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The fossils of Orsten-type preservation from Middle and Upper Cambrian in Hunan, China

——Three-dimensionally preserved soft-bodied fossils (Arthropods)

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Abstract **Exquisitely preserved three-dimensional soft-bodied fossils and typical Orsten-type preservation have been found from the strata of Middle and Late Cambrian in western Hunan, China. A preliminary description is provided for *Hesslandona* sp. (Phosphatocopida, Crustacea, Arthropoda) and *Skara* sp. (Skaracarida, Crustaceam, Arthropoda). The scientific significance of Orsten-type preservation and prospects for future work on these fossils from Hunan are outlined.**

Keywords: Orsten-type preservation, Hunan, Middle and Late Cambrian, Phosphatocopida, Skaracarida, Crustacea, Arthropoda.

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Fossils characteristic of Orsten-type preservation were originally recovered in 1975 from the Upper Cambrian of southern Sweden by Klaus J. Müller, the father of Cambrian conodonts[1,2]. The name 'Orsten' is derived from the nodules in which remarkable, three dimensional fossils of entirely soft-bodied organisms are entombed. In the area where the fossils were first discovered, the nodules are known by the name 'orne sten' (= pig stone), referring to the early usage of such stones to cure pigs[3]. Although a wide variety of microfossils can be recovered from these nodules, including conodonts and small shelly faunas[3], the fossils that have now become famous as a result of the tireless efforts of the research group led first by Müller and, subsequently Dieter Walossek, are a diverse array of small (less than 2 mm) soft-bodied organisms that are preserved in three dimensions through secondary phosphatisation. Since their initial discovery almost 30 years ago, fossils of the same style of preservation have been recovered from similar deposits around the world including Poland[4] Russia[5] Australia[6], Canada[7], the United Kingdom[8] and Brazil[9], ranging in age from early Cambrian to the early Cretaceous[3]. Thus, the term 'Orsten' has come to describe a unique style of fossil preservation that even in comparison to Lagerstätten such as the Maotianshan Shale, Burgess Shale and Jehol Biota, provides unparalleled insight into the biology of long extinct organisms. Thus, given its derivation and widespread understanding of its meaning, we suggest that 'Orsten' should be transliterated into Chinese, i.e. according to the sound of the word Orsten, to refer to fossils of this style of fossil preservation.

Although fossilized embryos have previously been referred to the Orsten style of preservation[10], it has been argued that the fossilization of embryos must rely on a distinct mode of phosphatisation[11]. This is because the Orsten style of preservation, like Burgess Shale type preservation, is predicated upon the presence of a cuticular substrate and, hence, Orsten and Burgess Shale type deposits are dominated by cuticularised arthropods[11]. Thus, fossilized embryos, of the type described by Xiao et al.[12], should be excluded from the Orsten concept. Characteristically Orsten-type preservation, represented by remains of Phosphatocopida and Skaracarida, was discovered in Hunan by Dong Xiping in 2002. Here, We describe *Hesslandona* sp. (Phosphatocopida, Crustacea, Arthropoda)[13] and *Skara* sp. (Skaracarida, Crustacea, Arthropoda)[14], introduce the scientific significance of these fossils typical of Orsten-type preservation, and prospect the future work on the fossil material from Hunan.

1 Material and method

The Orsten-type fossils reported in this paper were recovered from Upper Cambrian in Wangcun section, Yongshun County, western Hunan, South China. Additional material has been recovered from Middle Cambrian in the Wangcun section, and Middle and Upper Cambrian in Wa'ergang section, Taoyuan County, and Paibi section, Huayuan County, western Hunan, South China (Fig. 1). These remains were recovered as by-products from processing for conodonts from dark gray medium- to thick-bedded or nodular micrites, rich in organic matter and scattered pyrite, exhibiting evidence of bioturbation. The micrite also yields conodonts and fossilised embryos[15], trilobites, brachiopods, small-shelly fossils, sponge spicules and radiolarians, etc. The samples were processed by routine etching with 10% technical acetic acid in plastic pails with a capacity of 10000 cm^3. The cycle of sieving and changing acid required ten to fourteen days. The samples (including duplicate samples) generally needed to be processed in three to four cycles for complete dissolution. During the processing, the reaction time and the pH value of the solution were adjusted according to the lab temperature (around 20℃ in winter and up to 35℃ in July and August). All the samples were processed in plastic pails with two layer screens as recommended by Müller (1985)[2]. All the residues were sorted manually

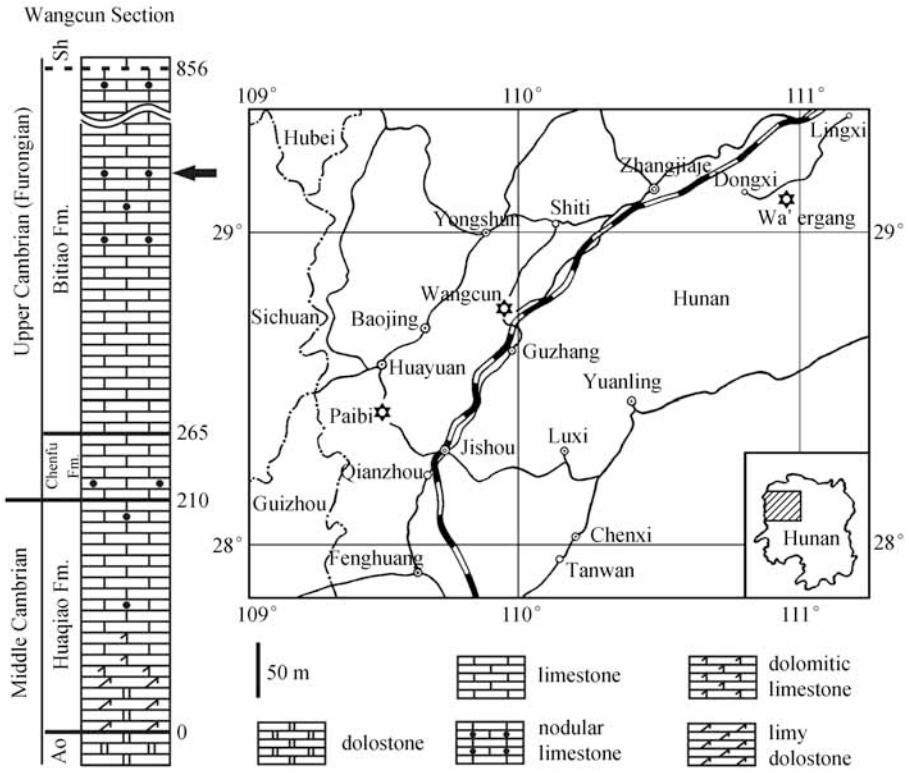

Fig. 1. Right, Location map of Orsten yielding sections in western Hunan, China. The arrow indicates the stratigraphic horizon bringing about the figured specimens in the present paper. It is 506 m higher than the bottom of Huaqiao Formation. Sh, abbreviation of the overlying Shenjiawan Formation; Ao, abbreviation of the underlying Aoxi Formation.

under optical microscopes by laboratory assistants. Orsten fossils were recognized and separated from the other fossils by Dong Xiping. All the pictures of the Orsten fossils in the present paper were taken with ESEM machine (LEO 435 VP made in UK) in The Lab Center of Research Institute of Petroleum Exploration and Development, Beijing.

2 Systematic paleontology

The figured specimens are deposited at the Geological Museum, Peking University, GMPKU 2201－2202.

Phylum Arthropoda

Class Crustacea, Brünnnich, 1772

Phosphatocopina, Müller and Walossek, 1991

Hesslandona Müller, 1964, emended Mass, Waloszek and Müller, 2003

Type species-*Hesslandona necopina* Müller, 1964

Hesslandona sp. (Fig. 2; Fig. 3 (a), (b))

Body: The body proper, in ventral aspect, which is completely enveloped by the shield, comprises at least seven segments. Minimally, the first six segments are dorsally fused to the shield, being a cephalothoracic shield including two limb-bearing trunk segments.

The body expands along the inner dorsal length of the shield. The maximum width of the body is located at the second post-antennular appendages, the mandibles.

The antennulae insert into the anterior margin of the labrum. The antennae insert laterally to the posterior part of the labrum and antero-laterally to the sternum. The mandibles are the third limbs of the body. The post-oral ventral surface of the segments of the second to fourth post-antennular pair of limbs is combined in a single sternitic unit, the sternum. This expands from behind the labrum to the posterior end of the first post-mandibular segment. It is tongue-shaped and slopes posteriorly, being widest to the anterior and narrowest towards the posterior. The sternum is strongly sclerotised. Posterior to the sternum is an additional sclerotised rectangular and domed sternitic plate, belonging to the second pair of post-mandibular limbs. The membranous fields separate the first and second sternitic plates. The segments of the third and fourth post-mandibular pairs of limbs have no distinct ventral sternitic plate. The area is membranous and slightly narrower than the respective preceding one. With poor preservation, the fourth post-mandibular limbs are broken, and the segment of them is free from the shield and bend to the abdomen.

Antennulae: The antennulae are known from their insertion areas at the lateral flanks of the labrum, pedun-

Fig. 2. ESEM of the specimen of *Hesslandona* sp. GMPKU2201, ventral view, displaying the whole body. Scale bar 30 μm. 1, antennula, "first antenna"; 2, antenna, "second antenna"; 3, mandible; 4, labrum; 5, shield; 6, maxillula; 7, sternum; 8, sternum II; 9, maxilla; 10, thoracopods.

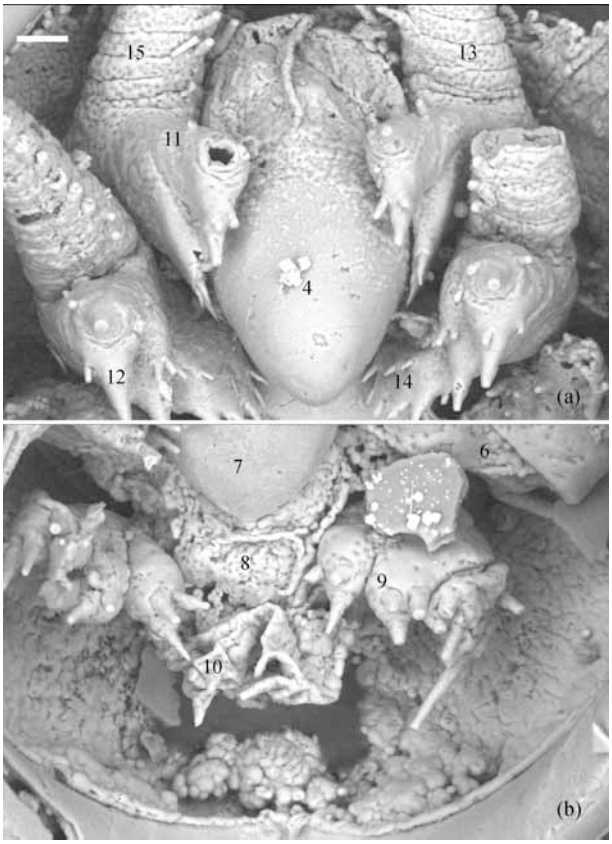

Fig. 3. (a) The head structure of the same specimen of Fig. 2; Scale bar 20 μm. (b) The sternum and limbs of the same specimen of Fig. 2, Scale bar 16 μm. 4, labrum; 6, maxillula; 7, sternum; 8, sternumII; 9, maxilla; 10, thoracopods; 11, endopod; 12, setae; 13, annulus; 14, proximal endite; 15, exopod.

cle-like.

Antennae: The antennae insert laterally to the posterior part of the labrum and antero-laterally to the sternum. The insertion area is located on a laterally directed slope. It is triangular with a laterally pointed tip and directed at 45° to the body axis from near the postero-lateral edge of the labrum antero-laterally. The antennae exhibit bilateral symmetry and consist of a single limb stem and two rami. This limb stem is a fusion product of the coxa and basipod, a two-divided endopod and a multi-annulated exopod. The endopod arises medio-distally from the apex of the limb stem distal to the gnathobase and consists of two portions. The proximal portion is spindle-shaped and medio-distally drawn out into a short thorn-like spine, guided by two spinules distally and proximally on the anterior and one proximally inserting spinule on the posterior side. The terminal segment is also drop-shaped and drawn out medio-distally into a spine, flanked by three spinules. The position of the endopod corresponds to the latero-distal excavation of the labrum. The exopod arises laterally some distance from the outer slope of the limb stem. Some of the exopods are broken, the rest consist of 14 annuli. The first three of the annuli are seta-less, more distal annuli bear setae.

Mandibles: The insertion areas of the mandibles are lateral to the an terior part of the sternum. They are spindle-shaped and exhibit bilateral symmetry. They consist of a prominent limb stem and two rami. The limb stem is subtrapezoidal in anterior view. The lateral margin bears setae and is pointed. The anterior and posterior margins are excavated, with the posterior one being much stronger than the anterior one. Medially, the limb stem is drawn out into an oblique, proximo-distally compressed gnathobase. The gnathobase bears a row of short asymmetrically arranged spines along the whole length of its median edge. From the medio-distal area of the limb stem, a three-segmented ramus arises. This structure consists of a largely reduced basipod and the two-divided endopod, with the remaining part of the limb stem being the coxa. The basipodal part is spindle-shaped in antero-posterior aspect, with three strong setae and four slim setae. The endopod arises more laterally out of the basipodal piece on the apex of the limb stem distal to the gnathobase. The proximal endopodal portion is spindle-shaped in antero-posterior aspect with its pointed tip medial, and medio-distally drawn out into a spine. It is distinctly larger than the basipodal endite. The exopods are similar to the exopods of antennae, which consist of 14 annuli. The inner margins of annuli bear setae except the basipodal two annuli.

First pair of post-mandibular limbs (maxillula): The first pair of post-mandibular limbs inserts laterally to the posterior part of the sternum. The limbs consist of the basipod, the proximal endite, and two branched endopod and exopod. The proximal endite inserts medio-proximally to the basipod. It is drop-like and irregularly adorned with six setae. The basipod is subtrapezoidal with a concave latero-distal margin, where the exopod inserts. Several setae are located at the median basipod, arranged in two series. The endopod arises medio-distally from the basipod, but it is poorly preserved. The exopod inserts proximo-laterally at the basipod. The other segments are poorly preserved.

Second pair of post-mandibular limbs (maxillae): The second pair of post-mandibular limbs is similar to the first pair. The proximal endite bears three setae. The basipod is subtrapezoidal and bears three setae. The endopod and exopod are too poorly preserved to reveal any information.

Third pair of post-mandibular limbs (thoracopods I): The third pair of post-mandibular limbs is poorly preserved, but is fully developed and several setae are seen.

Fourth pair of post-mandibular limbs (thoracopods II): They are too poorly preserved to indicate any information.

Comparison This specimen is similar to those of the possible growth stage III of *Hesslandona unisulcata* emend by Mass et al.[13] in the following characters: 1) The segments are equal, there are seven segments; 2) With two sterna, the second sternum bears the second pair of post-mandibular limbs; 3) The second pair of post-mandibular limbs is fully developed; 4) The third pair of post-mandibular limbs is fully developed; 5) The fourth pair of post-mandibular limbs is partly developed, manifested as a bud. Nevertheless, because of the limitation of available material, we temporarily leave our specimen in open nomenclature.

Locality and horizon Upper Cambrian Bitiao Formation in Wangcun section, Yongshun County, western Hunan, South China.

Class Crustacea, Brünnnich, 1772

Order Skaracarida Müller et Walossek, 1985

Family Skaraidae Müller et Walossek, 1985

Genus *Skara* Müller, 1983

Type species Skara anulata Müller, 1983

Skara sp. (Fig. 4; Fig.5 (a), (b))

Shield: The soft shield comprises about 1/5 of the body length, lacks any ornamentation and its lateral rim fades anteriorly into the forehead. In cross-section the shield approximates an inverted U-shape. The rim starts above the antennae. The caudal rim of the shield looks straight. The shield is almost as high as wide. Fringes at the dorsocaudal rims of shield and tergite are not developed.

Forehead and labrum: The forehead extends from the shield by about 1/4 to 1/5 of the shield length and is not distinctly separated from the shield. The frontoteminal

Fig. 4. ESEM of the specimen of *Skara* sp. GMPKU2202. The whole specimen in lateral view. Scale bar 30 μm. 1, labrum; 2, forehead; 3, antennula; 4, shield; 5, antenna; 6, maxillula; 7, maxilla; 8, attachment point; 9, arthrodial membrane; 10, telson.

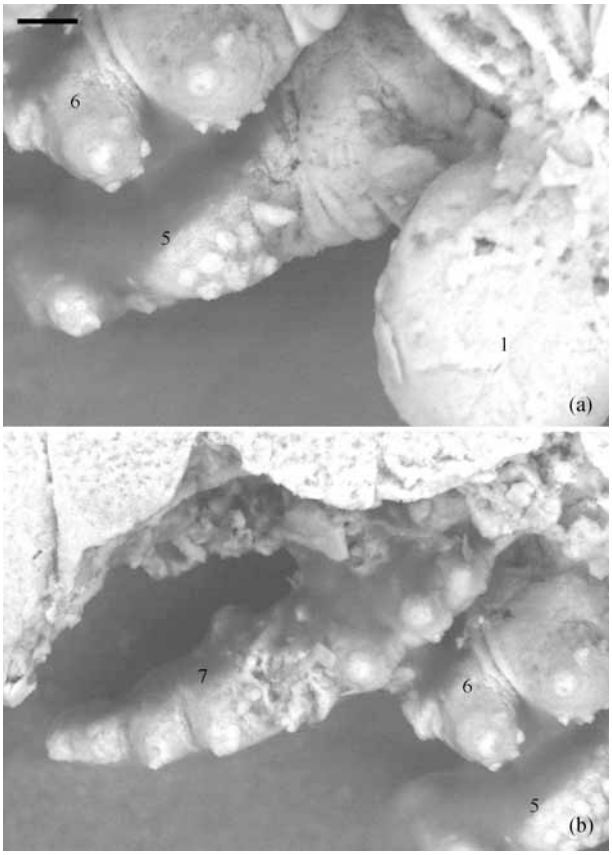

Fig. 5. (a), (b) Showing the details of appendages of the same specimen of Fig. 4. (a) Scale bar 10 μm; (b) scale bar 13 μm. 1, labrum; 5, antenna; 6, maxillula; 7, maxilla.

process or organ is completely preserved in the specimen. The distal end of the nose-shaped labrum is broadly rounded, slightly depressed at the tip and overhanging the mouth region. Behind the recessed origin, which is bor-

dered by shallow transverse furrows, the side of the labrum is bulged.

Appendages: The figured specimen has six pairs of appendages: five cephalic pairs and one pair of maxillipeds. With the exception of the antennula, which is uniramous, the other appendages are all biramous. Only the proximal portion of the left antennula and part of the right mandibula and postmadibular endopods of the specimen are preserved. The setae on endites, basipods and endopodal podomeres are all broken, such that only their origins are preserved.

Antennula: Only the proximal portion of the right antennula is preserved. The uniramous antennula is the smallest appendage. The outer surface of the proximal portion shows a division into several short ringlets.

Mandibula: The mandibula is inserted behind the labrum. It is the most prominent limb. The coxa has a slightly oblique gnathobase (shovel-like endite), which points posteromedially flanking the rounded distal end of the labrum. The succeeding proximal podomere is wider than long and medially elongated into a setose process. The distal two podomeres are broken off.

Postmandibular appendages: Apart from a successive size decrease, and related to this some minor differences in shape and armature with setae, the maxillae have almost the same design. The exopods of the maxillae are broken. Only the proximal portion of maxillula is preserved. Endite, basipod and endopodal podomere setae are all broken, such that only their origins are preserved. Like the mandibula, the protopods are oval-shaped in cross-section. In accordance with an oral orientation, they occur successively in a more axial position. Due to their bulging endites, the coxae are medially enlarged and peg-like. The anterior and posterior sides of the protopods are morphologically distinct. Anteriorly, the coxa is uniform. However, on the posterior side its distal margin extends medially to the proximal endite. This part of the coxa probably functioned as a joint for the whole distal limb portion. There are 3—7 setae on each endite. All endites are posteromedially elongated into a pilose spine. In front of it, pilose setae are positioned, which curve towards the mouth. They are possibly inferred to form a sieve from proximal to distal. The basipod is divided into a median and outer portion and arises from the sloping back of the coxa. The exopod originates from the sloping surface of the triangular portion of the basipod. The exopod is not preserved. The endopod is tube-shaped, having the same shape as the mandibula. It is composed of three podomeres which are wider than long. The three endopodal podomeres decrease markedly in size successively.

Maxilliped: The pair of maxillipeds is not preserved.

Trunk: The slender trunk is composed of 11 ring-shaped segments and a telson, the posterior portion of which is broken off. There is a hole from the shield to trunk segment three which is caused by breakage. This reveals a cylindrical internal cavity filled with amorphous phosphatic matter.

Segments: The length decreases successively, while the width increases from the first segment to the sixth, subsequently tapering towards the end of the preserved trunk. This results in a spindle-shaped trunk. All segments are ring-shaped and connected by well-developed arthrodial membranes. The segments are jointed to one another by lateral attachment point. The ventrocaudal rims of segments seven to eleven are slightly extended posteriorly. The ventrocaudal rims of segments seven to nine bear three tooth-shaped, slightly raised, posteriorly directed spines which become smaller in correlation with successive segmental size decrease. The distance between lateral shorter median spines also decreases.

Comparison *Skara* is a primitive soft-integument crustacean, which was mainly found in the dark limestone of southern Sweden. Two species of the genus have been described previously, *S. anulata* and *S. minuta*. The figured specimen recovered from Hunan may be referred to *Skara* on the basis of the following characters: The body has two tagmata: a cephalon with appendages, and a trunk composed of 11 ring-shaped conical segments, a telson, curved cephalic shield, frontal process, nose-shaped labrum, appendages arranged in successively decreasing size-order, a trunk composed of 11 ring-shaped and conical segments, the length of which decreases successively, and the presence of spines on segments seven to nine. It is characterized by the following traits: The head shield is small and does not overhang the body. The forehead extends from the shield terminating in a tubular dorsofrontal process. The labrum is very prominent, nose-shaped and posteroventrally directed. Nevertheless, because of the limited material, we do not propose it as a new species and temporarily leave it in open nomenclature.

Locality and occurrence Upper Cambrian Bitiao Formation in Wangcun section, Yongshung County, western Hunan, South China.

3 The scientific significance of the fossils of Orsten-type preservation

Just like the famous fossils of Chenjiang Fauna, the fossils of Orsten-type preservation are also soft-bodied animals with important biological information. Compared to the flattened fossil material of Chenjiang Fauna, the Orsten material is relatively rare, and no internal organs such as blood vessels and nerve system have been found, except muscle tissue[16]. Nevertheless, the Orsten fossils are three-dimensionally preserved and extremely lifelike, with their original topology and finest structure preserved to the resolution of one micron. Moreover, the different stages of ontogeny could be also preserved. In short, the discovery of Orsten fossils in China is as important as the discovery of the Chengjiang Fauna for the study of the origin and evolution of arthropods.

The upper part of Middle Cambrian through Lowermost Ordovician is made up chiefly of limestones in Western Hunan. The Orsten--yielding dark gray medium- to thick-bedded or nodular micrites are very common. Having processed more than 14000 kg limestone, we recovered Orsten fossils in quite a few horizons, ranging from conodont *Shandongodus priscus-Hunanognathus tricuspidatus* zone through *Cordylodus proavus* zone in the three key sections[17] (Fig. 1), and we suppose more horizons would be found in the near future. Indeed, another 6000 kg limestone has been being processed since early 2004, and more exciting Orsten fossils are expected to be found. In the light of this, the research work on Orsten recovered from China will most probably be productive, though it just started. The present paper is the first report of the Orsten material recovered from Hunan. Subsequently, we will publish additional papers on the Orsten material we have found and will find.

4 Conclusions

(1) The fossils of Orsten-type preservation found in Hunan fill in the gaps of China in terms of the geographical distribution of Orsten. They resemble the typical Orsten found in Sweden in terms of the fidelity of preservation.

(2) The Orsten material found from the strata of Late Cambrian in Hunan is similar to that found in Sweden in the aspect of the faunas. Moreover, the fossils of Orsten-type preservation and larvae which have not been reported elsewhere in the world have been also found from the strata of Middle Cambrian in western Hunan.

(3) Just like the typical Orsten material from Sweden, the Orsten material of Hunan opens a new window to the study of the origin and evolution of arthropods, hitherto unknown in China. The results of their study will represent an important supplement to those of the Chengjiang Fauna.

(4) The new contributions to the early evolution of arthropods and other groups may be made, based on the combined studies on the Orsten material, fossil embryos[15] and the larvae not reported previously, by means of the techniques of MicroCT and so on.

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