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DISCOVERIES ON GRAPTOLITES BY X-RAY STUDIES

Abstract. — The X-ray method has been used for analysing pyritized graptolites with the purpose of finding traces of the unknown soft parts. The investigated material comprises mainly Llandoverian graptolites from Bornholm, Denmark, which occur in dark grey shales and frequently are pyritized. The graptolites are generally uniformly filled with pyrite throughout the rhabdosomes. However, at a few horizons from the *cyphus* Zone, pyrite is observed specially concentrated in the distal part of the thecal tubes, both in diplograptids and monograptids. In other specimens from the same horizon pyrite is found in rounded concentrations just outside the thecal apertures.

Continuous extraskeletal pyrite is rare, but is nevertheless found (preferably around the distal parts of some *Retiolites* rhabdosomes). The pyrite replacements within the thecae and outside the thecal mouths have almost equal form and size throughout each rhabdosome, and may have replaced decaying soft parts. However, with the present material it has not been possible to clarify any exact structures.

INTRODUCTION

The X-ray method for analyzing fossils was initiated by Brühl (1896) and Lemoine (1896), but especially in the last 40 years remarkable discoveries, including traces of soft parts, have been made with refined radiographic techniques in different fossil groups. Even soft parts of Palaeozoic fossils, which rarely are preserved, have been disclosed, in tentaculitids (Blind and Stürmer 1977), cephalopods and arthropods, especially trilobites, e.g. Stürmer (1969, 1970) and Stürmer and Bergström (1973, 1976).

Under anaerobic conditions at the sea-bottom, where the decomposition of the soft parts has been impeded in the fine grained sediments, pyrite may be formed in the place of the soft parts (Emery and Rittenberg 1952). Examinations with X-rays can reveal original structures as pyritized material offers a good contrast due to the high absorption coefficient of pyrite.

The present investigation was initiated with the purpose of finding traces of soft parts of the graptolites. Only the peridermal morphology of the graptolites is known, and this restriction is one of the reasons for the continued discussion of the affinities of the graptolites. Morphological discoveries during the last 30 years have implied that the graptolites have been closely allied to the Hemichordata, e.g. Kozłowski (1949, 1966). However, one of the most recent investigations of the ultrastructures of the graptolite and pterobranch periderms have shown considerable differences in fabric pattern and mode of secretion of the tissues. These results imply that there is no reason to suggest an immediate phylogenetic relationship between the Pterobranchia and the Graptolithina (Urbanek 1976).

No definite traces of soft parts of the graptolites have ever been described, but many models based on soft parts of the Pterobranchia, especially of the Rhabdopleuridae, have been applied in discussions of the ecology of the graptolites, e.g. Bulman (1970), Kirk (1972) and Rickards (1975). Consequently, a proper understanding of the soft parts of the graptolites would be of importance for both the interpretation of the phylogenetic relationship and mode of life.

MATERIAL AND X-RAY METHODS

The present investigation has been carried out on a material of dark bituminous shales with graptolites preserved in low to full relief, infilled with pyrite. This state of preservation shows that anaerobic conditions prevailed at the sea-bottom, and that the formation of pyrite was completed at an early stage, so that the delicate graptolite periderm was protected from the usual flattening under the weight of the overlying sediment.

Around 500 slabs containing a varying number of graptolites have been radiographed and the number of graptolites investigated by far exceeds 5000.

The main part of the examined graptolites are from the Llandoverian Series (Silurian) exposed on Bornholm, Denmark, where well-preserved pyritized graptolites are found at several horizons (Bjerreskov 1975). Samples from each layer with pyritized specimens have been radiographed. Furthermore, a few specimens from the most highly bituminous shale present on Bornholm, the Lower Ordovician alum shale with *Dictyonema* and *Clonograptus*, and some slabs from the Middle Ordovician *Dicellograptus* Shale on Bornholm have been investigated. In addition, a few slabs of Lower-Middle Ordovician graptolites shales from Slemmestad, Southern Norway, have been examined. However, none of the radiographs of the Ordovician graptolites has revealed any remarkable details, mainly on account of incomplete pyritizations in the present specimens.

The radiographs were made with a Carl Drenck Fedrex 140 X-ray apparatus. The target distance is 65 cm. Soft X-rays were used, 25—40 kV (normally 30—35 kV) and 2 mA. Generally the film material used was Agfa Scientia plates 23D50. The exposure times were 2—3 hours.

RESULTS OF THE INVESTIGATIONS

The pyritized graptolites are generally filled with evenly distributed pyrite enclosed by the carbonized periderm. The graptolites are opaque when treated with suitably soft X-rays (pl. 18: 1). Occasionally the carbonized periderm is seen as a thin bright line separating the internal pyrite from the surrounding sediment, while the median septum and the interthecal septa may be exposed in a similar way (pl. 21: 3).

The pyrite fillings may take different forms, but this is only rarely seen at a few horizons, mainly in the Lower Llandoverian. There are two kinds of deviation from the complete filling with pyrite:

1. Incomplete pyritizations within the rhabdosome.
2. Exoskeletal pyrite in contact with the rhabdosome.

1. Incomplete filling with pyrite

Incomplete filling with pyrite has been noticed both in diplograptids and monograptids from the *revolutus* Zone (equivalent to the *cyphus* Zone). In a few cases the incomplete filling shows concentrations of pyrite in the distal parts of the thecal tubes, occurring regularly throughout each separate rhabdosome (pl. 18: 2—4). A possible explanation is that the precipitation of pyrite started at the apertures in contact with the surrounding sediment. However, reduction processes in the decaying soft parts may also have caused the pyrite concentration in the distal portions of the thecae, and the pyrite may in that instance reflect the approximate position of the graptolite zooid.

In a few graptolites the pyrite tends to be concentrated along the dorsal interthecal septum of each theca. This has been found in the distal thecae of *Glyptograptus* sp. and *Monograptus revolutus* Kurck from the *revolutus* Zone (pl. 19: 1, 2). These pyritizations occur regularly throughout the rhabdosomes, indicating that identical conditions have existed in each separate theca, may be originating from decaying of the soft parts. Possibly the pyrite is associated with the supposed stalks of the zooids, which may have been placed close to the dorsal interthecal septa of the thecae, representing the most stable part of the rhabdosome.

2. Extraskeletal pyrite

Specimens preserved with external pyrite are not very common among the investigated graptolites. However, in several retiolitid specimens, particularly abundant at the transition from Llandoverian to Wenlockian, pyritizations differ significantly from the general pattern. Commonly the pyritization in the retiolitids is as in the associated monograptid graptolites with sharply limited fillings (pl. 19: 3). However, in a few cases the distal part of pyritized specimens of *Retiolites geinitzianus angustidens* Elles and Wood is surrounded by a pyrite cover outside the periderm (pl. 19: 4, 5). Whereas the associated *Monograptus vomerinus* (Nicholson) and *Cyrtograptus lapworthi* Tullberg do not show any signs of extraskeletal pyrite (pl. 19: 5).

If those retiolitids had been homogeneous throughout the rhabdosomes the proximal parts might also have been expected surrounded by pyrite, as the mesh of the reticulum is uniform throughout the rhabdosomes, thus offering the same opportunities for pyritization.

It is possible that the retiolitids of the time of the burial housed soft parts or maybe were surrounded by some sort of tissue which could have acted as a centre for precipitation of the pyrite. In that case the distribution of pyrite would suggest a lack of soft parts at the proximal end of the rhabdosome, occasioned maybe by the earlier death of proximal than distal individuals.

In addition, pyritizations are found on the outer side of the rhabdosomes of some diplograptids and monograptids. These specimens occur in the same horizon in the *revolutus* Zone where the incomplete pyrite fillings were found.

Pyrite is occasionally seen just outside the thecal apertures in *M. revolutus*. The thecae with diminishing hooks in the middle part of the rhabdosome and the distal thecae show this form for apertural pyrite (pl. 20: 1—3), but no external pyrite has been identified with certainty in the delicate proximal part with hooked thecae (pl. 20: 4). The dorsal thecal hoods in the mesial to distal thecae are seen clearly in some cases (pl. 20: 3). The pyrite precipitate in the apertures most commonly has a rounded shape with an average diameter about 0.3—0.5 mm, which is slightly more than the thecal width. *Monograptus atavus* Jones (pl. 21: 5), which is common at the same horizon and frequently filled with pyrite, occasionally also shows external apertural pyrite, but generally the apertures in this species are covered by a thin carbonized film (observed in light-microscope).

Among the diplograptids external pyrite has been seen in different genera. From the above mentioned horizons in the *revolutus* Zone a few fully pyritized specimens of *Pseudoclimacograptus undulatus* (Kurck) have been found with pyrite protruding out from the thecal apertures, but with no well defined shape (pl. 21: 2). The carbonized periderm and the well developed thecal hoods are clearly seen in the investigated specimen.

At the same horizon *Rhaphidograptus toernquisti* (Elles and Wood) is abundant and is commonly fully pyritzed. The carbonized periderm in *R. toernquisti* appears to be rather thick, and the thecal hoods are clearly seen on the radiographs. Here as in *M. revolutus* the rhabdosomes can occur in full relief with pyrite protruding out from the apertures (pl. 21: 1, 3—5). As in *M. revolutus* the pyrite is developed in rounded shapes and the external pyrite bodies reach about the same size in all apertures within the same rhabdosome.

In a few specimens pyrite is seen as a thin layer along the thecal walls outside the periderm (pl. 21: 4). This might here be due to the heaviness of pyritization.

The pyrite outside the thecal mouths may be interpreted as pyritizations which have grown through the openings of the periderm, all precipitated when the soft parts had disappeared. It is also possible that the pyrite bodies have replaced the decaying soft parts. If the soft parts were dissolved during the decomposition, the solutions may have penetrated into the underlying sediment, resulting in asymmetrical pyritizations. Both symmetrical and asymmetrical pyritizations have been found within the same specimens.

DISCUSSION

Despite the large number of graptolites examined no definite shapes and details of the soft parts have been revealed during this investigation. It may be argued that all soft parts have disappeared, either before the graptolites were buried or during decomposition within the bottom sediment. If this had been the case, the precipitation of pyrite would be expected to be distributed more at random.

However, the rather homogeneous shape of the pyrite bodies from theca to theca throughout several rhabdosomes found in only a couple of horizons suggests that decaying soft parts in extreme cases might have acted as nuclei for pyrite precipitation. There are no details preserved to reveal the morphology of the soft parts. It is too far-fetched to assume that the external apertural pyrite reflects the presence of a sort of lophophore, assuming a soft part morphology as in *Rhabdopleura*, but the general size seems to be acceptable for zooids with such a structure. Nor does the intraskeletal pyrite reveal the definite shape of the soft parts, but occasional vague indications of these appear from the pyrite concentrations near the thecal apertures and along the dorsal wall of the thecae.

The current general assumption that the graptolites were surrounded by some sort of extrathecal tissue cannot be verified. Only a very few graptolites, e.g. *R. geinitzianus angustidens*, commonly show pyrite on the external side of the carbon films. On the whole, however, external pyrite is rarely formed.

The results of the studies presented here have shown details that may be interpreted as pyritizations of the decomposition of the soft parts of the graptolites. The lack of details in the pyrite precipitation might partly be due to the composition of the imbedding sediment. This is a poorly sorted dark grey shale with grain size of about 30% sand, 45% silt, and 25% clay. Further use of the radiographic method, especially on highly bituminous and more fine grained graptolite shales, should be encouraged.

It should be remembered that the radiographic technique also serves a practical purpose, being useful for general investigation and portrayal of pyritized graptolites. Additional information may be gained from delicate graptolites, expecially with regard to the extremely slender proximal parts which are often difficult to distinguish and prepare on the surface of the slabs. Some thecal structures can also be made out, e.g. the presence of small hoods. Finally, the three-dimensional form of the rhabdosomes and the detailed thecal structures can easily be illustrated using stereoscopic radiographs.

ACKNOWLEDGEMENTS

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DISCUSSION

P.R. Crowther:

I would like to congratulate Dr. Bjerreskov on her stimulating paper and am in full agreement with her conclusions, following my own experiments with X-ray techniques at the Sedgwick Museum, Cambridge. Although for complex, three-dimensional structures the correct interpretation of radiographs requires some specialised expertise, this is less important when dealing with smaller fossils such as graptolites. Graptolite workers commonly deal with completely flattened types of preservation and are therefore accustomed to making identifications from "silhouettes'. An X-ray projection of a three-dimensional fossil onto a two-dimensional radiograph is essentially analogous to the results of compression onto a bedding plane during compaction.

The major advantage of radiography over other examination techniques is that, assuming a suitable density contrast exists between fossil and matrix, identifications are not restricted to those few specimens that happen to be revealed by splitting the rock along one particular bedding plane. A radiograph displays the entire pyritised fauna contained in the rock. It is possible to slice up several metres of section into suitably thin slabs, X-ray them and thus obtain a complete record of the fauna, so reducing the possibility of missing rarer members. Borehole cores through pyritised strata provide an ideal source of material.

Providing pyritisation has not been too selective, radiography enables detailed population studies to be undertaken. The use of stereo pairs is ideal for giving a clear picture of graptolite colonies with a complex topology e.g. *Monograptus turriculatus* with its spiral rhabdosome drawn out into a cone shape. It also enables the determination of relative positions of individual specimens within the rock and whether or not the fauna is restricted to certain bedding planes.

There is no doubt that radiography is a powerful tool for the graptolite worker and its potential has yet not been fully exploited.

A. Urbanek:

Even the presence of an external pyrite is not necessarily an evidence in favour of the presence of the external soft tissues. Different mucous substances and secretions of zooids which most probably covered the outer surface of the skeleton may also serve as the centres of nucleation and pyrite precipitation.

EXPLANATION OF PLATES 18—21

All the figures are radiographs

Plate 18

1. *Rhaphidograptus toernquisti* (Elles and Wood 1906). The *revolutus* Zone, Bornholm. The specimen shows evenly distributed pyrite enclosed by the periderm. MMH 14080. ×10.
2, 3. *Glyptograptus* sp. The *revolutus* Zone, Bornholm. The two specimens show concentrations of pyrite in the distal parts of the thecal tubes. *2 Glyptograptus* sp. 1, MMH 14081. ×10. *3 Glyptograptus* sp. 2. MMH 14082. ×10.
4. *Monograptus revolutus* Kurck, 1882. The *revolutus* Zone, Bornholm. Specimen with pyrite concentrated in distal part of the thecal tubes. MMH 14083. ×10.

Plate 19

1. *Glyptograptus* sp. 2. The *revolutus* Zone, Bornholm. Pyrite tends to be concentrated along three dorsal interthecal septa. MMH 14084. ×10.
2. *Monograptus revolutus* Kurck, 1882. The *revolutus* Zone, Bornholm. Pyrite is concentrated along the dorsal interthecal septa. MMH 14085. ×10.
3. *Retiolites geinitzianus angustidens* Elles and Wood, 1908 and *Monograptus vomerinus* (Nicholson, 1872). The *lapworthi* Zone, Bornholm. Specimens with sharply delimited fillings of pyrite. MMH 14086. ×5.
4. *Retiolites geinitzianus angustidens* Elles and Wood, 1908. The *lapworthi* Zone, Bornholm. The distal part is surrounded by a pyrite cover outside the periderm. MMH 14087. ×10.

5. *Retiolites geinitzianus angustidens* Elles and Wood, 1908, *Monograptus vomerinus* (Nicholson, 1872), and *Cyrtograptus lapworthi* Tullberg, 1883. The *lapworthi* Zone, Bornholm. The specimens of *R. geinitzianus angustidens* are surrounded by a pyrite cover, preferably in the distal parts. MMH 13667. ×1.

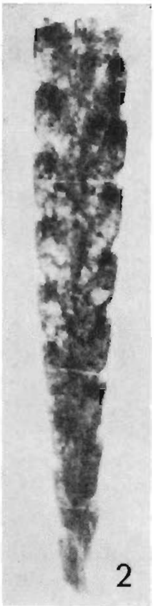
Plate 20

Monograptus revolutus Kurck, 1882. The *revolutus* Zone, Bornholm. Specimens with pyrite just outside the thecal apertures.

1. MMH 14088. ×10.
2. MMH 14089. ×10.
3. MMH 14090. ×10.
4. MMH 14091. ×10.

Plate 21

1. *Rhaphidograptus toernquisti* (Elles and Wood, 1906). The *revolutus* Zone, Bornholm. Specimen with pyrite just outside the thecal apertures. MMH 14092a. ×10.
2. *Pseudoclimacograptus undulatus* (Kurck, 1882). The *revolutus* Zone, Bornholm. Pyrite with ill defined shape protruding out from the thecal apertures. MMH 14093. ×10.
3. *Rhaphidograptus toernquisti* (Elles and Wood, 1906). The *revolutus* Zone, Bornholm. Specimen with pyrite just outside the thecal apertures. MMH 14094. ×10.
4. *Rhaphidograptus toernquisti* (Elles and Wood, 1906). The *revolutus* Zone, Bornholm. Pyrite precipitated outside the thecal apertures and along the thecal walls outside the periderm. MMH 14092b. ×10.
5. *Rhaphidograptus toernquisti* (Elles and Wood, 1906) and *Monograptus atavus* Jones, 1909. The *revolutus* Zone, Bornholm. *R. toernquisti* with pyrite protruding out from the thecal apertures, and *M. atavus* with pyritisations only within the rhabdosome. MMH 14095. ×10.



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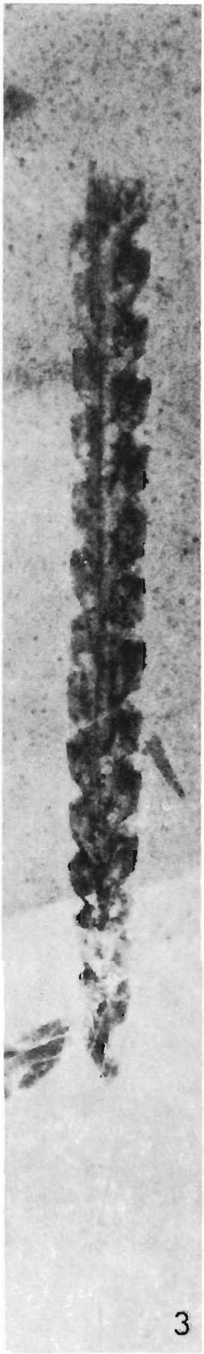

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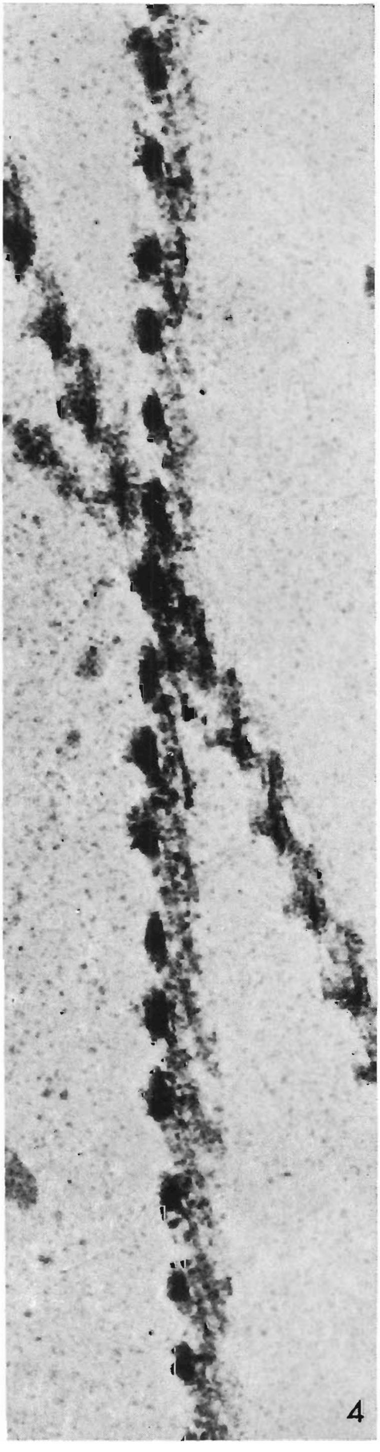

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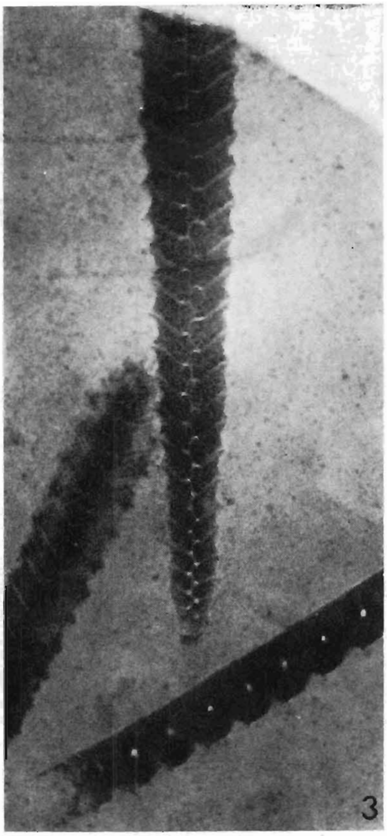
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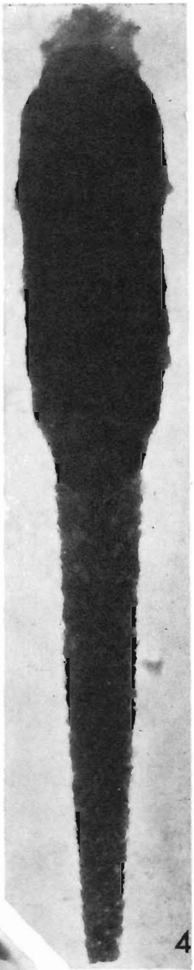
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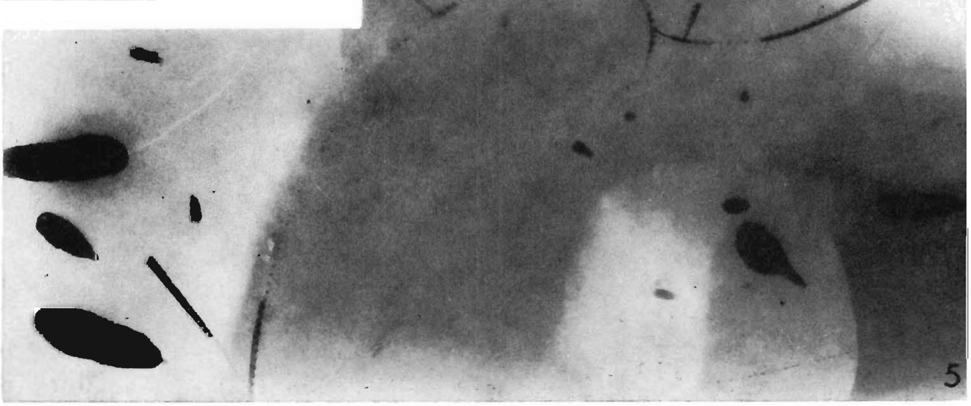
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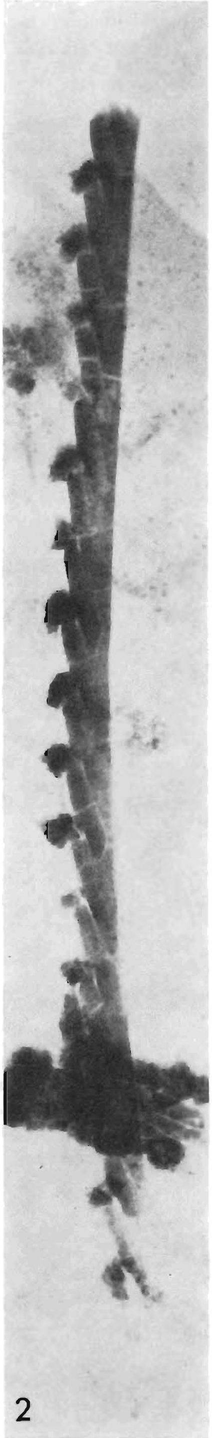
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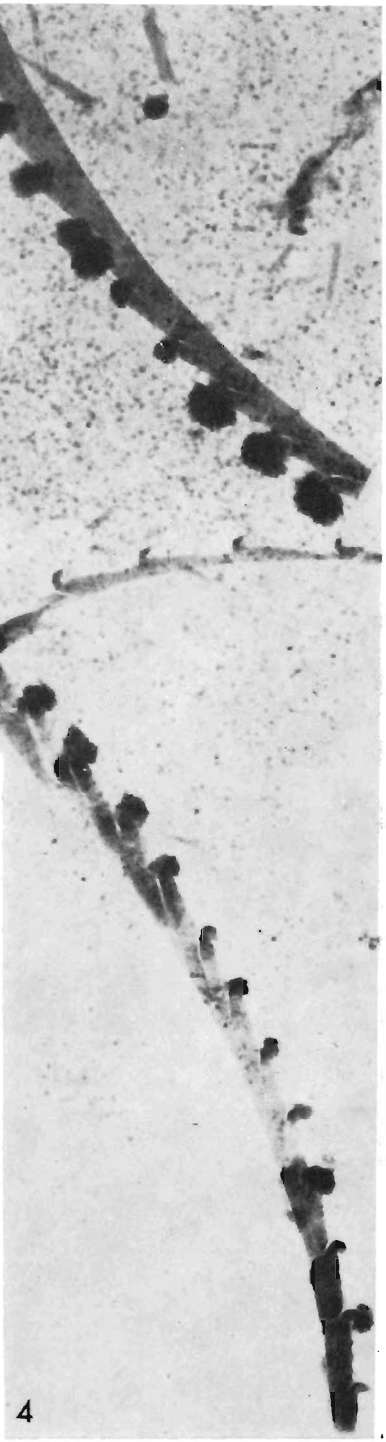
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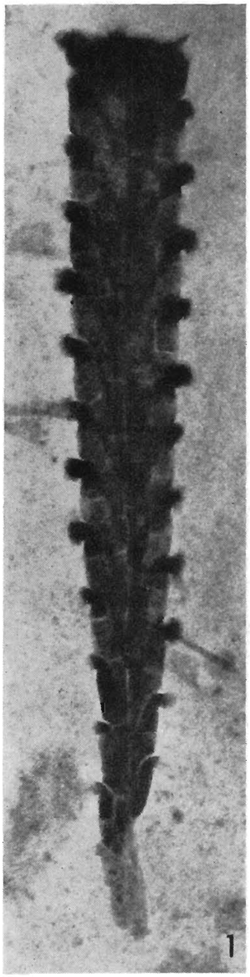

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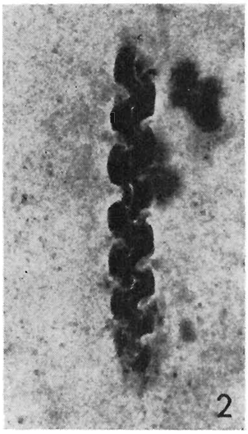

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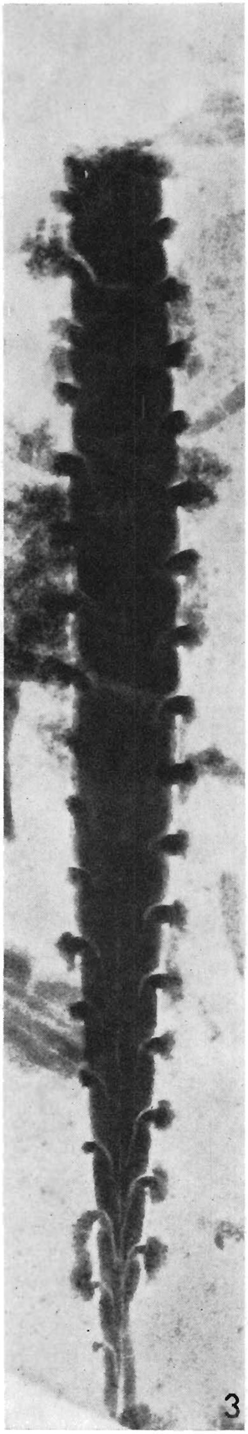

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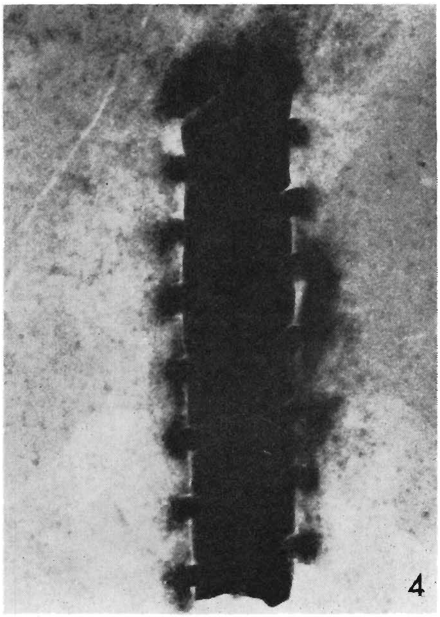

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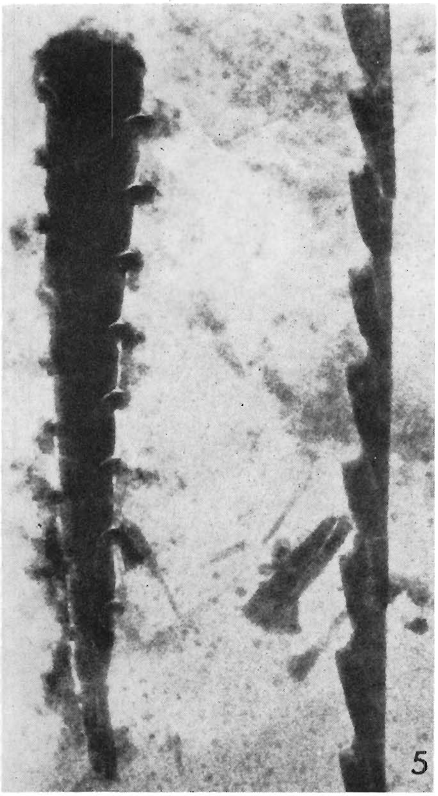

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