pipe-like intrusive body. However, when studied in detail it appears that the shape is actually somewhat angular, resembling a hexagon. The hexagonal shape can be discerned both on satellite images and on the gravity map. According to Talvitie*et al.* (1975) the sides of the hexagon coincide with prominent fracture directions in the area. Talvitie *et al.* also consider the depression to be formed by tectonic movements. An angular shape would in the first place indicate tectonic movements although it is conceivable that an originally circular structure could be transformed into a more angular shape by the erosion due to the interference of the regional fracture pattern.

The geophysically determined depth of the depression is of the order of 400—500 m. Baldwin (1963) has presented a formula for calculating the depth of a fresh meteorite crater when the diameter is known. For Söderfjärden such a calculation gives a depth of about 500 m or the same magnitude as the interpreted depth. This would mean that if Söderfjärden is impact structure it is rather unaffected by erosion.

In vertical section the gravity interpretation indicates a certain asymmetry of the depression, *i.e.* the western contact is considerably steeper than the eastern contact. In meteoritic terms this would mean that the meteorite struck the earth in an oblique trajectory moving from east to west. On the other hand, in any kind of subsidence some degree of asymmetry is rather common.

Uplift of the bottom

The central part of the depression seems to consist mainly of more or less fractured bedrock. This could correspond to the central uplift which is typical of larger meteorite craters. On the other hand, the gravity study possibly indicates the existence of lighter material beneath the bedrock, which again would harmonize better with igneous activity at deeper levels.

The seismic survey shows that there are »uplifts» of fractured bedrock also in other parts of the depression. The north-south running profile with several uplifts and quite steep contacts between the different units clearly suggests that some sort of block faulting has occured within the depression. Such movements are probably not in agreement with a meteoritic origin.

Shock-metamorphic features

Some mineralogical structures frequently found in shock-metamorphic rocks are also encountered in the Söderfjärden breccia and adjacent altered granite.

The local abundance of kink bands in micas suggests to some sudden and strong deformative agent, even though kink bands as such are not unique in meteorite target rocks. Shock-lamellae like planar elements in quartz are not so abundant but still fairly common. An obvious shock-deformation has caused plagioclase to be more apt to chemical alterations, and also some glass, now mainly devitrified, has formed.

The multiple planar sets of shock elements in quartz are commonly used as a criterion for the meteoritic origin of a crater as *e.g.* in a current classifying of impact structures in Canada (Robertson and Grieve 1975). On the other hand, there has been criticism against the acceptance of shock-lamellae in quartz as an adequate criterion for the meteoric impact origin of the crater (*e.g.* McCall 1968). It might also be conceived that when a deformative pressure is very fast accumulating against walls of a volcanic pipe and dykes by an intrusive tuff or tuffisite, the physical changes are bound to happen very abruptly, shock-metamorphically.

Lake Lappajärvi (Lehtinen 1970, 1976) and Lake Sääksjärvi (Papunen 1969, 1973) are two rather close inferred crater sites having shock-metamorphic features. In comparison with their rock types the closest counterparts to Söderfjärden come from the impact breccias and from the less metemorphosed breccias of Lappajärvi. Somewhat more »porphyritic» rocks occur at Södefjärden only in few boulders. Any shock metamorphism has been relatively mild at Söderfjärden, and especially at Lappajärvi the effects have been much stronger.

If the Söderfjärden is a meteorite crater the reason to the moderate shock intensity could naturally be a low impact velocity, but one could also speculate whether the force of the impact had been moderated by a water layer of some ten meters in depth.

Chemical composition

The chemical composition of the tuffaceous breccia and the underlying bedrock are very similar as can be seen from analyses from drill hole 1 (Table 3).

The only chemical differences which possibly have significance are the lower sulfur content and the higher fluorine content of the breccia. The chemical similarity

Table 3

Chemical comparison of the tuffaceous breccia and the underlying bedrock, drill hole 1

	Tuffaceous breccia		Gneissose granite (Vaasa-granite)
	59.1 m depth	63.4 m depth	71.8 m depth
SiO_2	67.62	68.26	66,98
TiO_2	0.52	0.45	0.53
Al_2O_3	14.80	13.71	14.00
Fe_2O_3	0.35	0.42	0.67
FeO	3.6	3.0	3.4
MnO	0.06	0.05	0.06
MgO	3.00	3.10	3.00
CaO	0.83	0.83	1.11
Na_2O	2.09	2.41	2.17
K_2O	3.46	4.29	4.28
P_2O_5	0.004	0.006	0.012
S	0.02	0.03	0.26
Ign. loss	3.32	2.68	3.10
F	260 pp m	130 pp m	< 10 pp m
Ni	60 »	50 »	60 »
Co	60 »	60 »	60 »
Cu	30 »	30 »	40 «
Zn	100 »	90 »	130 »
	99.70	99.28	99.59

between the rocks strongly suggests that the breccia material is crushed and altered country rock. This would most naturally indicate that the tuffaceous breccia has originated from a meteorite impact. On the other hand, violent magmatic activity could possibly have the same effect on the country rock.

The cobalt and nickel content of the rocks as well as the high cobalt: nickel ratio remain very constant. As an iron meteorite probably would increase the nickel content of the impactite (Lehtinen 1976) the lack of nickel contamination would rule out the iron meteorite alternative.

Age

The Lower Cambrian age of the sediment fill of the depression puts the age of the structure at a minimum of not much less than 600 Ma. Considering the small size of the depression as a sedimentary basin it would probably not stay unfilled for a very long time, and the Jotnian, *i.e.* 1 300—1 400 Ma, is probably a rather high estimate of a maximum age. Anyway, the sedimentary pile has not been penetrated so the possibility of Jotnian sediments forming the lowest part of the formation cannot be excluded. If this were the case, it would indicate that the formation of the depression

Table 4
Ages of some circular structures in Fennoscandian bedrock.

Locality	Age (in Ma)	Reference
Lappajärvi	close to 1.850—1.900	Lehtinen (1976)
Åva	1.830	Neuvonen (1970)
Jänisjärvi	c. 700	Masajtis (1975)
Alnö	575	Doig (1970)
Iivaara	430	Doig (1970)
Sokli	c. 350	Vartiainen and Woolley (1974)

has been a protracted and more or less continuous process, which in turn would make a meteorite impact rather unlikely as a cause.

Consequently the age of the depression could conceivably have a bearing on the origin of the structure; an age near the Cambrian would indicate a rather short time of formation whereas a Jotnian or higher age would indicate a more continous formation process. Reversely this would mean that if the Söderfjärden depression is caused by a meteorite impact or a single magmatic event, its age should be rather near 600 Ma.

In comparison with the ages of other circular structures of various origins and situated relatively close to Söderfjärden some general observations can be made. The ages (table 4) as seen here would consist of two larger groupings. Among the older ages is that of Lake Lappajärvi. It has not yet been exactly determined, but it is possibly not much younger than those of Svecofennian synorogenic intrusives (Lehtinen 1976). From the ring-shaped intrusion of Åva in the archipelago of south-western Finland is obtained a zircon-sphene concordia age of 1 830 Ma (Neuvonen 1970). For the Lake Sääksjärvi shock-metamorphic rocks (Papunen 1973) there is no date yet.

The Alnö alkaline complex in Sweden on the western coast of the Bothnian Sea is geographically closest to the younger structures of Söderfjärden. For that Doig (1970) determined an age of 575 Ma on biotite by K-Ar method. According to him this date can be connected with ages of a larger alkaline province, as reconstructed plate-tectonically to continue from Canadian localities. The ijolite of Iivaara in eastern Finland was dated at 430 Ma (Doig, *op.cit.*). For the Sokli carbonatite in northeastern Finland Vartiainen and Woolley (1974) report mineral ages averaging c. 350 Ma. According to them the ages above emphasize a close temporal relationship to the Caledonian orogeny. Masajtis (1975) reports an age of c. 700 Ma for the circular structure of Lake Jänisjärvi in Karelia, U.S.S.R.

As compared to the above localities the Söderfjärden depression is temporally seemingly closer to the younger structures, but in regard to the alkalinity of those no similarity has yet been found at Söderfjärden.

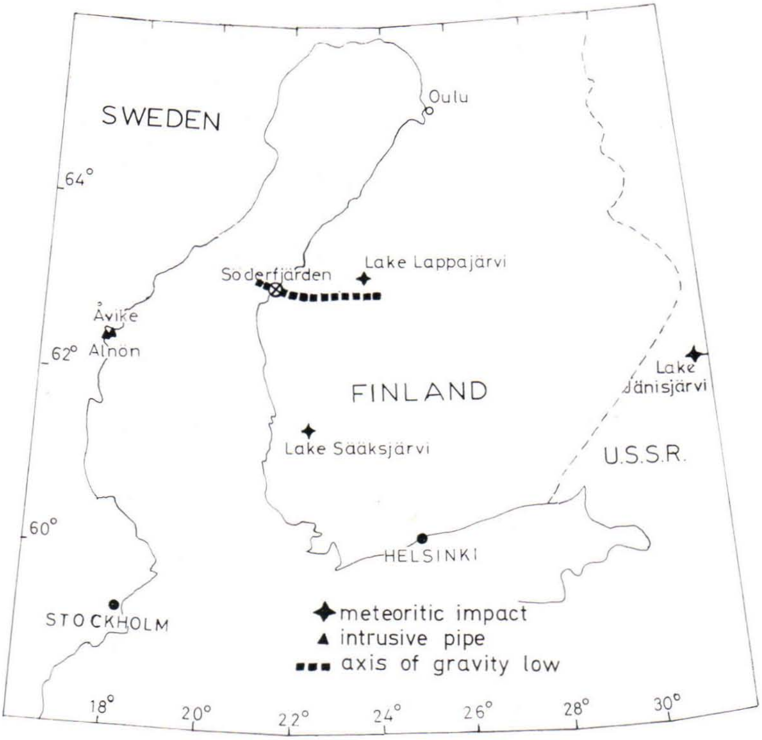


Fig. 20. Regional setting of the Söderfjärden structure in regard to similar structures.

Regional setting

The Söderfjärden structure is located in a region where there within a radius of about 200 km exist both recognized meteorite impacts and pipe-like intrusions (Fig. 20).

Lake Lappajärvi (Lehtinen 1976) which lies about 100 km east of Söderfjärden, and Lake Sääksjärvi some 200 km southeast of Söderfjärden (Papunen 1973) are considered to be impact structures. About 200 km to southwest again the carbonatite intrusion of Alnö and the inferred kimberlite pipe of Åvike are situated (v. Eckerman, 1948, Söderström 1966).

It is a notable coincidence that the Söderfjärden structure is located at the axis of an elongated negative gravity anomaly of 10—15 mgal which runs for some 200 km east-west from the Bothnian Gulf into the Finnish mainland. As the gravity anomaly could indicate a zone of weakness and deep fracturing in the crust, igneous activity could conceivably be more frequent than normal along this zone.

Concluding remarks

In the opinion of the authors the geological and geophysical information collected does not present unequivocal support for any of the genetical explanations proposed above. Instead on can find evidence pointing to each of the three main theories.

Anyway, the existence of the tuffaceous breccia seems to rather definitely rule out a purely tectonical explanation. The formation of the depression seems to involve one or several cryptoexplosions, induced either by the hypervelocity impact of a meteorite or by magmatic activities. When weighing those two alternatives against each other, the chemical similarity between breccia and country rock is a strong argument for a meteorite impact. The lamellae in quartz described are customarily regarded as a shock-metamorphic feature proving a meteoritic origin. However, it has not been convincingly proven that shock-metamorphic features of at least that moderate level of intensity could not form by forceful magmatic activity.

The sub-angular shape and the geophysical interpretation results, especially the indicated block movements within the depression, are more compatible with a force working from below. A violent volcanic explosion and the subsequent formation of a caldera would be a possible magmatic explanation, another alternative would be an intrusive plug ascending forcefully to a level some hundred meters below the rock surface. From there it would stope and strongly fracture the roof, causing its collapse. The chief obstacle for the magmatic theories, however, is the total lack, at least at the present state of knowledge, of evidence of introduced magmatic material.

ACKNOWLEDGMENTS

The authors wish to thank Paraisten Kalkki Oy — Pargas Kalk Ab for placing the Söderfjärden material at their disposal and for allowing its publication.

We are pleased to express our appreciation to Professors K. J. Neuvonen and H. Papunen, Institute of Geology and Mineralogy, University of Turku, for critically reading the manuscript.

The publication of the paper in this series was made possible through the kind assistance of Professor Herman Stigzelius, Director of the Geological Survey of Finland.

Dr. B. Winterhalter, Geological Survey of Finland, showed a keen interest and gave constructive criticism during the course of the work, for which thanks are due.

REFERENCES

Baldwin, R. B. (1963) The measure of the Moon. Univ. of Chicago Press. Chicago. 488 p.

Clark, S. P. (Ed.) (1966) Handbook of physical constants. Geol. Soc. Am., Mem. 97. 587 p.

Cloos, H. (1941) Bau und Tätigkeit von Tuffschloten: Untersuchungen an dem schwäbischen Vulkan. Geol. Rundsch. 32, 709—800.

Doig, R. (1970) An alkaline province linking Europe and North America. Can. J. Earth Sci. 7, 22—29.

Eckerman, H. v. (1948) The alkaline district of Alnö island. Sveriges Geol. Unders., Ser. Ca 36. 176 p.

Freeberg, J. H. (1966) Terrestrial impact structures — a bibliography. U.S. Geol. Surv. Bull. 1 220. 91 p.

Hietanen, A. (1938) On the petrology of Finnish quartzites. Bull. Comm. Géol. Finlande 122. 118 p.

Jankauskas, T. V. (1974) K stratigrafii kembriya Pribaltiki. Pp. 17—26 in Regional'naya geologiya Pribaltiki. Zinatne, Riga.

Laitakari, Aarne (1942) Kivilajikartan selitys, B 3, Vaasa. General geological map of Finland, 1 : 400 000. 66 p.

Lanne, E & Pernu, T. (1974) Muhoksen muodostuman seismisesti määritetyt rajat. Dep. Geoph. Univ. Oulu, Contr. 46. 12 p.

Lehtinen, M. (1970) New evidence for an impact origin of Lake Lappajärvi, Western Finland. Bull. Geol. Soc. Finland 42, 89—93.

—»— (1976) Lake Lappajärvi, a meteorite impact site in western Finland. Geol. Surv. Finland, Bull. 282. 92 p.

Lindström, M. & Staude, H. (1971) Beitrag zur Stratigraphie des unterkambrischen Sandsteines des südlichsten Skandinaviens. Geol. Paleontol. 5, 1—7.

Lonka, A & Papunen, H. (1968) Pyrite-bearing sandstone blocks, western Finland. Bull. Geol. Soc. Finland 40, 99—106.

Marmo, V. & Laitakari, A. (1952) Lounais-Suomen rikkikiisukonkreetioista. English summary: On the pyrite concretions of South West Finland. Geologinen tutkimuslaitos, Geotekn. julk. 53, 1—14.

Masajtis, V. L. (1975) Astroblemae on the territory of the USSR. Sov. Geol. No. 11, 52—64. (In Russian).

McCall, G. J. H. (1968) Lake Lappajärvi, Central Finland: a possible meteorite impact structure. Nature 218, 1 152.

Mens, K. A. & Pirrus, E. A. (1975) Basal conglomerate of the Lükati stage of Estonian Lower Cambrium (English summary). Pp. 130—143 *in* Geologija kristalličeskogo fundamenta i osanočnogo čehla Pribaltiki. Zintane, Riga.

Neuvonen, K. J. (1970) Paleomagnetism of the dike systems in Finland V. Remanent magnetization of the Åva intrusives. Bull. Geol. Soc. Finland 42, 101—107.

Nockolds, S. R. (1954) Average chemical compositions of some igneous rocks. Geol. Soc. Am. Bull. 65, 1 007—1 032.

Papunen, H. (1969) Possible impact metamorphic textures in the erratics of the Lake Sääksjärvi area in southwestern Finland. Bull. Geol. Soc. Finland 41, 151—155.

—»— (1973) Chemical composition and origin of the shock metamorphic rocks of the Sääksjärvi area, Finland. Bull. Geol. Soc. Finland 45, 29—34.

Pettijohn, E. J. (1975) Sedimentary rocks. Harper & Row, New York. 628 p.

Robertson, P. B. & Grieve, R. A. F. (1975) Impact structures in Canada: their recognition and characteristics. J. R. Astron. Soc. Canada 69, 1—21.

Saksela, M. (1935) Über den geologischen Bau Süd-Ostbothniens. Bull. Comm. Géol. Finlande 110, 1—35.

Simonen, A. & Kouvo, O. (1955) Sandstones in Finland. Bull. Comm. Géol. Finlande 168, 57—87.

Söderström, L. (1966) The kimberlites of Åvike bay, on the Bothnian coast of Sweden. Geol. Fören. i Stockholm, Förh. 88, 351—360.

Streckeisen, A. (1972) Classification and nomenclature of plutonic rocks. Geol. Rundsch. 63, 773—786.

Talvitie, J., Pernu, T. & Raitala, J. (1975) The circular Vaasa structure in the Baltic shield, western Finland. Dep. Geoph. Univ. Oulu, Contr. 59. 15 p.

Vartiainen, H. & Woolley, A. R. (1974) The age of the Sokli carbonatite, Finland, and some relationships of the North Atlantic alkaline igneous province. Bull. Geol. Soc. Finland 46, 81—91.

Veltheim, V. (1962) On the pre-Quaternary geology of the bottom of the Bothnian Sea. Bull. Comm. Géol. Finlande 200. 166 p.

—»— (1969) On the pre-Quaternary geology of the Bothnian Bay area in the Baltic Sea. Bull. Comm. Géol. Finlande 239. 56 p.

Winterhalter, B. (1972) On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation. Geol. Surv. Finland, Bull. 258. 66 p.

LOWER CAMBRIAN FOSSILS AND ACRITARCHS IN THE SEDIMENTARY ROCKS OF SÖDERFJÄRDEN, WESTERN FINLAND

by

Risto Tynni

CONTENTS

INTRODUCTION

The dating of the Cambrian period is based on fossils. The amount of actual fossils in Lower Cambrian sediments is often exceedingly small, with the result that fossil material sufficient for dating cannot always be obtained from drill-core samples. Recent microfossil investigations of the Cambrian period show that, the correlation of the microflora in many Cambrian deposits in Europe is possible.

Constituting the most noteworthy microfossil group from the standpoint of dating are the widely distributed acritarchs that grew in plankton and occurred in an abundance of species starting as early as the Middle Riphean. A conspicuous feature of the microflora of the Lower Cambrian is the resemblance to the fossils of the Upper Proterozoic (Konzalova 1973). Accurate dating calls for taking into account the total range of acritarch forms.

When the sedimentary rock deposit of Söderfjärden was discovered, I was assigned the task of dating the deposit by micropaleontological means. In the following, I shall describe the fossil and microfossil material and my conception of the age of the deposit.

RESEARCH METHODS AND SAMPLE PREPARATIONS

A stereomicroscope was used for the detection of fossils in unprepared core samples. For the purposes of microfossil analysis, the shale samples (ca. 20—30 g) were suspended in water and treated with HCL and HF to dissolve the silicate material. Sandstone and quartzite samples were first crushed mechanically and then dealt with like the shale. Pyrite was removed by dissolving it in strong HNO_3. Limestone was dissolved in HCL. The microfossils were concentrated from all the sedimentary rocks by using a $CHBr_3$ solution with a density of 2.2.

Slides were made from the residue containing microfossils by using Clophen-Harpix as a medium. The slides are preserved at the Geological Survey. Possible algal structures have been studied from thin sections and core samples.

FOSSILS AND FOSSIL TRACES

Fossils are not visible to the naked eye in the Söderfjärden drill cores, but an investigation made with a stereoscopic microscope brought to light in the sedimentary series a few vestiges of fossils less than three millimeters in length. The most common occurrences appear to be brachiopoda fragments (Plate I: 3) embedded in shale at a depth of 119 m. These fragments represent a tiny brachiopoda form known from, for example, the Lower Cambrium.

Two small pluglike fossils were found in shale at the 119-m level. They measured 2.2 and 1.5 mm in length. At the broader end, the cross section is elliptical, and at the narrower, round. Roughly, the form resembles the cephalopoda type *Volborthella tenuis* Schmidt as well as, on the other hand, the Mollusca type *Torellella laevigata* Linnarson. A cross section of the form (Plate I: 2) confirmed in the fossil structural features typical of the *Volborthella tenuis* form, which resemble strikingly the longitudinal section presented by Korkutis (1971) as well as Vogt's (1924) representation of the longitudinal section. The occurrence of *Volborthella* at the 119-m level is a probability, and this circumstance would place the time of sedimentation of the shale within the Lower Cambrium.

Volborthella tenuis has been met with in many places in Lower Cambrian deposits in the Baltic and Scandinavian regions. Observations of this cephalopoda have been reported from, among other places, the Lower Cambrian »Sparagmite Formation» of Lake Mjøsen, in southern Norway (Vogt 1924); from the upper part of the Lower Cambrium at File Haidar, Gotland, Sweden (Thorslund and Westergård 1938); from the Mickwitzia sandstone at Lugnäs, Västergötland, Sweden (Thorslund and Westergård, *op. cit.*); in addition to which mention might be made of Öpik's (1925, 1929) observations from Estonia and his view that the *Volborthella tenuis* zone is contained in the major portion of the Lükati bed and the uppermost portion of the Lontova bed (Öpik 1956). Among other Scandinavian observations, I should like to mention Martinsson's (1974) description of the Cambrian of Norden as well as to refer the reader to Bentson's (1974) bibliography. As for more recent *Volborthella* observations reported from Estonia, noteworthy are the ones made in the Lükati deposits on the island of Hiiumaa (Kala 1972) and the occurrence discovered in the lower part of the Tiskre bed (Mens and Pirrus 1972).

Further, at the depth of 119 m, there were found two small (ca. 1.5 mm long) arching, conical, pyritized terminal portions of hyolithus-type forms (Plate I: 4). The form had originally been thin-shelled, judging by the circumstance that the shell disappeared during fossilization — whereas it has been preserved in the case of *Volborthella*. The angle of the sides of the cone is noticeably larger in these than in the *Volborthella* form. Moreover, the cross section (Plate I: 5) is appreciably more

Fig. 1. A probable worm burrow in an erratic sandstone boulder from the Söderfjärden basin. Photo E. Halme.

elliptical than in the *Volborthella*. The angularity of the shell typical of most of the hyolithus forms is only very slightly apparent in the Söderfjärden case. In type, it corresponds in cross section to the oblong hyolithus form. It also resembles the small *Torellela laevigata* forms, which Strömer (1925) has described from the Lower Cambrium of Norway. The genus *Coniotheca* Missarzhevsky, which has been described from Lower Cambrian sediments of the Siberian platform, likewise resembles the pyritized horn-shaped fossil organism discovered at Söderfjärden.

A flattened, originally conical shell about 1 mm long and composed of chitin (Plate I: 8) was found in shale at a depth of 129 m. It might possibly be part of a larger, conceivably wormlike organism. Pyritized traces actually left by worms have been met with at a depth of 99 m in a sandstone layer as well as at the 119-m level in shale. These vestiges are generally exceedingly thin and threadlike. With regard to fossilized vestiges, mention should also be made of pyritized remains suggesting a cellular structure (Plate I: 6).

Erratics of sandstone with tubular traces, probably worm burrows 3 mm in diameter were found southeast of the Söderfjärden basin (Fig. 1). These traces resemble those occurring in sandstone erratics found by Veltheim (1969) on the island of Hailuoto and the adjacent mainland. Veltheim considers them to be similar to worm burrows and trails found in late Precambrian and early Paleozoic sandstones.

THE OCCURRENCE OF MICROFOSSILS (ACRITARCHS) IN THE SEDIMENTARY SEQUENCE

The portion of the sedimentary sequence investigated comprises the depth interval 139.55—73.6 m. The micropaleontological study includes 21 levels from different depths. The types of sediment are shale, sandstone, quartzite and a carbonaceous sediment (partly sandstone and quartzite). The most abundant and variegated microflora occurs in shale in the lower and middle parts of the investigated core. A clear maximum in the acritarch forms (Evitt 1963) occurs in the shale at a depth of 129 m, where there are hundreds of acritarch individuals per slide among organic detritus. The amount of noncarbonate carbon is about one percent. Above the 90-m level, the shale appears to be poorer in microfossils than below it, especially with respect to variety of species. The number of microfossils in the arenaceous, quartzitic, and carbonaceous portions of the core is exceedingly low.

The flora shows specific variations according to depth in the sedimentary sequence. It is therefore possible to make comparisons between the acritarch forms present in, for example, the 129- and 92.3-meter levels and to try to draw parallels between these horizons and known microfossil communities.

MICROFOSSIL MATERIAL

Leiosphaeridia Eisenack 1958, Downie and Sarjeant 1963

The great majority of the microfossils present in the formation consist of structurally simple, spherical, — but due to sediment compaction — flattened, folded and in many cases broken *Leiosphaeridia* Eisenack types. The *Leiosphaeridia* types of microfossils are classified into different species, mainly on the basis of size as well as thickness of shell and surface structure. Quite a few *Leiosphaeridia* species occur in the Söderfjärden material. The largest forms are $>100\ \mu$, ca. $160\ \mu$, and the smallest ca. $6\ \mu$. *Leiosphaeridia* forms have been met with in greatest abundance in shale at depths of 73.6 and 85.4 m.

In the Cambrian period, *Leiosphaeridia* forms were relatively common, but the form genus is known from the Precambrian to geologically young times. Structurally simple and comparatively thin-shelled, they are easily damaged; hence they are not well suited to species identification nor geological correlation.

The traces of pressure from pyrite crystals growth on the surface have in many instances produced a pseudostructure that hampers identification. Examples of *Leiosphaeridia* types are to be seen in Plates II, III and IV.

Regarded as *Leiosphaeridia* forms are mainly fossils that evidently possesed an originally smooth surface and those with structural features belonging to no other morphological family.

Stictosphaeridium Timofeev 1966

Characteristic of the *Stictosphaeridium* Timofeev genus is the presence of stripes on the surface. The surface of a small *Leiosphaeridia* type with a diameter of ca. 25 μ found at a depth of 81.8 m has an apparently dense primary pattern of stripes (Plate IV: 25), so it probably corresponds to the *Stictosphaeridium* form.

The *Kildinella* Timofeev genus is also characterized by a certain wrinkling of the surface. The *Leiosphaerdia* type represented in Plate IV: 27 probably corresponds to the *Kildinella* form. The main occurrence of *Kildinella* falls, according to Timofeev (1971), into the Riphean but continues on sporadically into the Lower Cambrian.

Greater attention has been focussed in the study on more complex types than the *Leiosphaeridia* because they are better suited to the purposes of dating and correlation.

Tasmanites Newton 1875

The *Tasmanites* Newton genus occurs generally rather well preserved in shale samples. The thick-shelled form is spherical and about 100—130 μ in diameter with a dense occurrence of tiny pores (spaced 2—4 μ apart). This type has no pylomes. The *Tasmanites* forms are yellowish in color (Plate IV: 29 and 30), and morphologically they are closely comparable to the *Tasmanites bobrowskii* forms found in Lower Cambrian deposits in the Bialowieza area by Wazynska (1967), in the Estonian Lükati (Pirita) formation and in the Tiskre deposits (Umnova, Vanderflit 1971), as well as, to the *Tasmanites variabilis* form described by Volkova (1968) from the upper part of the Lower Cambrian in Estonia. The names are possibly synonymous. A form closely resembling them is also the *T. volkovae* Kirjanov, which Volkova (1974) has described from Cambrian deposits in Latvia.

Tasmanites bobrowskii occurs in the Söderfjärden series at depths of 99—85.4 m, and at the 92.3-m level it accounts for some 36 % of the acritarch forms. In addition, at the depths of 92.4 and 89.2 m, there occurs the larger *Tasmanites piritaensis* Posti et Jankauskas. In diameter, the form measures about 150—200 μ. (Plate II: 12, 13, IV: 26). The pores are located on top of small protuberances on the surface of the shell (Jankauskas and Posti 1976). Its occurrence is fairly common in the Söderfjärden core at depths of 89.2 and 92.4 m. In Estonia, the species has been met with in Lükati-stage sediments.

Tasmanites nanus n. sp. Plate IV: 28

A small, thick-shelled form with a pylome. It resembles the *T. minutus*, except that it is appreciably smaller, with a diameter of ca. 25 μ. The thickness of the shell is ca. 3 μ. In the shell can be seen a dense system of radial lines, which presumably corresponds to perforations. Extremely rare at a depth of 119 m.

A fragment decoratively covered on the surface with a pattern of pores was met with in shale at the depth of 119 m. The surface structure resembles the *Tasmanites piritaensis* Posti et Jankauskas form (Jankauskas and Posti 1976), but what is involved is just a fragment from a larger body. It may correspond to cell tissue of the *Laminarites* type (Plate V: 31).

Archaeodiscina (Naumova 1960) Volkova 1968

Thin-shelled, spherical form, on the shell of which is a black, round thickening whence a radial system of stripes runs. Otherwise it brings to mind the genus *Leiosphaeridia*. The form occurs in the upper portion of the sequence, though rather uncommonly (Plate V: 32 and 33). The species is *Archaeodiscina umbonulata*, first described by Volkova from the upper part of the Estonian Lower Cambrian. The species has also been met with in the Lower Cambrian of the Ardennes (Vanguestaine 1974).

Cymatiosphaera (Wetzel 1933) Deflandre 1954

In the shale of Söderfjärden, the form genus occurs more abundantly (nearly 40 %) at a depth of 129 m. Involved are several species, but the predominant one is a form about 40—70 μ in diameter, in which the surface is divided by ridges into polygonal fields. The form divided into larger surface fields probably corresponds to the *Cymatiosphaera* sp. described by Volkova (1974, Taf. 28: 8) from the Latvian Middle Cambrian (Paradoxides oelandicus zone). The Söderfjärden material is represented by Plate V: 39.

Cymatiosphaera solfensis n. sp. Plate II: 14 and 15, V: 35—38. On the surface can be distinguished about 5 polygonal fields (Campi). The walls are thin and slightly bent. About 40—60 μ in diameter. It has been proposed to name the species *solfensis*, after the place where the find was made. The form resembles the *C.* sp. described by Volkova in 1974 from the Latvian Middle Cambrian, except that the Söderfjärden form is divided into a larger number of fields, which are rather irregular in shape. It is possibly the same form as the one described by Volkova (1969) in the drill core from Middle Cambrian sediments at Padz, Poland (*Cymatiosphaera* sp.).

C. ovillensis described from the Spanish Middle Cambrian (Cramer and Diéz 1972) also resembles this species, but it is smaller. The same type of form is approached by the larger *Cymatiosphaera* forms described by Slavikova (1968) from the Czechoslovakian Middle Cambrian. Plate V: 34 shows other, smaller *Cymatiosphaera* form found in the Söderfjärden area. They are less common than the two aforementioned larger forms.

Cymatiosphaera sp. 2. Plate V: 40 a, b.

The outer shell of the sphere composes intricately wrinkled walls and the form resembles in this respect *C. undulata*, which Hajos (1964) has described from a Miocene deposit in Hungary. The Söderfjärden form differs, however, in having higher polygonal walls. About 27 μ in diameter. Rare, for only a single individual has been met with, at a depth of 116.2 m.

Cymatiosphaera sp. 3. Plate V: 41

The outer shell of these acritarchs is at least in part cubeshaped. Compare with *C. centrigera*, which has a cubiform shell. It differs from the genus *Polyedryxium* Deunff in that it lacks ornamental features. It also differs from the *Octaedrixium*-Rudaskaja forms with their rounded edges, but resembles closely *Bion cruciferum* Eis. 1951 found in Ordovician erratics by Eisenack (1959). Several individuals were observed in shale from a depth of 96.3 m.

Cymatiosphaera sp. 4. Plate V: 42 a, b.

The diameter of the sphere is about 25 μ, but that of the polygons only about 5 μ. Only a few individuals were detected in samples from the depth of 81.8 m.

Dictyodium Eisenack 1955

Dictyodium aff. *indefinita* (Tim.) Plate V: 43 and 44, VI: 45 and 46. Synonym: *Protoleiosphaeridium indefinita* Timofeev 1959. Spherical form, on the surface of which can be distinguished a straight-edged, often irregular polygonal pattern. The surface is often covered by on evidently secondary, sepia-colored, comparatively thick layer appearing to be ragged in outline. This is possibly resinous matter. Diameter ca. 25—30 μ, width of margin in many instances 3—4 μ. Numerous observations made at depths of 129 and 119 m.

The form type closely resembles the *Retisphaeridium* Staplin, Jansonius & Pocock genus, but a characteristic of it is that the polygonal walls do not extend into the equatorial region. In the Söderfjärden material, the polygonal walls are not at least markedly missing zonally insofar as the thickening of the equatorial zone does not corredpond to this zone.

The species resembles *D. tenuiornatum* Eisenack but is smaller. On the other hand, it closely resembles *D. hasletianum* Vanguestaine 1974. It has been described from the Middle Cambrian deposit of Grand-Halleux. It most closely, however, resembles the *D. cambriense* species (Slavikova 1968) described from the Middle Cambrian of Barrandia (Czechoslovakia). Take for comparison also *Retisphaeridium dichamerum* Staplin, Jansonius & Pocock 1965. This morphological type has generally been classified as Cambrian, but it (*P. indefinita*) has also been observed in Upper Eocambrian deposits of the Karelian Isthmus.

Granomarginata Naumova 1960

The type species *G. prima* of the genus was first described from the Lower Cambrian in the USSR. Around its spherical central body, this form has a relatively narrow margin. At the 129-m level in the Söderfjärden material, there occurs a strikingly broad-margined species (Plate VI: 47). The border encircling the solid central body resembles a veil and is granular. Some of these forms at least correspond to the *G. squamacea* species described by Volkova (1968, 1969) from the Estonian Cambrian. It has been met with throughout the Lower Cambrian but in greatest abundance in the lower and middle parts of the Lower Cambrian. The occurrence of *G. squamacea* has been observed also in Cambrian deposits in Greenland and Scotland (Downie 1974). Konzalova (1974) has also run across the form in older deposits, representing the Upper Proterozoic of Bohemia. The species has further been described from a Cambrian deposit in Latvia (Volkova 1974).

Granomarginata sp. Plate VI: 49

A form with a narrow edge and a rough surface, ca. 25 μ in diameter. Only one observation made, at the 129-m level.

Leiomarginata Naumova 1960

Leiomarginata simplex Naumova 1960. Plate VI: 50—53.

A round, thick-shelled form with folded stripes on the surface, described from a Lower Cambrian deposit in Estonia (Naumova 1960, Volkova 1968). Fairly common in the Söderfjärden material, yellowish in color. About 15—20 μ in diameter. The stripes in some cases have formed around oblong openings or cracks in the shell.

Archaeofavosina Naumova 1960

Archaeofavosina sp. Plate VI: 54

At the 129-level in the Söderfjärden material, there occur fairly thick-shelled spherical forms with low, rounded protuberances of varying size on the surface. About 50—55 μ in diameter, yellowish in color. This acritarch resembles *Tasmanites*, but no pores can be distinghished.

Trachysphaeridium Timofeev (1966) 1969

Trachysphaeridium sp. Plate III: 18, VI: 55—57.

The fairly thick, single-layered shell is spherical and rough of surface. The shell almost invariably bears traces of folds, as in the case of *Leiomarginata simplex*. Diameter 70—90 μ, color yellowish. Common at, for instance, the 129-m level. The form genus is known to occur in many places starting from the final stage of the Precambrian.

Lophosphaeridium Timofeev 1959, emend. Lister 1970

Vesicle hollow, single-walled with ornament of solid tubercules. Excystment is by cryptosuture (Eisenack, Katalog, Bd. IV). Form genus rare in shale portions. The form met with at a depth of 96.3 m at Söderfjärden (Plate VII: 61) corresponds probably to the *L. tentativum* form described by Volkova (1968). It has been met with in the upper part of the Lower Cambrian in Estonia.

Lophosphaeridium sp. l. Plate VII: 58 and 59

A smaller form resembling the foregoing with a thin shell and tiny tubercules. About 20 μ in diameter. Met with at a depth of 81.8 m.

Lophosphaeridium sp. 2. Plate VII: 60

Also small, but with a thicker shell than the foregoing. Depth 101.8 m.

Lophosphaeridium sp. 3. Plate VII: 62

Form with a thin shell folded on the surface and with very tiny tubercules. Diameter ca. 25 μ. Form resembles *Archaeofavosina venus* Salujha, Rehman & Arora 1971. Met with as a rarity at a depth of 129 m.

7 1278012532

Leiovalia Eisenack 1965.

Leiovalia sp. Plate VII: 64

Smooth- and thin-shelled ellipsoid form about 65—130 μ in length. Occurs especially in shale at the 129-m level. It resembles the *L. tenera* Kirjanov form, which Volkova (1974) has described from the Cambrian of Latvia. *Leiovalia similis* Eisenack is of the size as the form from Söderfjärden. It has been found in Baltic limestone. The type found in Ordovician material from the bottom of the Bothnian Sea (Tynni 1975) differs markedly from the Söderfjärden type.

Ooidium Timofeev 1957

Ooidium sp. Plate VII: 67

Almost spherical shell, at one end of which is an area with tubercles on the surface, but elsewhere the shell is only slightly rough. Length about 75 μ. It is larger than the mainly Middle Cambrian forms described by Timofeev (1959). As an extremely rare specimen, only one individual has been found at Söderfjärden at the depth of 129 m. It is apparently an early occurrence of the form genus, for *Ooidium* is a form typical of the Middle Cambrian and the first half of the Upper Cambrian (Timofeev). However, the occurrence of *Ooidium* has even been noted in, for instance, Vergal sediments of the Lower Cambrian (Jankauskas 1974).

Acanthodiacrodium Timofeev 1958

Acritarch forms with processes belonging to the *Acanthomorphitae* Downie, Ewitt, Sarjeant 1963 subgroup are rather scantily present in the Söderfjärden samples, for at the 129-m level only one *Acanthodiacrodium* sp. specimen was observed (Plate VII: 65). In form, it is broadly elliptical, about 24 μ long, with short spines (ca. 2 μ) sparsely present at opposite ends. It resembles the *Lophorytidodiacrodium (lentiforme)* Tim. form met with in the Kaljala shale deposit on the Karelian Isthmus but is smaller (Suomalainen & Tynni 1970).

Baltisphaeridium Eisenack 1958 is known from as early a date as the Lower Cambrian in the Baltic region — for example, Estonia (Volkova 1968, Jankauskas & Posti 1976). Similar forms, however, with some poorly preserved structural features, also occur in the sedimentary rock of Söderfjärden. Of these the most prevelent type probably corresponds to that depicted by Volkova (1968, Tab. XII, Fig. 6).

Cymatiogalea Deunff 1961, *Comasphaeridium* Staplin, Jansonius and Pocock 1965

In certain instances, it is impossible to separate between possible *Archaeohystrichosphaeridium* Timofeev 1959, *Baltisphaeridium* and *Cymatiogalea* Deunff 1961 forms. In Plate VIII: 71—75, there appears a possible *Cymatiogalea* sp. An uncommon occurrence is also a form with exceedingly thin, hair-like — at least at the ends — spines. This form (Plate VII: 68 and 70) resembles *Comasphaeridium* Staplin, Jansonius and Pocock 1965. The diameter of the central body is ca. 20—35 μ. Met with only at the 129-m level. It also resembles the *Baltisphaeridium strigosum* Jank. form described by Jankauskas and Posti (1976) from the Lower Cambrian of the Baltic. (Connected with *Comasphaeridium?*) According to Downie (1974), *Comasphaeridium*, together with *Micrhystridium* and *Granomarginata squamacea*, characterizes the beginning of the Cambrian.

Goniosphaeridium Eisenack 1969

Goniosphaeridium? sp. Table IX: 85

At the 129-m level, one partially visible form measuring about 29 μ in total diameter, apparently pentagonal at the edges, with conical processes and a vesicle diameter of 23 μ, was seen (cf., *Polygonium gracile* Vardova 1966, *Impluviculus stellaris* Martin 1975).

Hystrichosphaeridium Deflandre 1937

Hystrichosphaeridium sp. Table VII: 69

Diameter of central body ca. 21 μ; processes on surface with a horn-like appearance and situated at even intervals. An average of 7 processes occur in the marginal portion. Form met with at the depth of 129 m. Very closely resembles smallish *Hystrichosphaeridium ? insigne* Fridrichsone forms described by Fridrichsone (1971) from Cambrian deposits in Latvia. Volkova (1974) has also run across the same form in Latvia, presenting it under the name *Baltisphaeridium insigne*. According to this source, it varies in size between 24 and 35 μ.

Micrhystridium Deflandre 1937

In the Söderfjärden series, the form genus proved a rarity. A clearly distinguishable *Micrhystridium* specimen was met with only at the 129- and 96.3-m levels. The smaller of them resembles *M. nannacanthum* Deflandre and, on the other hand, the *M. tornatum* Volkova form. The Söderfjärden form is ca. 15 μ in diameter (Table IX: 87), and on this basis it corresponds more closely to the large *M. tornatum* form than *M. nannacanthum*. *M. tornatum* is fairly common in the Lower Cambrian deposits of Estonia (Volkova 1968).

Micrhystridium sp. Table IX: 86

The spherical central body is about 18 μ in diameter, and the broad, conical spines measure approximately 5 μ. Structurally, the form resembles *Goniosphaeridium*. Only one observation made, at the depth of 129 m.

Micrhystridium pallidum Volkova fo. *minor* n. fo. Table IX: 88—90

At the 119- and 129-m levels, small spheres measuring 5—7 μ in diameter with short spines were met with either individually or in clusters. Most of the spheres were blackened by pyrite. Though they resemble the Volkova species, which has a diameter varying between 9 and 15 μ, they are nevertheless definitely smaller. Eisenack's (1965) *Synsphaeridium tuberculatum* also resembles the Söderfjärden form, except that it is larger.

Multiplicisphaeridium Staplin 1961

Multiplicisphaeridium clavatum n. sp. Table IX: 84

At the 129-m level, only one ragged *Multiplicisph.* type was met with. It evidently had only four clavate processes, which resemble in shape the processes of *M. piriferum*. The diameter of the central body is ca. 25 μ. The form resembles the form (sporomorphe MR 17/24) from the Upper Precambrian (Brioverien) presented by Roblot (1963) in Fig. 23.

Vulcanisphaera Deunff 1961

Vulcanisphaera microspinosum n. sp. Table VIII: 76, 78, 81.

On the surface, small protuberances occur densely and from them radiate 4—7 short (1—2 μ) spines. The diameter of the vesicle is about 25 μ. An uncommon form, only a few observations having been made at the 96.3-m level.

Comp. *Stelliferidium* Deunff, Gorka, Rauscher 1974.

Vulcanisphaera sp. Table VIII: 77 and 80

Central body ca. 20 μ in diameter. On the surface, conical protuberances with tiny, thin spines. Rare for, with only a few observations at the depth of 89.5 m. Compared with the preceding form, it is smaller and the protuberances are sparser and larger. *Vulcanisphaera* is known from, for instance, the Olenus zone of the Upper Cambrian (Potter 1974), but the discovery of the new forms in the upper part of the Söderfjärden series probably signifies earlier forms of the genus. Table IX: 82, 83 in all likelihood represent forms closely related to the foregoing *Vulcanisphaera* species. Their surface structure is not clearly visible.

Acritarch forms with tetrad marks

Two spore types were observed in the Söderfjärden material in which the tetrad mark is visible. Owing to its rareness, no sure conclusions can, however, be drawn on the basis of these observations. Table IX: 93 represents a roundish, triangular type of spore, which is apparently double-shelled on the surface. The outher membrane is ragged, possibly on account of wear. The diameter is ca. 27 μ. The form resembles the trilete spores, including *Trachytriletes krystofovichii* found by Naumova (1949) in blue clay belonging to the East Baltic (Eocambrian).

Table IX: 92 shows a *Leiotriletes*-type individual, the trilete mark of which, however, might correspond to surface folds that had accidentally taken on the trilete shape. Comp., surface wrinkles of *Leiomarginata simplex*.

Compared with algae, the time of appearance of the higher developed spores is still open to discussion (cf., for ex., Potonié 1956). The same forms as Naumova and, in addition, others with trilete patterns have been described by Timofeev not only from the East Baltic Eocambrian and Cambrian but also from the Visingsö formation and Eocambrian samples collected in the Norwegian province of Finnmark (Timofeev 1960, 1963). Vidal (1976) later studied microfossils from outcrops of the Visingsö beds and drill cores from the middle and upper parts of the beds. According to this researcher, the upper part of the beds contains the same kind of acritarch forms as had been previously known from Vendian and Lower Cambrian deposits in the USSR, China and other regions. Vidal proposes for this unit a Vendian dating. Vidal did not recognize the spore type at Visingsö but considered the interpretation of the terrestrial or semiterrestrial spores to be erroneous.

The same subject matter is further illuminated by the small (under 10 μ) triradiate, patterned *Ambiguaspora* spores met with in samples from the Upper Vendian of Leningrad and Latvia (Volkova 1976). In this type, the tetrad mark is clearly distinguishable, extending to the margins. The spores are assumed to belong either to aquatic plants of the Vendotaenides group or to other, possibly semiaquatic plants.

REVIEW OF THE VARIATIONS IN THE SPECIES PRESENT IN THE SEDIMENTARY SEQUENCE

The acritarch species occurring at different depths differ considerably from each other. This is clearly evident at, for instance, the 129- and 92.3-m levels, where the microfossil density is great and the sediment the same. On the lower level, there is a larger variety of species, the majority being various *Leiosphaeridia* (ca. 37 %) and *Cymatiosphaera* (ca. 36 %) forms. Abundantly present are also poorly preserved colonies of *Synsphaeridium* or *Gloecapsomorpha* types (ca. 15 %). The worn condition hampers estimating their abundance, which is possibly larger. *Leiomarginata simplex* (ca. 5 %), *Granomarginata squamacea* (ca. 2 %) as well as numerous forms accounting for about 1 % or less (*Comasphaeridium*, *Cymatiogalea*, *Vulcanisphaera*, *Lophosphaeridium*, *Trachysphaeridium*, *Leiovalia*, *Ooidium*, *Hystrichosphaeridium*, *Dictyodium*, *Multiplicisphaeridium*); on the 92.3-m level, the variety of species is smaller than the foregoing. *Leiosphaeridia* (ca. 55 %) constitutes the maximum, but the large proportion of *Tasmanites bobrowskii* (ca. 36 %) is important from the standpoint of dating. The angular *Cymatiosphaera* type (ca. 2 %), *Cymatiogalea* (ca. 3 %), *Leiomarginata* (ca. 3 %) and a number of rarer acritarchs than these make up the minority.

The variation in species along the core indicates an evolution of species of the algae types in question that took place during sedimentation. *Tasmanites bobrowskii* represents an earlier form of the *Tasmanites* genus that had not yet developed a pylome (Wazynska 1967). Now, *Tasmanites* is compared to a form of marine green algae (Chlorophyceae) (Wall 1962). In the lower strata *Tasmanites* with clearly distinguishable pores is missing, for it emerges from a depth of about 99 m, reaching its maximum at the 92.3-m level. Also Volkova (1968) has noted the lower limit of *Tasmanites variabilis* (synonym), placing it in the Lower Cambrian, around the middle of the Lontova series (Ulbjaste/Palamuse).

Tasmanites piritaensis makes an appearance in the Söderfjärden sedimentary sequence approximately 6.5 m after the initial occurrence of *T. bobrowskii*, which means that it is younger than the latter, dating evidently from the Lükati stage (Jankauskas and Posti 1976). It is noteworthy that at Söderfjärden also. *T. bobrowskii* occurs at the 92.4-m level, along with *T. piritaensis*.

The optimal occurrences of *Cymatiosphaera solfensis* and *C.* sp. 1 are stages antedating the rise of *Tasmanites*, but they nevertheless probably belong to the Cambrian period. This is also indicated by the variety of the *Acanthomorphitae* forms, although the number of individuals is rather low, besides which many of the forms must be regarded as early ones. At the depth of 129 m, the numerous, poorly preserved *Synsphaeridium* or *Gloecapsomorpha* colonies emphasize the share of the blue-green algae (*Cyanophyceae*) in the collection of species, the question of the origin of the main part of which is open.

COMPARISONS WITH CERTAIN ACRITARCH ASSEMBLAGES OF THE CAMBRIAN PERIOD AND STRATIGRAPHIC OBSERVATIONS

A preliminary study of the microfossils present in the sedimentary rocks of Söderfjärden showed that the acritarch forms of Söderfjärden are significantly of the same type as have been brought to light mainly from sedimentary rocks belonging to the Lower Cambrian in the Baltic region, specifically the areas of Leningrad (Naumova 1949, Timofeev 1956, 1959), Estonia (Volkova 1968, Jankauskas and Posti 1976), Latvia (Lieldiena, Fridrichsone 1968, Birkis, Brangulis, Volkova and Rosanov 1970, Fridrichsone 1971, Volkova 1974) and Lithuania (Jankauskas 1975). Similar acritarch forms have been met with also in Poland (Jagielska 1966, Wazunska 1967, Volkova 1969), Czechoslovakia (Vavrdova 1966, Slavikova 1968, Konzalova 1975) and several places in Western Europe (Gardiner and Vanguestaine 1971, southeastern Ireland), (Martin 1975, Belgium), (Downie, Lister, Harris and Fettes 1971, Scotland), etc.

Baltic region

The largest number of similarities has been found between the Lower Cambrian acritarch assemblages of Söderfjärden and Estonia (Volkova 1968). In Table 1 are presented the most typical acritarch forms of the Söderfjärden layer sequence and the Lontova sequence belonging to the lower parts of the Lower Cambrian in Estonia. Part of the divergence in the nomenclature is due to the difference between the systematics adopted; but, owing to the lack of sufficient comparative material, a combination of synonymous forms has been avoided.

The prevalent view is that in Estonia the upper part of the Lower Cambrian and the Middle and Upper Cambrian *in toto* are missing (Öpik 1956). According to the latest research, the youngest Cambrian deposits in Estonia correspond to the Tiskre sandstone stage in Estonia and the Izhora sandstone stage in the Ingrian region. Tiskre deposits have been preserved only in northern Estonia. They are regarded as belonging to the Lower Cambrian (Öpik 1956, Mardla *et al.* 1968) or the Middle Cambrian, corresponding to the Izhora sandstone stage. According to a differing view, the Izhora stage likewise belongs to the Lower Cambrian (see., Jankauskas 1974). The Izhora sandstone stage contains *Acrotreta*, *Linguella* and *Obolus* fossils, of which only *Linguella* has been met with in the Estonian Lower Cambrian (Mardla *et al.*, *op. cit.*).

The Cambrian deposits of Latvia have been identified as being of approximately the same age as those of Estonia. Lieldiena and Fridrichsone (1968) have described acritarch assemblages corresponding to Lower and Middle Cambrian formations.

Among the acritarch assemblages of the Cambrian period in Latvia, the assemlages of the Lontova and Pirita beds are probably closer to the Söderfjärden flora type than the rest.

Table 1

Typical acritarchs in Söderfjärden and in the Lontova beds in Estonia.

	Acritarchs from the Söderfjärden core	Acritarchs of the Lontova beds (Volkova 1968)
Leiosphaeridia sp	(+)	+
Granomarginata squamaceae	+	+
Granomarginata prima		+
Leiomarginata simplex	+	+
Tasmanites tenellus		+
Tasmanites bobrowskii	+	
Tasmanites variabilis		+
*Tasmanites piritaensis**)	+	
Archaeodiscina umbonulata	+	+
Trachysphaeridium sp.	+	
Cymatiosphaera solfensis	+	
Cymatiosphaera sp.	+	+
Dictyodium aff. indefinita	+	
Lophosphaeridium sp.	+	+
Baltisphaeridium cerinium		+
Baltisphaeridium compressum		+
Baltisphaeridium dubium		+
Baltisphaeridium ornatum		+
Baltisphaeridium papilosum		+
? *Baltisphaeridium* sp.	+	
Comasphaeridium sp.	+	
Hystrichosphaeridium insigne	+	(+)
Cymatiogalea sp.	+	
Micrhystridium tornatum	+	+
M. pallidium		+
M. pallidium f. *minor*	+	
Vulcanisphaera microspinosum	+	
Vulcanisphaera sp.	+	
Ooidium sp.	+	
Acanthodiacrodium sp.	+	

*) also from the Lükati beds (Jankauskas and Posti 1976).

In the Lontova and Pirita formations, which are younger than the Lomonosov formation, the maximum is composed of *Protosphaeridium* (*P. parvulum*) and *Microconcentrica* sp. 1. The genera *Stictosphaeridium*, *Leiosphaeridia*, *Margominuscula*, etc., are represented by a number of species, similarly the hystrichosphaers by a few forms. The guide species are *Tasmanites*? sp. 1 and 2, *Granomarginata* cf. *prima Naum.*, *Microconcentrica typica* Naum., *Archaeohystrichosphaeridium* cf. *complicatum* Tim., *Cymatiosphaera* cf. *cubus* Dff. (Lieldiena and Fridrichsone 1968).

According to Lieldiena and Fridrichsone, the species of acritarch of the Lomonosov formation (formerly Oranienbaum) corresponding to the lower part of the Lower Cambrian are *Protosphaeridium pusillum* Tim., *P. rigidulum*, *P. gibberosum*, *P. parvulum* Tim., *Microconcentrica* sp. 1, *Granomarginata* sp., *Archaeohysterichosphaeridium* sp., *Archaeodiscina* sp. 1. Hystrichosphaeri forms are rather uncommon.

The acritarch forms in the lithostratigraphic unit, which is younger than the foregoing Cambrian deposits in Latvia, differ greatly in composition from the microflora of the older Cambrian strata. This is due to the sharp decrease in *Microconcentrica* sp. 1 and the appearance of new forms: *Favososphaeridium favosum* Tim., F. sp. 1, *Archaeodiscina* sp. 2, *Ocridosphaeridium plivativum* Tim. and *Lophosphaeridium subglobosum* Tim. Many of these forms are commonly present in the Middle Cambrian of Öland (Timofeev 1966) and the Leningrad area (Timofeev 1959, Lieldiena and Fridrichsone 1968). The Middle (?) Cambrian Tiskre beds in Latvia are represented by sandstone with intercalations of silt and clay. Among acritarch species, noteworthy is the predominant *Protosphaeridium* sp. 1, besides which there occur a few small forms, *Archaeodiscina* sp. 4, *Asperatopsophosphaera* 2, a number of hystrichosphaeri species, etc.

New data have been produced by Birkis, Brangulis, Volkova and Rozanov (1970) on the stratigraphy of the Cambrian period in Latvia on the basis of core material obtained from new drillings. In the Latvian strata corresponding to the Lükati stage in northern Estonia (*Eophyton* sandstone), there occur the following forms also characteristic of those found in Lükati: *Baltisphaeridium cerinium* Volk., *B. dubium* Volk., *B. orbiculare* Volk., *Micrhystridium tornatum* Volk., *M. pallidum* Volk., *Archaeodiscina* Volk., *Tasmanites* sp., *Leiosphaeridia* Typ. B., *Leiomarginata* aff. *simplex* Naum. and *Granomarginata squamacea* Volk. The same stratum contains fragments of *Volborthella tenuis* and *Lycatiella*.

In Cambrian deposits younger than the Izhora formation, the acritarch forms in the Baltic region are generally of a markedly different type from the ones described by Timofeev (1959, 1966). Characteristic of the Middle and Upper Cambrian are, inter alia, *Diacrodium*, *Dasydiacrodium* and *Ooidium* forms, which, with a few exceptions, are absent from the Söderfjärden material. The exceptional and exceedingly rare *Diacrodium* and *Ooidium* individuals met with at Söderfjärden are probably early forms of the genera.

According to Öpik (1956), the so-called *Volborthella tenuis* time and the late *Platysolenites* time correspond to the maximum of the Lower Cambrian transgression in the blue clay province. In the paleogeographic maps presented by this researcher, the Gulf of Bothnia is marked as a marine province at as early a stage as the *Discinella holsti* time, whereas during the *Volborthella tenuis* time the sea also covered the western part of Finland. In Öpik's view, the *Volborthella tenuis* zone corresponds to the upper part of the Lontova bed as well as the Lükati bed. It is quite possible, on the very basis of the evidence provided by the microfossils, that the Söderfjärden sequence or a part of it belongs to the *Volborthella tenuis* zone of the Lower Cambrian.

Åland region (Åland Islands)

Sandstone dikes dating from the Cambrian period are known to occur in Åland (the Åland Islands). Tanner (1911) described a small brachiopoda form resembling the genus *Kutorgina* or *Acrotreta*, met with in the sandstone dike of Långbergsöda-Öje. Tanner regarded it, with certain reservations, as possible, on the basis of the find, to study the north Baltic Lower Cambrian, although he knew that the brachiopoda form in question was not the same as the one known to be present in the Scandinavian-Baltic Lower Cambrian area. Metzger (1922) designated the brachiopod as *Acrotreta tanneri*, but in 1968 Martinsson changed the label to *Ceratreta tanneri*, submitting that the form belonged to the Upper Cambrian (Martinsson *op. cit.*, 1974). The genus was first described from the Upper Cambrian of Montana (Bell 1941).

The Acritarch investigation of the sandstone containing *Ceratreta tanneri*, which is still in progress, has shown it to have an abundant content of microfossils, among them to a notable degree diacrodium types. The data support Martinsson's dating and show, in addition, that the sandstone in question can be proved on palynologic grounds to be younger than the sedimentary sequence of Söderfjärden. It is noteworthy that some of the sandstone dikes of the Åland Islands contain an older-type acritarch association, which reveals that the sandstone dikes are of different ages.

Area of the Visingsö formation, southern Sweden

The part of the formation deposited during the late Precambrian has yielded microfossils and stromatolites, which have been described as early as 1880 (see., bibliography in Vidal 1974). According to the results of the most recent research, the part of the deposit containing microfossils originated during the late-Riphean and Vendian stages (Vidal, *op. cit.*). The majority of the microfossils are simple spheromorphs characterized by surface ornamentation: the genera (according to Timofeev) *Kildinella*, *Protosphaeridium*, *Stictosphaeridium*, *Trachysphaeridium*, *Trematosphaeridium*. A combination type is represented by *Bavlinella* (Shepeleva 1962) as well as *Synsphaeridium* (Eisenack 1965) On the other hand, the smooth-shelled *Leiosphaeridia* is apparently missing.

The large spheromorph *Chuaria circularis*, typical of the late Precambrian, belongs to the Visingsö forms, as do the structurally more complex *Peteinosphaeridium reticulum* Vidal, *Octoedryxium truncatum* (Rudavskaja 1973) Vidal, *Pterospermopsimorpha concentrica* (Sin and Liu 1973) Vidal and a problematic form with a reticulate surface. The majority of them belong to the topmost part of the Visingsö formation. Compared with the forms of the Söderfjärden formation, the foregoing are markedly deviant and represent older acritarch species.

The area of the Muhos formation

A comparison of the acritarch forms of Söderfjärden with the species present in the Muhos formation shows quite distinct differences. Missing from the Muhos formation are the hystrichosphaeridiums, *Tasmanites*, the clear-cut *Cymatiosphaera* and the majority of the rest of the form types present at Söderfjärden, with the exception of the simple forms closely resembling the genus *Leiosphaeridia.* Typical forms found in the Muhos formation are *Synsphaeridium* Eisenack, *Protosphaeridium* Tim., *Kildinella* Tim., *Favosphaeridium* Tim., *Symplassosphaeridium* Tim., etc. (Tynni and Siivola 1966, Timofeev 1969, Tynni 1978).

In the Muhos formation the microfossil population is on the average definitely lower than in the Söderfjärden formation. The Muhos formation is the oldest of the ones discussed in the foregoing, the age of its diagenesis having been estimated by K—Ar determination to be about 1 300 Ma (Simonen 1960).

SUMMARY

A micropaleontological and fossil study of the Söderfjärden sedimentary sequence and a comparison of the results with research findings relating, in the first place, to the Baltic Lower Cambrian as well as the Vendian stage of central Sweden indicate that the Söderfjärden sediment originated during the Lower Cambrian. It is possible that the main part of sedimentation of Söderfjärden corresponds to the blue clay of the Lontova stage, which is younger than the Vendian Laminarites clay from the Leningrad area or the Eocambrian clay of the Karelian Isthmus.

The upper part of the Söderfjärden sedimentary sequence is evidently comparable to the Lükati stage in Estonia.

ACKNOWLEDGMENTS

Dr. H. Ignatius has contributed to the undertaking and execution of this paleontological research project. Dr. B. Winterhalter was of valuable assistance at many stages in the progress of the study. Mr. K. Hokkanen prepared the specimens and was of assistance otherwise, especially in the search for fossils. The translation of the Finnish manuscript into English was done by Mr. Paul Sjöblom.

The electron scanning micrographs presented in the plates I and II were taken by Mr. Hans Eklund.

REFERENCES

Bell, W. C. (1941) Cambrian Brachiopoda from Montana. J. Paleontol. 15, 193—255.

Bengtson, S. (1974) Bibliography of the Cambrian of Norden. Pp. 258—283 *in* Cambrian of the British Isles, Norden, and Spitsbergen, ed. by C. H. Holland. Wiley & Sons, London.

Birkis, A. P., Brangulis, A. P., Volkova, N. A. & Rozanov, A. Yu. (1970) New data on the Cambrian stratigraphy of Western Latvia. Dokl. Acad. Sci. USSR, Earth Sci. Sect. 195, 58—61.

Cramer, F. H. & Diez, M. d. C. R. (1972) Acritarchs from the Upper Middle Cambrian Oville Formation of Leon, Northwestern Spain. Rev. Espanola Micropaleont., No. extraord., 39—50. Madrid.

Deflandre, G. (1937) Microfossiles des silex Crétacés II. Flagellés incertae sedis. Hystrichosphaeridés. Sarcodinés. Organismes divers. Ann. Paléontol. 26, 51—72.

—»— (1954) Systématique des Hystrichosphaeridés: sur l'aception du genre Cymatiosphaera O. Wetzel. C. R. Somm. Soc. Géol. France 1954, 257—258.

Deunff, J. (1961) Un microplancton à Hystrichosphéres dans le Tremadoc du Sahara. Rev. Micropaléontol. 4 (1), 37—52.

Deunff, J., Gorka, H. & Rauscher, R. (1974) Observations nouvelles et précisions sur les Acritarches à large ouverture polaire du Paléozoique inférieur. Geobios 7 (1), 5—18.

Downie, C. (1974) Acritarchs from near the Precambrian-Cambrian boundary — A preliminary account. Rev. Palaeobot. and Palynol. 18, 57—60.

Downie, C., Evitt, W. R. & Sarjeant, W. A. S. (1963) Dinoflagellates, Hystrichospheres and the classification of Acritarchs. Stanford Stud. Geol. 7 (3), 3—16.

Downie, C., Lister, T. R., Harris, A. L. & Fettes, D. J. (1971) A palynological investigation of the Dalradian rocks of Scotland. Inst. Geol. Sci., Rep. 71 (9). 30 p.

Eisenack, A. (1965) Die Mikrofauna der Ostseekalke. 1. Chitinozoen, Hystrichosphären. Neues Jahrb. Geol. Paläontol., Abh. 123 (2), 115—148.

—»— (1969) Zur Systematik einiger paläozoischer Hystrichosphären (Acritarcha) des baltischen Gebiets. Neues Jahrb. Geol. Paläontol., Abh. 113 (3), 245—266.

Eisenack, A., Cramer, F. H. & Diez, M. d. C. R. (1976) Katalog der fossilen Dinoflagellaten, Hystrichosphären und verwandten Mikrofossilien. Bd. 4, Acritarcha, 2. Teil. Schweizerbart. Stuttgart.

Evitt, W. R. (1963) A discussion and proposals concerning fossil dinoflagellates, hystrichospheres and acritarchs. II. Proc. Nat. Acad. Sci. 49, 158—164; 288—302.

Fridrichsone, A. I. (1971) Acritarches *Baltisphaeridum* and Hystrichosphaeres (?) from the Cambrian sediments of Latvia (English abstract). Pp. 5—22 *in* Paleontologiya i stratgrafiya Pribaltiki i Belorussii Sb. III. Izd. Mintis, Vil'nyus.

Gardiner, P. R. R. & Vanguestaine, M. (1971) Cambrian and Ordovician microfossils from South-east Ireland and their implications. Geol. Surv. Ireland, Bull. 1, 163—210.

Goldschmidt, V. M. (1925) Ueber fossilführende untercambrische Basalablagerungen bei Ustaoset. Fennia 45 (1), 3—11.

Hajos, M. (1964) A Mecseksi Miocén Diatomaföld Rétegek Mikroplanktonja. Das Mikroplankton der Kieselgurschichten im Miozän des Mecsekgebirges. Jahresber. ungarischen geol. Anstalt f. 1964, 139—171.

Härme, M. (1972) Signs of life in Precambrian strata in Finland. Actes du Colloque Intern. sur les Corrél. du Précambrien, Agadir-Rabat 3—23 mai 1970. Notes & Mém. Serv. géol. Maroc, (Rabat) 236 et Coll. Int. CNRS 192, 237—244.

Jagielska, L. (1966) Mikroflora w utworach eokambru i dolnego kambru wscholdnie Polski. Kwart. Geol. 2, 251—262.

Jankauskas, T. V. (1974) K stratigrafii kembriya Pribaltiki. Pp. 17—26 *in* Regional'naya geologiya Pribaltiki. Zinatne, Riga.

—»— (1975) New lower Cambrian acritarchs of the Baltic region. Paleontol. J. 9 (1), 92—102.

Jankauskas, T. V. & Posti, E. (1976) New Cambrian acritarchs from the East Baltic area (English summary). Eesti NSV Tead. Akad. Toim. Keemia-Geol. 25 (2), 145—151.

Kala, E. (1972) On the age of the Tiskre beds in the Isle of Hiiumaa (English summary). Eesti NSV Tead. Akad. Toim. Keemia-Geol. 21 (3), 276—278.

Konzalová, M. (1974 a) Acanthomorph acritarchs from the Bohemian Upper Proterozoic (English summary). Časopis pro mineral. a geol. 19 (3), 281—285.

—»— 1974 b) Acritarchs from the Bohemian Precambrian (Upper Proterozoic) and Lower-Middle Cambrian. Rev. Palaeobot. Palynolog. 18, 41—56.

Korkutis, V. (1971) About the first finds of *Volborthella* in the Lower Cambrian of the South Baltic area (English abstract). Pp. 194—196 *in* Paleontologiya i stratigrafiya Pribaltiki i Belorussii. Sb. III. Izd. Mintis. Vil'nyus.

Lieldiena, E. K. & Fridrichsone, A. J. (1968) O stratigrafii kembrijskikh otlovii. Pp. 33—52 *in* Stratigrafiya nizhnego paleozoya Pribaltiki i korrelyatsiya o drugimi regionami. Izd. Mintis, Vil'nyus.

Mardla, A. K, Mens, K. A., Kajak, K. F., Kala, E.A. & Erisalu, E. K. (1968) K stratigrafii kembrijskikh otlozhenij Estonii. Pp. 22—32 *in* Stratigrafiya nizhnego paleozoya Pribaltiki i korrelyatsya o drugimi regionami. Izd. Mintis. Vil'nyus.

Martin, F. (1975) Acritarches du Cambro-Ordovicien du massif du Brabant, Belgique. Bull. Inst. r. Sci. Nat. Belg. 51 (1), 1—33.

Martinsson, A. (1968) Cambrian paleontology of Fennoscandian basement fissures. Lethaia 1 (2), 137—155.

—»— (1974) The Cambrian of Norden. Pp. 185—283 *in* Cambrian of the British Isles, Norden, and Spitsbergen, ed. by C. H. Holland, Wiley & Sons. London.

Mens, K. & Pirrus, E. (1972) New data on the age of Tiskre beds in the NW Estonia (English summary). Eesti NSV Tead. Akad. Toim., Keemia-Geol. 21 (3), 278—281.

Metzger, A. A. T. (1922) Beiträge zur Paläontologie des nordbaltischen Silurs im Ålandsgebiet. Bull. Comm. Géol. Finlande 56. 8 p.

Missarzhevsky, V. V. (1969) Opisanie khiolitov, gastropod, khiolotelmintov, kamenid from neyasnogo sistematicheskogo polozheniya. Akad. Nauk. SSSR, geol. inst. Trudy 206, 105—175.

Naumova, S. N. (1949) Spory nizhego kembriya. Izv. Akad. Nauk. SSSR, Ser. geol. 1949, No. 4, 49—56.

—»— (1961) Spore complexes of the Riphean and Cambrian in the USSR (English summary). Dokl. sov. geol., mezhd. geol. kongr. XXI sessiya: Stratigrafiya pozdnego dokembriya i kembriya, 109—117.

Öpik, A. A. (1925) Beitrag zur Stratigraphie und Fauna des estnischen Unter-Kambriums (Eophyton-Sandstein). Tartu Ülikooli Geol.-Inst. toim. 3, 1—20.

—»— (1929) Studien über das estnische Unterkambrium (Estonium). Acta et Comm. Univ. Tartuensis, AXV. 2; reprint: Tartu Ülikooli Geol.-Inst. toim. 15. 56 p. 4 Pls.

—»— (1956) Cambrian (Lower Cambrian) of Estonia. 20th Int. Geol. Congr. Mexico. El sistema Cambrico, su paleogeografia y el problema de su bese. T. 1, 97—126.

Potonié, R. (1956) Synopsis der Gattungen der Sporae dispersae. 1. Teil: Sporites. Geol. Jahrb., Beih. 23. 103 p.

Potter, T. L. (1974) British Cambrian acritarchs — a preliminary account. Rev. Palaeobot. Palynolog. 18, 61—62.

Roblot, M.-M. (1963) Découverte de sporomorphes dans des sédiments antérieurs à 550 M.A. (briovérien). C.R. Acad. Sci. 256 (7), 1 557—1 559.

Salujha, S. K., Rehman, K. & Arora, C. M. (1971) Plant microfossils from the Vindhyans of Son Valley, India. J. Geol. Soc. India 12, 24—33.

Simonen, A. (1960) Pre-Quaternary rocks in Finland. Bull. Comm. Géol. Finlande 191. 49 p.

Slaviková, K. (1968) New finds of acritarchs in the Middle Cambrian of the Barrandian (Czechoslovakia). Věstn. Ustř. Úst. Geol. 43 (3), 199—205.

Staplin, F. L. (1961) Reef-controlled distribution of Devonian microplankton in Alberta. Paleontology 4, 392—424.

Staplin, F. L., Jansonius, J. & Pocock, S. A. J. (1965) Evaluation of some Acritarchous Hystrichosphere Genera. Neues Jahrb. Geol. Paläontol., Abh. 123, 167—201.

Strömer, L. (1925) On a Lower Cambrian Fauna at Ustaoset in Norway. Fennia 45 (1), 12—22.

Suomalainen, T. & Tynni, R. (1970) Der präquartäre Mikrofossilienbestand des Tonvorkommens von Kaljala auf der Karelischen Landenge. Bull. Comm. Géol. Finlande 245. 81 p.

Tanner, V. (1911) Über eine Gangformation von fossilienführendem Sandstein auf der Halbinsel Långbergsöda-Öjen im Kirschspiel Saltvik, Åland-Inseln. Bull. Comm. Géol. Finlande 25. 13 p.

Thorslund, P. & Westergård, A. H. (1938) Deep boring through the Cambro-Silurian at File Haidar, Gotland. Preliminary Report. Sveriges Geol. Unders., Ser. C 415. 57 p.

Timofeev, B. V. (1956) Hystrichospaeridae kembriya. Dokl. Akad. Nauk SSSR, 206 (1), 130—132.

—»— (1959) Drevneishaya flora Pribaltiki i ee stratigraficheskoe znachenie. Trudy vsesoyuz. neft. nauch.-issled. geol.-razv., inst. vyp. 129. 320 p.

—»— (1960) Sur la caracteristique micropaleontologique de la formation de Visingsö. Geol. Fören. i Stockholm, Förh. 28 (1), 28—42.

—»— (1963) On organic remains in the Eocambrian of Norway. Norsk Geol. Tidsskr. 43, 473—476.

—»— (1966) Mikropaleofitologicheskoe issledovanie drevnikh. Nauka. Moskva-Leningrad. 147 p.

—»— (1969) Sferomorfidy proterozoya. Nauka. Leningrad. 146 p.

Tynni R. (1975) Ordovician hystrichospheres and citinozoans in limestone from the Bothnian Sea. Geol. Surv. Finland, Bull. 279. 59 p.

—»— (1978) Muhoksen muodostuman mikrofossiilitutkimuksen tuloksia. (Microfossils of the Muhos formation). Geologinen tutkimuslaitos, Tutkimusrap. 30. 18 p.

Tynni, R. & Siivola, J. (1966) On the Precambrian microfossil flora in the siltstone of Muhos, Finland. C.R. Soc. géol. Finlande 38, 127—133.

Umnova, N. I. & Vanderflit, E. K. (1971) Kompleksy akritarkh kembrijskikh i nizhneorlovikskikh otlozhenij zapada i severo-zapada Russkoj platformy. Pp. 45—73 *in* Palinologicheskie issledovaniya v Belorussii i drugikh rajonakh SSSR. Minsk.

Vanguestaine, M. (1974) Espèces zonales d'Acritarches du Cambro-Trémadocien de Bélgique et de l'Ardenne Francaise. Rev. Paleobot. Palynolog. 18, 63—82.

Vardová, M. (1966) Paleozoic microplankton from Central Bohemia. Casop. Miner. Geol. 11, 409—414.

Veltheim, V. (1969) On the pre-Quaternary geology of the Bothnian Bay area in the Baltic Sea. Bull. Comm. Géol. Finlande 239. 56 p.

Vidal, G. (1976) Late Precambrian microfossils from the Visingsö Beds in southern Sweden. Fossils and Strata 9. 57 p.

Vogt, T. (1924) Forholdet mellem Sparagmit-systemet og det marine Underkambrium ved Mjøsen. Norsk Geol. Tidsskr. 7, 281—383, 8 Pls.

Volkova, N. A. (1968) Akritarkhi dokembrijskikh inizhnekembrijskikh otlozhenij Estonii. Akad. Nauk SSSR, geol. inst. Trudy 188, 8—36.

—»— (1969) Raspredelenie akritarkh v razrezakh severo-vostochnoj. Pol'shi i akritarkhi severo-zapada Russkoj platformy. Akad. Nauk SSSR, geol. inst. Trudy 206, 74—76, 224—236.

—»— (1974) Akritarkhi iz pogranichnykh sloev nizhnego-strednego kembriya zapdnoij Latvii. Pp. 194—198 *in* Biostratigrafiya i paleontologiya nizhnego kembriya Evropy i severnoj Azii. Izd. Nauka. Moskva.

—»— (1976) O nakhodke dokembrijskikh spor s tetranym rubtsom. Dokl. sov. geol., mezhd. geol. kongr. XXV sessiya: Paleontologiya morskaya geologiya, 14—18.

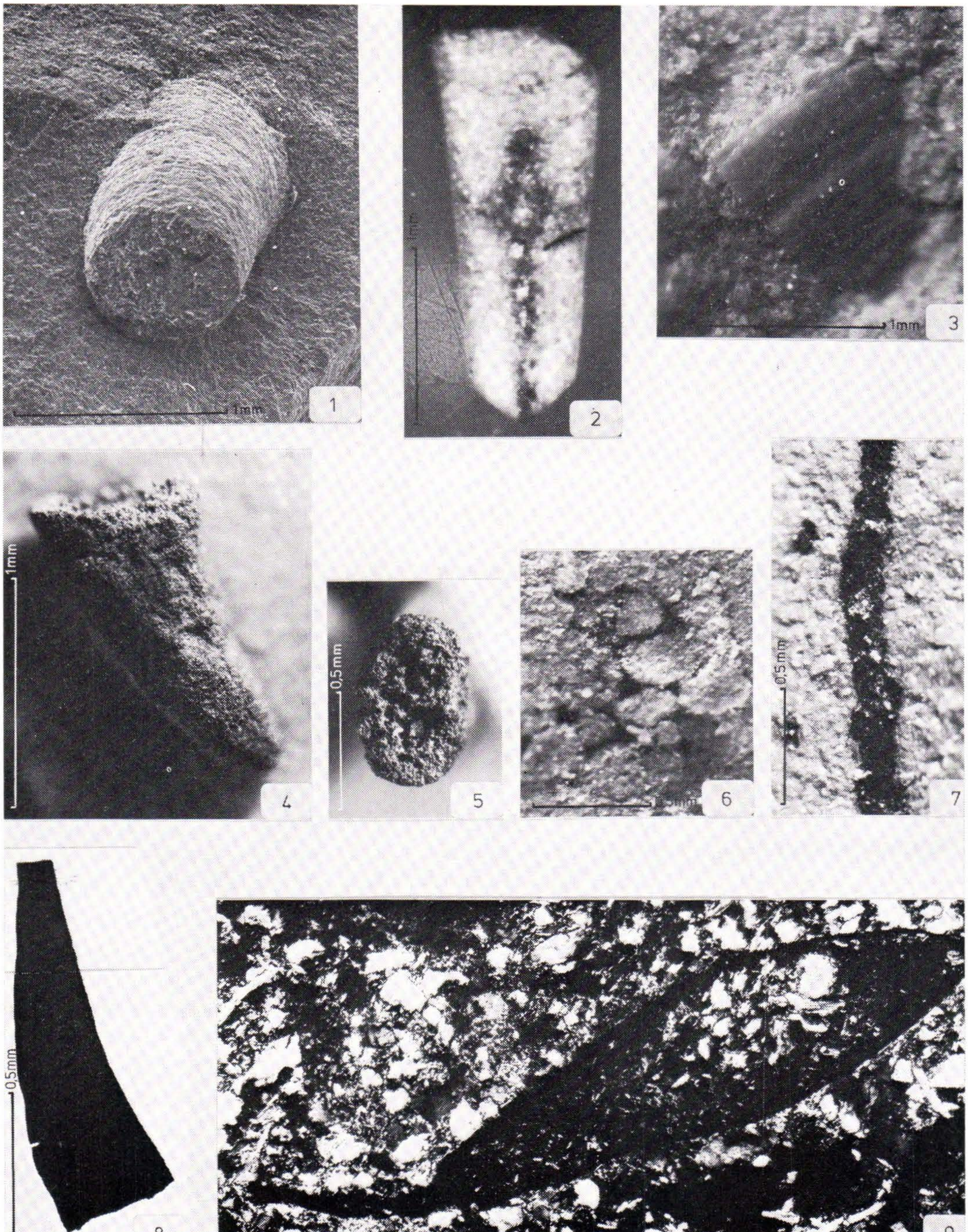
Wall, D. (1962) Evidence from recent plankton regarding the biological affinites of Tasmanites Newton 1875 and Leiosphaeridia Eisenack 1958. Geol. Mag. 99, 353—362.

Wazýnska, H. (1967) Wstepne badania mikroflorystyczne osadow sinianu i kambru z obszaru Bialowiezy. Kwart. Geol. 1, 10—20.

Wetzel, O. (1933) Die in organischer Substanz erhaltenen Mikrofossilien des Baltischen Kreide-Feuersteins. Palaeontographica 77, 141—188; 78, 1—110.

PLATE I

1. *Volborthella tenuis*, depth 119 m.
2. *V. tenuis*, longitudinal section, 119 m.
3. Brachiopoda fragment, 119 m.
4. Hyolithus type, 119 m.
5. Hyolithus type, cross section.
6. Pyrite pattern in siltstone, 119 m.
7. Pyritic worm tracks, 119 m.
8. Chitin shell of organism, 129 m.
9. Section of wormlike organism, length 1.1 mm. Thin section 94.09 m.



9 1278012532

PLATE II

10. *Leiosphaeridia* sp., 129 m.
11. *Leiosphaeridia* sp., 129 m.
12. *Tasmanites piritaensis*, 89.2 m.
13. *T. piritaensis*, 89. 2 m.
14, 15. *Cymatiosphaera solfensis*, 129 m., scale 20 μ.

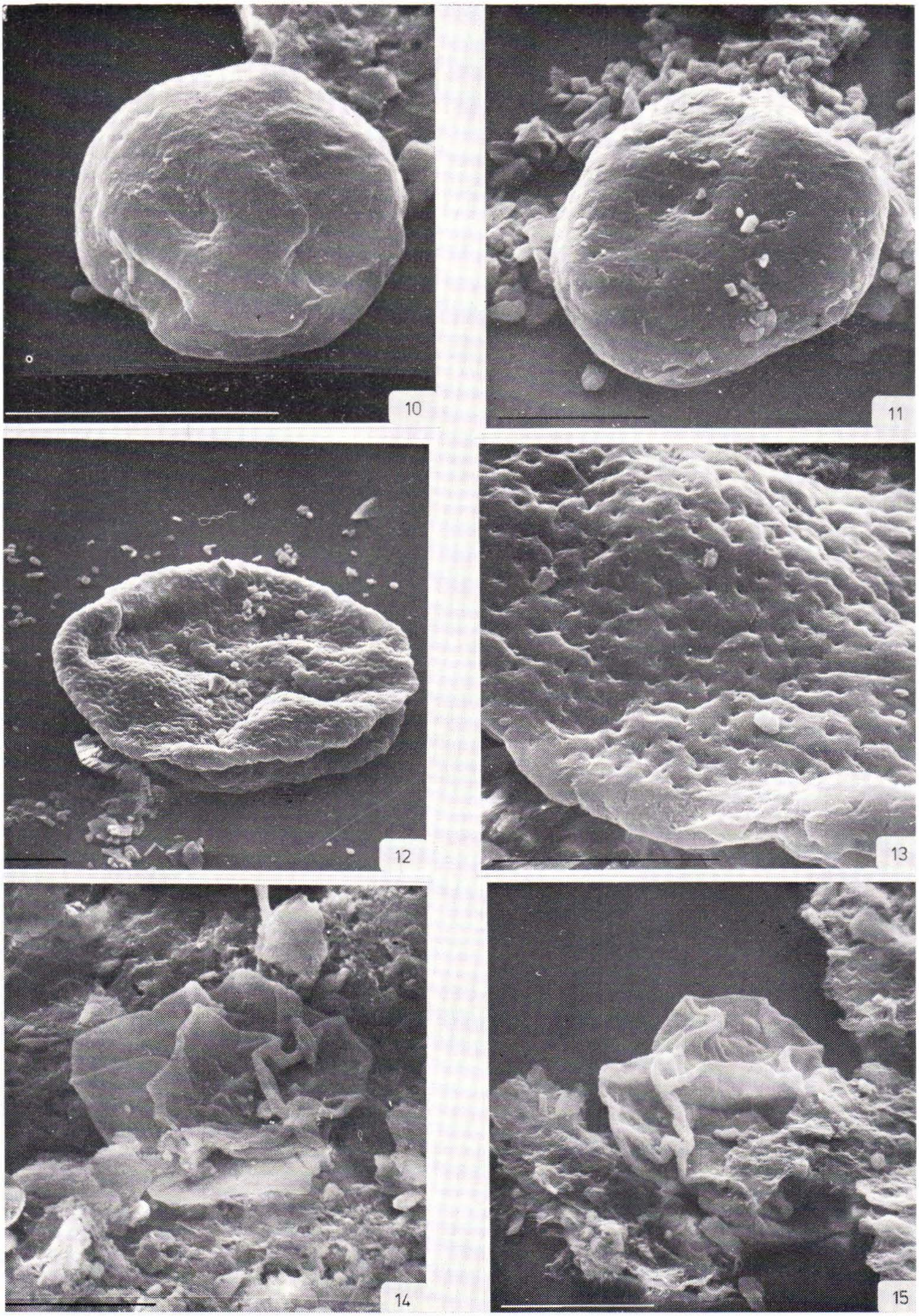

10
11
12
13
14
15

PLATE III

16. ?*Baltisphaeridium* sp., 129.8 m.
17. ?*Cymatiogalea* sp., 129.8 m.
18. *Trachysphaeridium* sp., 129 m.
19. *Leiosphaeridia* sp., 129 m., scale 20 μ.
20. *L.* sp., surface structure composed of pyrite grains, 89.5 m.
21. *L.* sp., 101.3 m.
22. *L.* sp., 129 m.

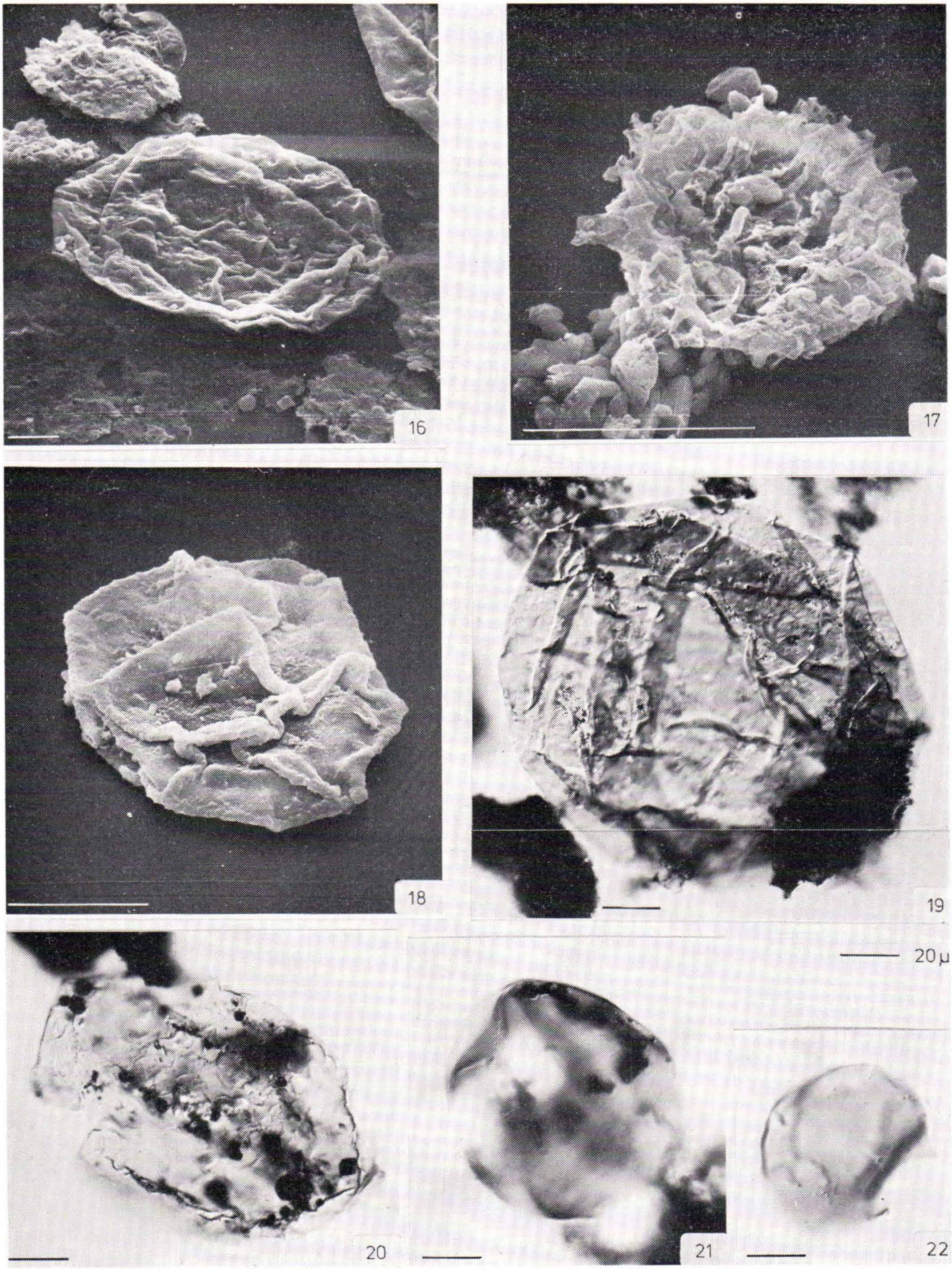

16
17
18
19
20µ
20
21
22

PLATE IV

23. *Leiosphaeridia* sp., 129 m.
24. *L.* sp., 81.8 m.
25. *Stictosphaeridium* sp., 81.8 m.
26. a, b. *Tasmanites piritaensis*, 89.2 m.
27. *Kildinella* sp., 73. 6 m.
28. *Tasmanites nanus*, 119 m.
29. *T. bobrowskii*, 92. 3 m.
30. *T. bobrowskii*, 85.4 m., scale 20 μ.

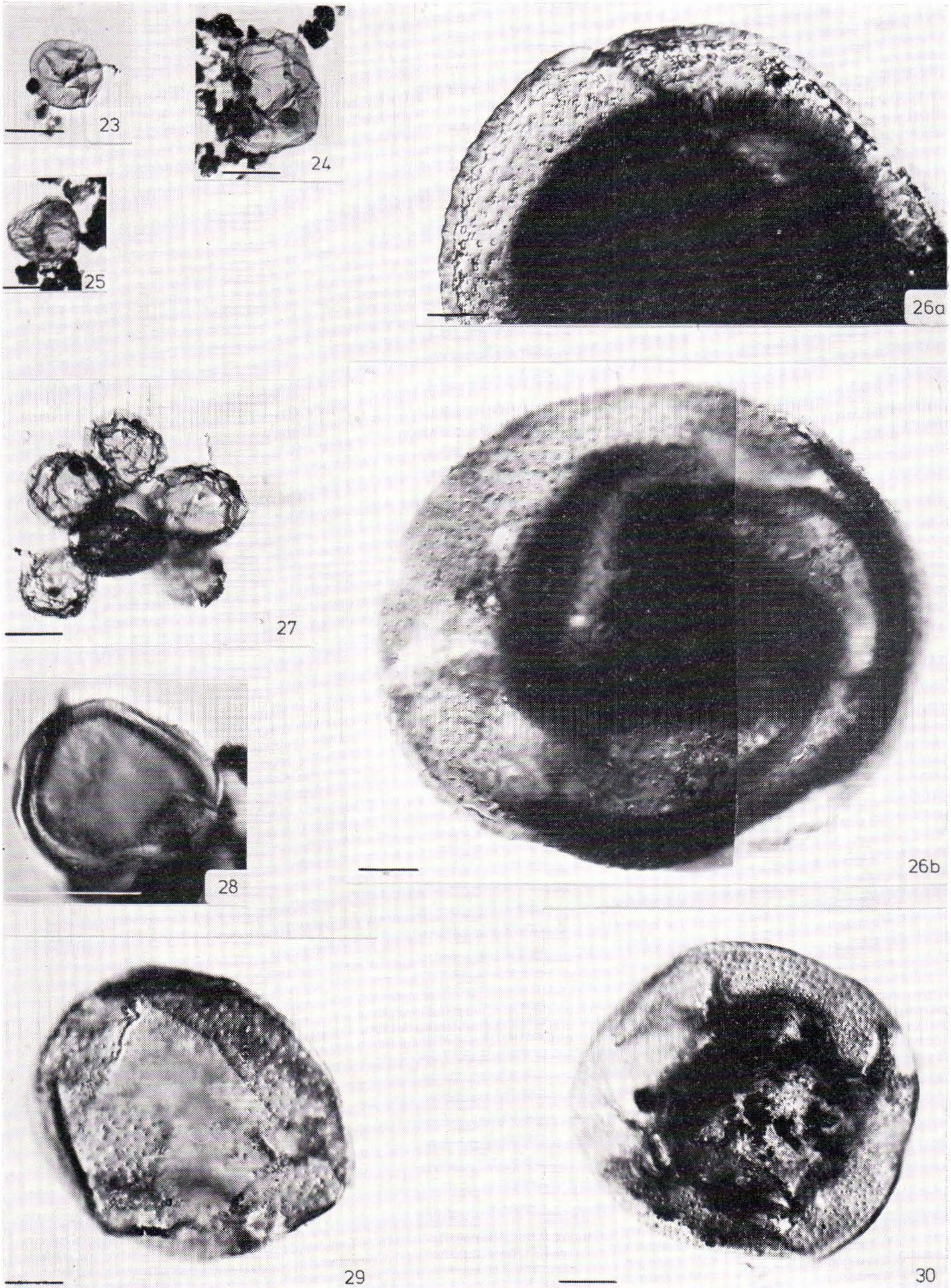

23
24
25
26a
27
26b
28
29
30

PLATE V

31. Poroide fragment, 119 m.
32, 33. *Archaeodiscina umbonulata*, 89.5 m.
34. *Cymatiosphaera* sp. 129 m.
35. *Cymatiosphaera solfensis*, 129 m.
36, 37, 38. *Cymatiosphaera solfensis*, 129 m.
39. *Cymatiosphaera* sp. Volkova, 116.6 m.
40. a, b. *Cymatiosphaera* sp. 2, 116 m.
41. *Cymatiosphaera* sp. 3, 96.3 m.
42. a, b. *Cymatiosphaera* sp. 4, 81.8 m.
43. *Dictyodium* aff. *indefinita*, 119 m.
44. *Dictyodium* aff. *indefinita*, 129 m.

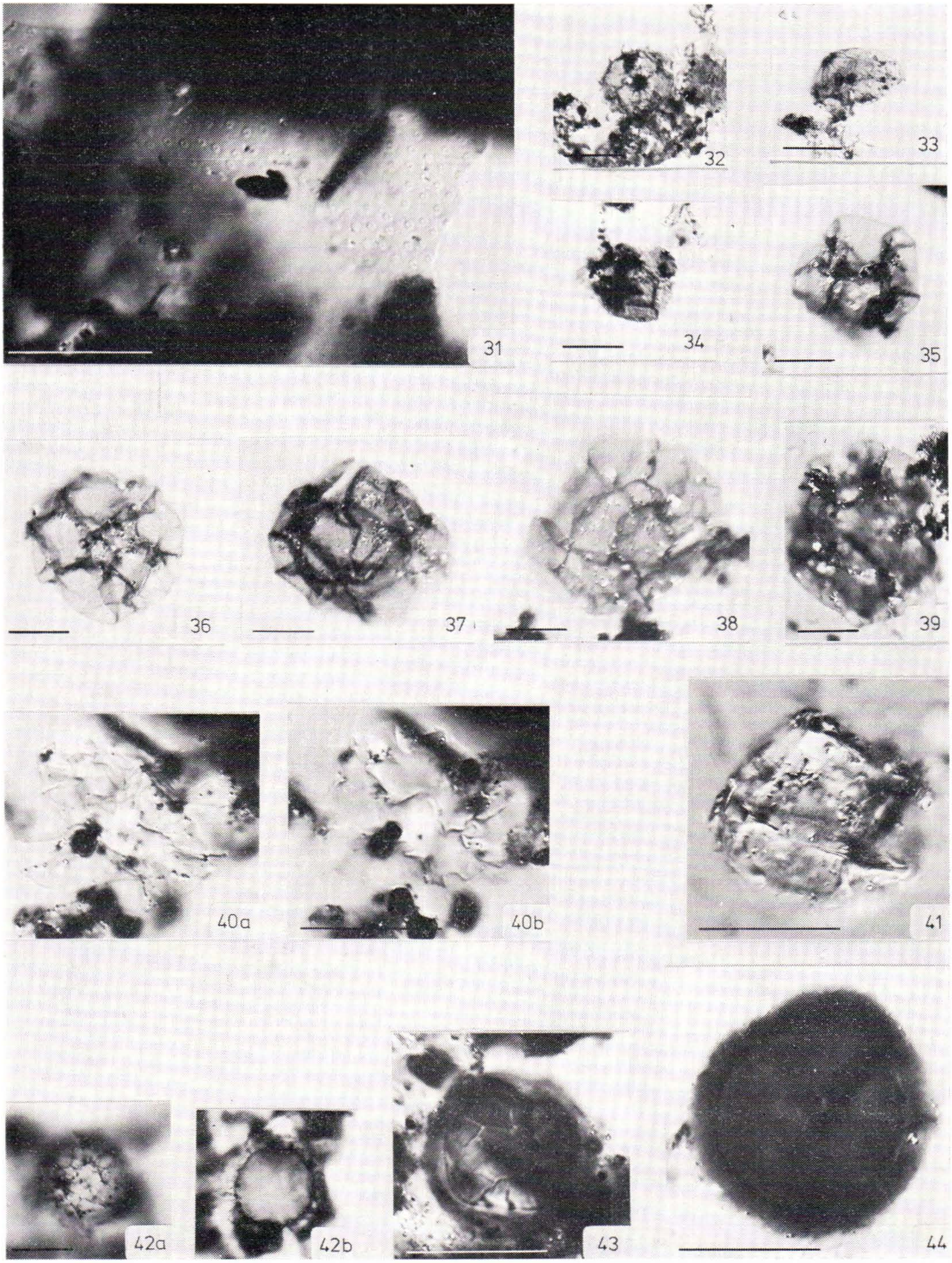

31
32
33
34
35
36
37
38
39
40a
40b
41
42a
42b
43
44

PLATE VI

45, 46. *Dictyodium* aff. *indefinita*, 129 m.
47, 48. *Granomarginata squamacea*, 129 m.
49. *Granomarginata* sp., 129 m.
50. *Leiomarginata simplex*, 116.2 m.
51. *Leiomarginata simplex*, 119 m.
52. *Leiomarginata simplex*, 129 m.
53. *Leiomarginata simplex*, 96.3 m.
54. a, b. *Archaeofavosina* sp., 116.2 m.
55, 56, 57. *Trachysphaeridium* sp., 129 m.

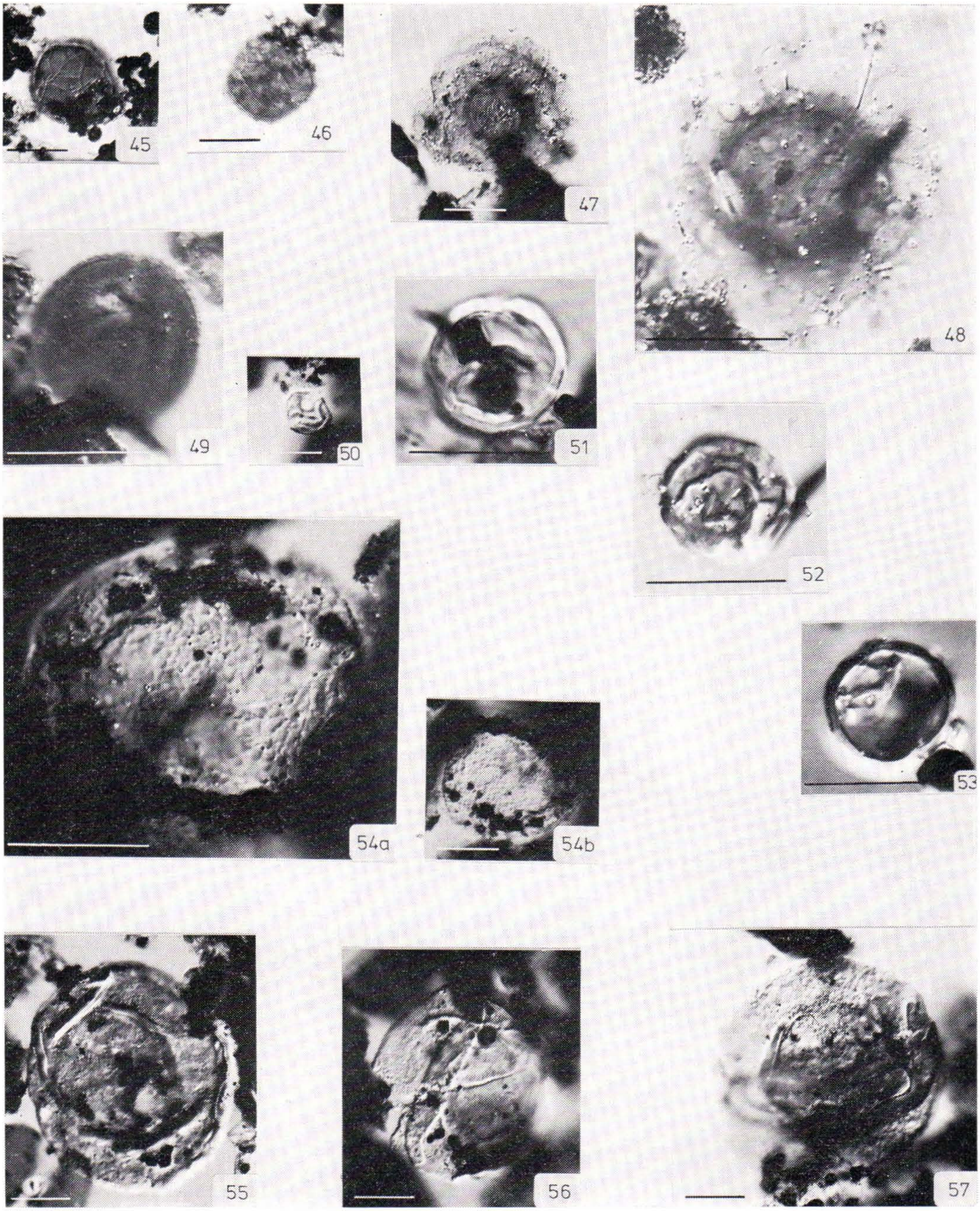

45
46
47
48
49
50
51
52
53
54a
54b
55
56
57

PLATE VII

58, 59. *Lophosphaeridium* sp. 1, 81.8 m.
60. *Lophosphaeridium* sp. 2, 101.8 m.
61. *Lophosphaeridium tentativum*, 96.3 m.
62. *Lophosphaeridium* sp. 3, 129 m.
63. a, b. *Lophosphaeridium* sp., 98.7 m.
64. *Leiovalia* sp. 129 m.
65. *Acanthodiacrodium* sp. 129 m.
66. ?*Baltisphaeridium* sp., 129 m.
67. *Ooidium* sp., 129 m.
68. *Comasphaeridium* sp. 129 m.
69. *Hystrichosphaeridium insigne*, 129 m.
70. *Comasphaeridium* sp., 129 m.

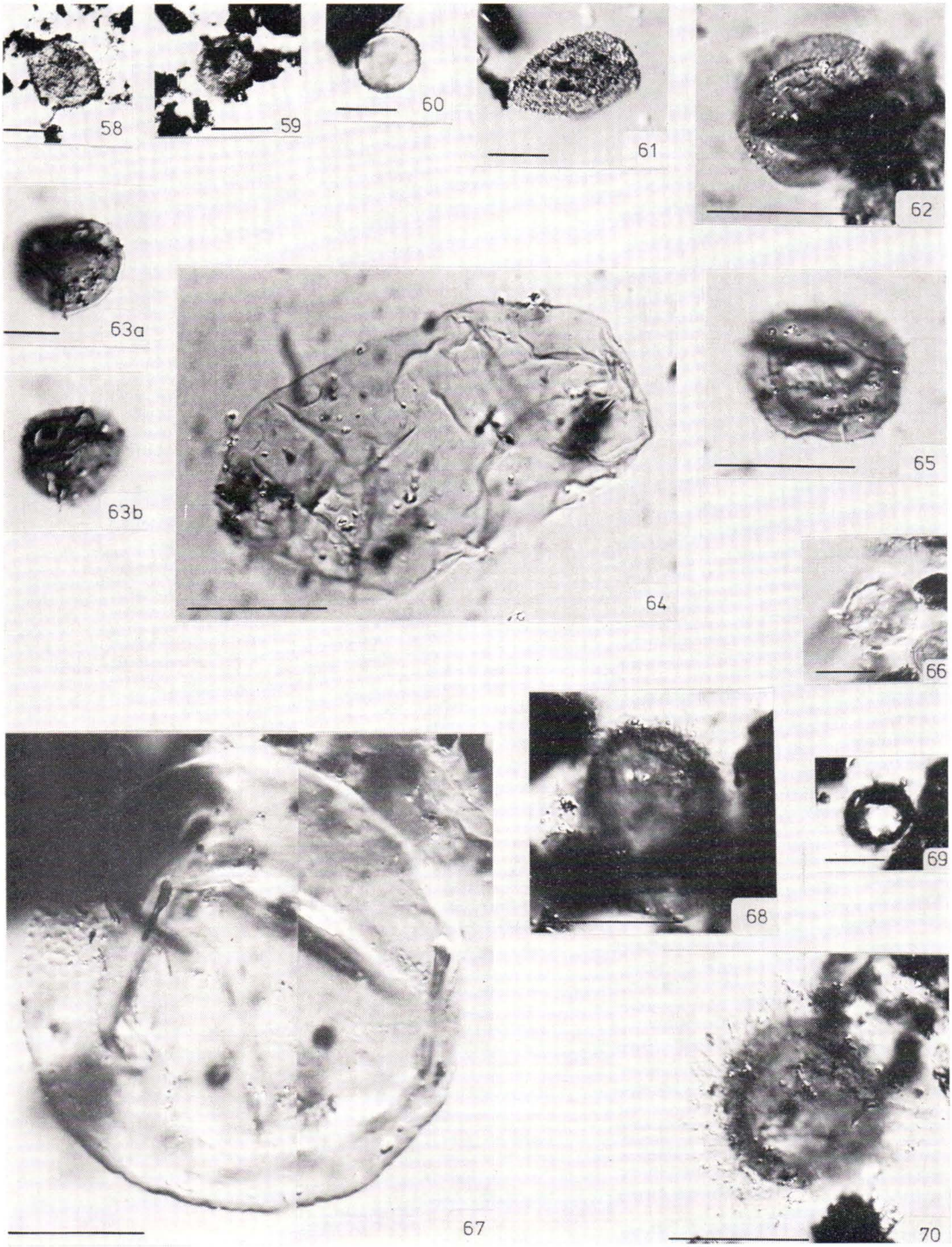

58
59
60
61
62
63a
63b
64
65
66
67
68
69
70

PLATE VIII

71, 72, 73, 74. *Cymatiogalea* sp., 119 m.
75. *Cymatiogalea* sp., 129 m.
76, 78, 81. *Vulcanisphaera microspinosum*, 96.3 m.
77. *Vulcanisphaera* sp., 89.5 m.
79. ?*Lophosphaeridium* sp., 116.2 m.
80. *Vulcanisphaera* sp., 81.8 m.

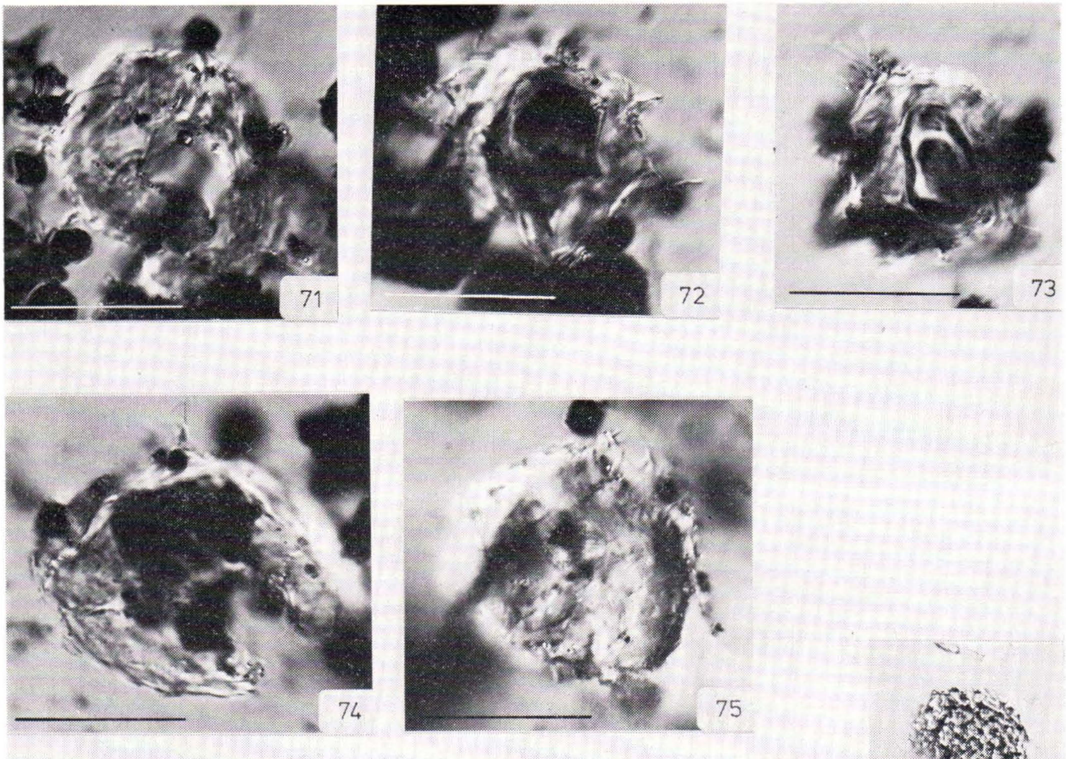
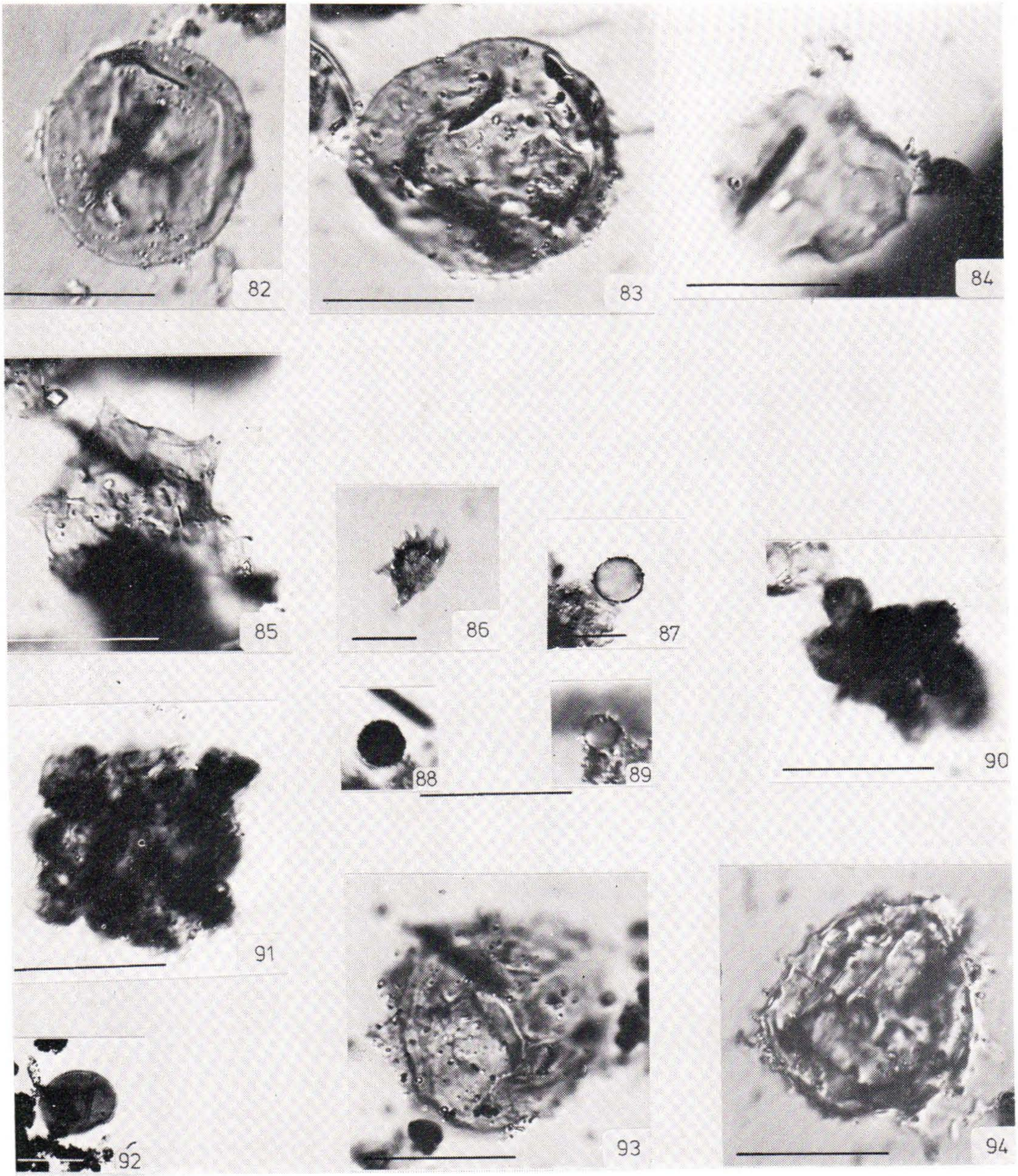

71
72
73
74
75
76
77
78
79
80
81

PLATE IX

82, 83. ?*Vulcanisphaera* sp., 129 m.
84. *Multiplicisphaeridium clavatum* 129 m.
85. *Goniosphaeridium* sp.
86. *Micrhystridium* sp., 129 m.
87. *Micrhystridium* aff. *tornatum*, 129 m.
88, 89, 90. *Micrhystridium pallidum* f. *minor*.
91. *Synsphaeridium* sp., 129 m.
92. *Leiotriletes*-typ., 81.8 m.
93. *Trachytriletes* sp., 116.2 m.
94. trilete- acritarch, 96.3 m.


82
83
84
85
86
87
88
89
90
91
92
93
94

ISBN 951-690-089-5