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K. J. Muller

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Exceptional preservation in calcareous nodules

By K. J. Müller
Rheinische Friedrich-Wilhelms-Universität, Institut für Paläontologie, Nussalle 8, *D*-53 *Bonn* 1, *F.R.G.*

[Plate 1]

Preservation of soft integument in calcareous nodules seems to be more widespread geographically and stratigraphically than hitherto realized. It cannot be recognized in the field, and to recover such material requires special etching techniques. Such preservation can be of exceptional quality, with fossils preserved three dimensionally either by secondary phosphatization or by silicification. Coating as well as the replacement of integument has been observed even within the same sample. Methodical search for such preservation may be based on the common denominators of depositional, geochemical, and environmental indicators in previously described occurrences. As such exceptionally preserved material may be rare within the samples, large quantities of rock have to be prepared. The examples described here are from anthraconitic limestones (Orsten) of the Upper Cambrian Alum Shale Formation in Sweden. They are now known from many localities and from different trilobite zones. In addition nodules from the Lower Cretaceous Santana Formation in Brazil, the Upper Devonian cephalopod limestone in the Carnic Alps, the Lower Triassic of Spitzbergen and the Miocene Barstow Formation in California have all yielded extremely fine material.

1. Introduction

Fossils three dimensionally preserved with their soft integument have been found in calcareous nodules and in phosphatic nodular limestones. Their investigation is of great interest for systematic and phylogenetic studies. Such material is not unique, but seems to be widespread both geographically and through geological time. In my opinion eventually such exceptional material will become available from the entire Phanerozoic following methodical search. Until recently, however, microfossils with preserved soft integument have been found only by chance in residues etched for other purposes such as for conodonts and fish remains. Thus the number of specimens recovered was generally rather limited and insufficient for detailed systematic study.

The first intensive search for such material has been started in Orsten from the Upper Cambrian of Sweden. In this sequence it is now known to be widespread over a large area including Vestergötland, Skåne, the island of Öland, as well as from a borehole in northern Poland (H. Szaniawski, personal communication 1983). In addition these exceptional fossils have been found in erratic boulders within the Pleistocene drift in northern Germany (Müller 1979*c*).

2. Problems in locating the fossils

The Upper Cambrian Alum Shale Formation in Sweden is one of the earliest formations from which Palaeozoic fossils were described (Linnaeus 1757; cited after Westergård 1922). In particular the trilobites (see, for example, Westergård 1922) and the conodonts (Müller

1959) have been studied intensively. In spite of this palaeontological attention the fossils with soft integument have escaped notice until recently. Thus, one cannot emphasize too strongly that this peculiar type of preservation can only be observed given special attention and techniques.

(a) *Visibility during fieldwork*

Microfossils with preserved soft integument cannot be observed during fieldwork. They become visible only after treatment of the rock with acid, which in turn involves special laboratory preparation. Accordingly many months may elapse between the fieldwork and the gratification elicited by a find. For efficient coverage a selection of the most promising lithologies has to be surveyed. Diagnostic characters that prove to be of critical importance are only revealed empirically. For example, specimens of *Agnostus pisiformis* with preserved soft integument were found only in a medium-grained light-beige limestone with small brownish to blackish spots. Similar minor lithological characters proved to be useful indicators for finding additional samples in other cases.

(b) *Minute size*

Phosphatization seems to be restricted to objects of less than 2 mm in size. It may affect isolated organs, when disjunct appendages fall within this size range, although they are parts of originally much larger individuals. This demonstrates that the size limitation has not been controlled by the dimensions of the animals themselves, but reflects the mode of preservation.

(c) *Rarity and inconspicuousness*

In most occurrences specimens with well preserved soft integument are very rare. To obtain a collection suitable for a detailed study, bulk samples of many kilograms have to be used.

To an untrained eye it is difficult to recognize specimens with preserved soft integument under the microscope. Their isolation requires extensive sorting under high magnifications ($\times 80$ to $\times 100$). As conodont picking is generally done under lower magnification ($\times 40$ to $\times 60$), the chances are rather limited that such preservation will be recognized during routine conodont investigations. Even for a trained worker it may be difficult to discover such material. This can be demonstrated by the example of the discovery of the first ostracod with preserved appendages found in the Upper Devonian cephalopod limestone of the Carnic Alps (Austria). A complete ostracod carapace was picked from an etched residue by a competent conodont student but the soft parts remained unrecognized. It was stored in a microslide until a graduate assistant tried to make an approximate generic determination for deposition in the main systematic collections of the Institute. He also failed to notice the appendages, simply because they were invisible in the position of the specimen on the bottom of the slide. Only a closer inspection ultimately led to their recognition while the carapace was mounted on a needle.

(d) *Fragility*

Mineralized soft integument can easily break away from microfossils during the preparation process. The conventional washing on a screen, as done for conodont investigations, is too drastic a treatment for such a fine preservation. It is more than likely that in many conodont samples finely preserved integument was destroyed by the rough handling before it might have been recognized. Treatment is more gentle if the rock is cradled on a plastic screen during dissolution. A schematic illustration of our procedure is given in figure 1. In addition, breakage can be avoided by picking of the samples without attempting to concentrate them further by

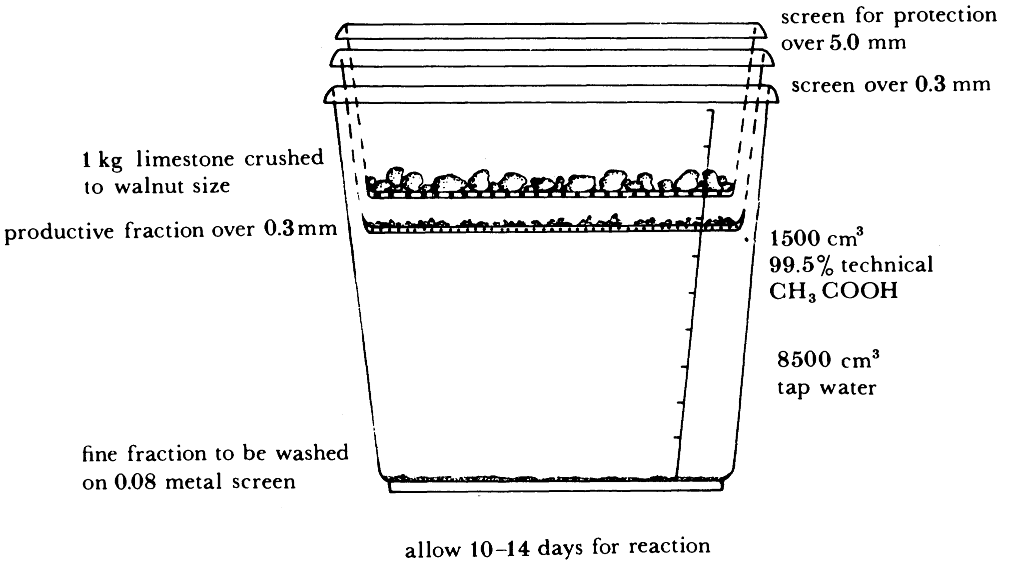

FIGURE 1. Sieves for gentle etching of limestone samples.

heavy-liquid techniques or magnetic separation. In any event it is doubtful if heavy-liquid separation could serve a useful purpose. This is because the surface of the phosphatized fossils is generally rather uneven and well suited for the adherence of small air bubbles. Voids inside the coated portions may be filled with gas and increase the buoyancy of the specimens. Similarly, magnetic separation is too rough a treatment for the preservation of such delicate details, which would be destroyed by abrasion.

3. Mineralization of soft integument

Soft integument has obviously been preserved quite differently in the various occurrences. To provide some guidelines for the recognition of new occurrences, some examples are described here. Phosphorite and silica are the two most important compounds for preservation of soft integument, and if located in either calcareous nodules or phosphatic limestones they can be isolated with mineral acids. In addition, iron sulphide seems to be fairly widespread as a petrifying agent. However, no suitable preparation technique is yet available for this type of preservation. Radiography of the specimens encased in the rock shows limited resolution on account of their minute size, while conventional mechanical preparation with a needle is both impractical and very time consuming. Possible applications of ore microscopy methods have yet to be explored. Other styles of mineralization may occur under more exceptional geochemical conditions.

Phosphatized soft integument is at present the most important source of information for detailed morphological investigations. The phosphatized arthropods from the Upper Cambrian of Sweden represent one of the best known examples of this type of preservational 'Lagerstätten'. Varied and rich faunal associations have been obtained from at least three trilobite zones: 1, 2 and 5 (Müller 1979*a*, 1982*a*, *b*). A fourth productive zone in the uppermost portion of the sequence, possibly belonging to the Tremadocian (conodont zone of *Cordylodus proavus*) was recently discovered on the island of Oland by D. Andres (1984, personal communication).

Their occurrence is not contiguous, and an outcrop in general exposes only a single or no more than two zones.

The source of the phosphate in the Alum Shale and Orsten is still uncertain. The soft tissue biomass of the arthropods is obviously an insufficient source of phosphorus to act as a petrifying agent. The phosphate may have originated from chemical weathering of granites, etc., on adjacent landmasses during the Upper Cambrian, and subsequently may have been concentrated by organic processes. As the arthropods are the predominant fossils with preserved soft parts in the Orsten, it seems likely that the presence of chitin or a similar substance might have provided a suitable environment or template for the precipitation of the phosphatic matter.

A comparable example was described by Bate (1972, 1973) from the Lower Cretaceous Santana Formation of Brazil. Here ostracods were etched with acetic acid from fish-bearing limestone nodules. Also parasitic copepods have been preserved here (Cressey & Patterson 1973). Similarly, although such preservation is common within a single nodule, this material in general is rare within the sequence and many apparently similar nodules lacked such preservation. In this case the source of phosphatic matter seems to be clear, as the ostracods were scavengers on a large dead fish with a substantial quantity of phosphate-rich proteins derived from the decomposing soft tissue.

Since the discovery of the Swedish material, further occurrences have been found elsewhere. Ostracods with preserved appendages were etched from an Upper Devonian light grey to beige cephalopod-bearing limestone at a single locality in the Carnic Alps (Müller 1979*b*, 1982*a*). In addition, Weitschat (1983*a*, *b*) described well preserved ostracods with appendages etched from cephalopod body chambers preserved in limestone nodules from the Lower Triassic of Spitzbergen. It is expected that more such material will be found in the future.

4. Modes of preservation

Soft integument and cuticular structures may be preserved either by coating (figures 2 and 3) or by replacement (figure 4). Both types may occur together, even on the same specimen. Considerable variation in preservation of details was noticed not only between the different localities but also in specimens from the same outcrop. In general coatings are more complete

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Description of plate 1

Figures 2–8. *Hesslandona* sp. with details demonstrating the mode of phosphatization. All etched from Upper Cambrian Orsten, *Agnostus pisiformis* Zone, Västergötland, Sweden. Figures 2, 4–8: Gum, Kinnekulle; figure 3: Stolan, Billingen.

Figure 2. Thick coating (co.) on left side of antennula. Right side is preserved by replacement. UB 773.

Figure 3. The inner lamella (i.l.) was replaced by phosphatic matter and subsequently was coated (co.). Carapace (c.) also coated. UB 774.

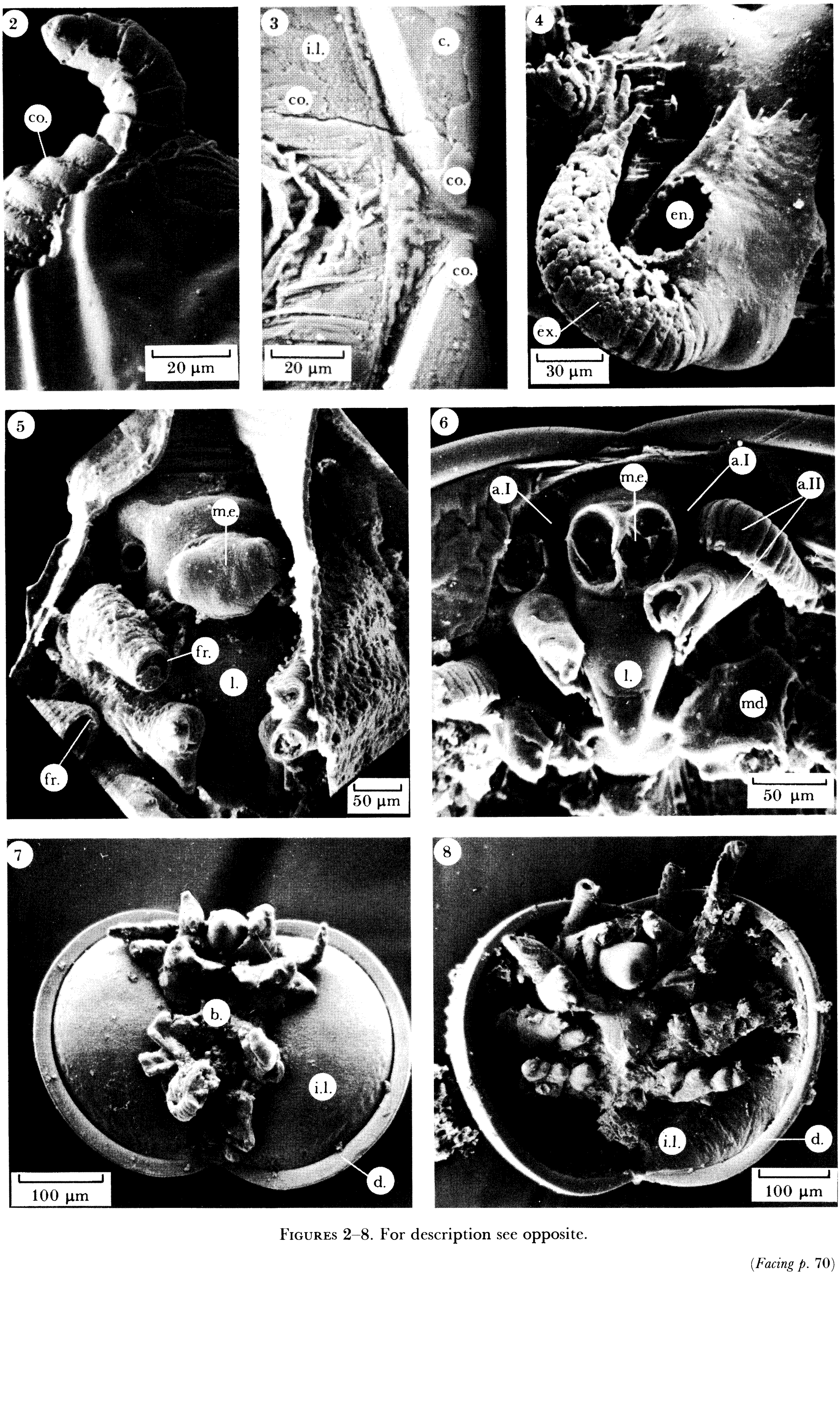
Figure 4. Incomplete replacement by accretion of phosphatic matter around numerous nuclei on exopodite (ex.) of the mandibula. Endopodite (en.) was not phosphatized, note the irregular accretion limits, in contrast to fractures (fr.) seen in figure 5. UB 775.

Figure 5. Anterior portion of body with inflated median eye (m.e.) on labrum (l.). UB 776.

Figure 6. Similar view of a specimen with imploded median eye. l., Labrum; m.e., median eye; a.I, antennula; a.II, antenna; md., mandibula. UB 777.

Figure 7. The pliable inner lamella (i.l.) was inflated (d., duplicature; b., body with appendages). UB 778.

Figure 8. Similar view of a specimen with recessed inner lamella (i.l.), leaving no space between carapace and inner lamella (d., duplicature). UB 779.



Figures 2–8. For description see opposite.

(*Facing p.* 70)

at the proximal portion of the fossils whereas parts such as the distal ends of appendages commonly remained unphosphatized, and accordingly were not preserved in the etched residues.

The coating may conceal fine surface structure. Thus, fine hairs may appear much thicker on the phosphatized specimens than they had been originally. In some cases it is difficult to distinguish between the various layers exposed by uneven breakage of a multi-layered cuticular structure and a secondary coating formed in several subsequent generations.

Substitution also shows a considerable variation in quality between the occurrences. Uneven and incomplete replacement can be recognized by semicircular precipitation limits caused by accretion of the phosphatic matter around numerous nuclei (figure 4). They appear quite different from fractures, which are straight, angular and have sharp edges.

The timing and mode of phosphate precipitation, as deduced from the fossils, may be important in future search for new occurrences. What is more, it may generate new ideas for elucidating the accumulation of phosphate deposits in the marine environment. The mineralization in the Orsten must have occurred either at the time of death of the animals or immediately afterwards, otherwise such delicate soft integument could not have been preserved so completely.

As among younger ostracods, the Phosphatocopina have a soft inner lamella which mainly served for respiration. Ventrally it is attached to the duplicature and dorsally to the body which, however, is completely preserved only in a few cases. The inner lamella had been replaced while it was still flexible, commonly by phosphatic matter, but in most cases it is not preserved in its original position. Either bulging induced by inflation (figure 7), that is, by blowing up from the inner side, which in some cases has even led to its destruction by rupturing, or by shrinking in such a fashion as to narrow the space between inner lamella and carapace (figure 8), have been observed frequently. Similar phenomena can also be observed in the region of the frontal eye (figures 5–6). Originally, I interpreted the first mode of preservation as caused by the development of gas within the body cavity stemming from the decay of tissues. However, this interpretation cannot explain the other mode, that of shrinkage. Moreover, as no signs of actual decay can be observed in the material this hypothesis has had to be discarded. An alternative explanation could be that the inner lamella retained semi-permeable properties before its mineralization. Hypersalinity within the body cavity would have caused influx of water and led to its distension. On the other hand hyposalinity would have caused outflow of water and led to collapse and implosion of the inner lamella. This mechanism thus explains both types of preservation on the basis of minor changes in the salinity of the surrounding sea water. It is open to discussion if such small changes could also trigger off precipitation of the phosphorite in the open sea. Biological events such as episodic proliferation of microorganisms may have also participated in the precipitation.

Phosphatized soft integument may also occur in coprolites. A well known example is from the Wealden of Bernissart, Belgium (Bertrand 1903). As coprolitic matrix usually does not dissolve in acetic or formic acid, such material cannot be isolated with standard etching techniques. It can be studied only on surface fractures or in thin sections. In addition the soft tissue within the coprolite has already been severely macerated by the digestive processes and the shredded remains are difficult to identify. The stomach content of a pliosaur contained an ostracod with preserved, probably phosphatized, soft parts (Dzik 1978). However, as yet this is an isolated find.

Detailed information on the precipitation of phosphatic matter may eventually be obtained by detailed study of depositional and diagenetic textures. However, comparisons with sedimentary structures in Recent phosphorites are still wanting.

5. Silicification

Secondary diagenetic silicification of what were originally calcareous hard parts is widespread geologically. Such material has been extensively studied by various authors (for references see Cooper & Whittington 1965) and an approach towards an explanation of its genesis was attempted (Müller 1979*d*). Generally, replacement was long after the decay of the soft integument. Complete organic structures may occur in cherts, for example, the Precambrian Gunflint chert and the early Devonian silicified peat of Rhynie (Scotland) (Knoll, this symposium).

A spectacular occurrence of silica and other mineral replacement is known from nodules of the Miocene Barstow Formation in the Mojave desert, California (Palmer 1957). Calcareous, petroliferous nodules of 0.5–5 cm in diameter, collected in a lacustrine sediment, contain perfectly preserved aquatic and terrestrial arthropods. They have been replaced by one or various minerals: among them quartz is the most abundant, but celestite, gypsum, bassanite, analcite, calcite as well as an organic compound also have been identified. The arthropod remains seem to be fairly common in the nodules. The chemistry of replacement is still unknown. It must be rather complex and may have involved a series of steps. Palmer (1957) observed a pupa of an insect that was partly replaced by an organic compound which was subsequently transformed into silica.

6. Conclusions

Routine collecting and trial etching of all available occurrences of limestone nodules and phosphate-bearing nodular limestones is recommended, with application of the techniques described here. As material with soft integument may occur very infrequently, the number of samples should not be kept too small, and each sample should, if possible, weigh at least 1 kg.

For practical purposes features considered useful for the selection of potentially productive samples are tentatively listed here.

(i) Limestone nodules or nodular limestone with a phosphate content are the most promising, and they may be the only lithologies with such preservation.

(ii) The rock should be unweathered.

(iii) The limestone should be sufficiently pure to disaggregate in the acid, leaving only a muddy residue, so that further handling of shale partings, etc., is avoided.

(iv) To minimize time expended on picking, lithologies that leave little residue after acid treatment and sieving are preferable.

(v) Still-water sediments are preferable to low energy ones. High energy deposits seem to be unsuitable for such a type of preservation.

(vi) Distribution of phosphatic matter within a sample is an important factor. If the staining reaction engendered with the ammonium molybdate–benzidine–sodium acetate test is limited to small 'islands' this is preferable to more evenly dispersed phosphatic matter. However, it is noteworthy, that Orsten samples with a negative staining test also yield well preserved soft parts.

(vii) The most important criteria for the selection of samples, however, are minor lithological characters. They are only identifiable by comparison with productive samples. Such characters may vary between occurrences and even between localities. In addition, productive layers should be resampled extensively. Mainly by using such criteria I was able to increase the success rate of the Swedish Orsten samples from less than 3% at the beginning to almost 15% in the latest collections.

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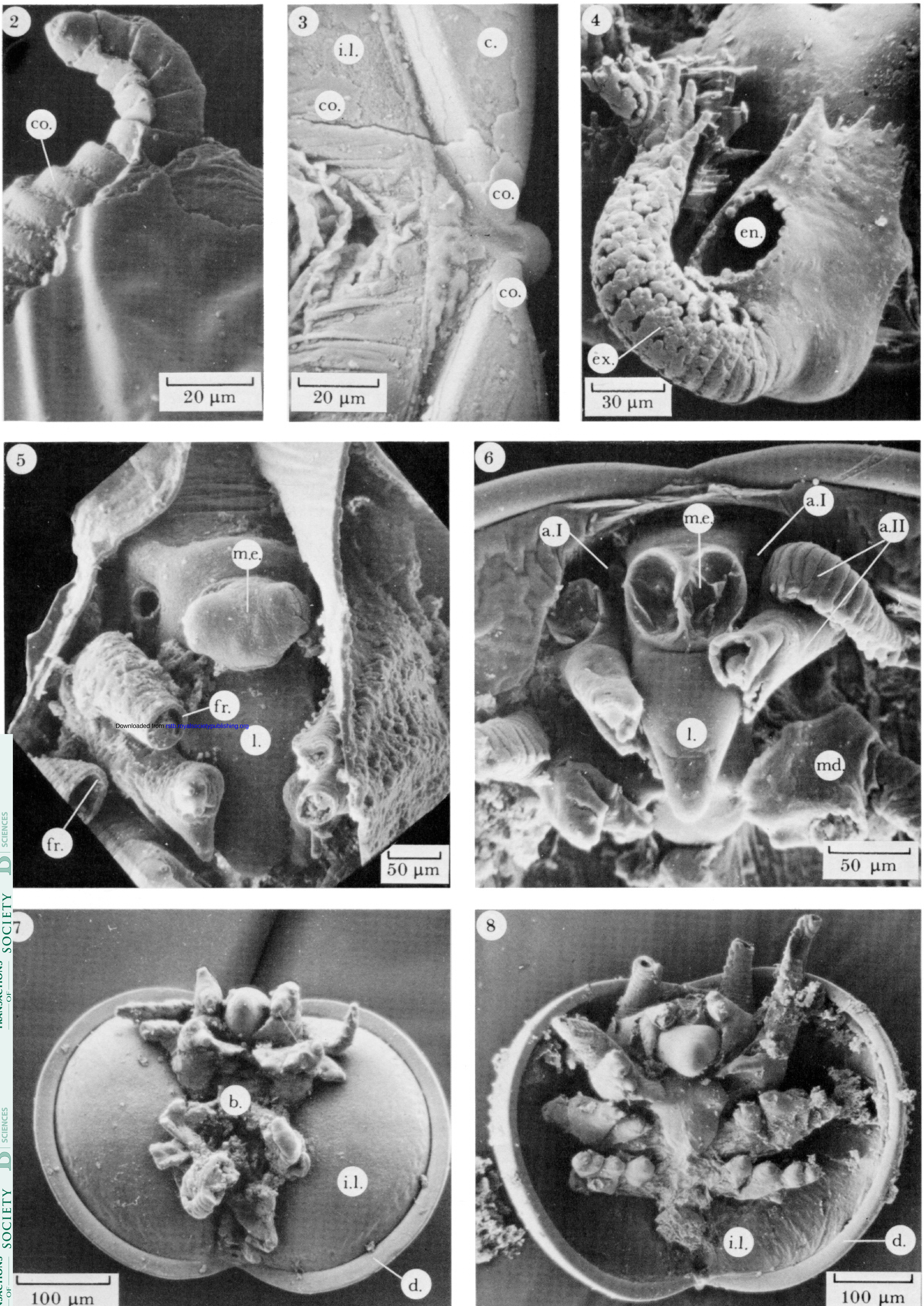

FIGURES 2–8. For description see opposite.