LINGULATE BRACHIOPODS AND BIOSTRATIGRAPHY OF THE CAMBRIAN-ORDOVICIAN BOUNDARY BEDS IN BALTOSCANDIA

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Doctoral thesis presented to the
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Institute of Earth Sciences
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ABSTRACT

Puura, I. 1996: Lingulate brachiopods and biostratigraphy of the Cambrian-Ordovician boundary beds in Baltoscandia. *Comprehensive Summary of Doctoral Dissertation.* Institute of Earth Sciences. Department of Historical Geology and Palaeontology. Uppsala University, 19 pp.

This study evaluates the taxonomy and stratigraphic utility of lingulate brachiopods from the Cambrian-Ordovician boundary beds in outcrops and core sections in Estonia, Ingria (St. Petersburg district of Russia) and Sweden.

From Middle Cambrian to Hunneberg (Lower Ordovician) strata of Estonia and Ingria, thirty-seven species (32 named) are described, assigned to 26 named genera (of which one is new). The distribution of lingulates is documented from more than 40 outcrops and 10 drill cores. Seven lingulate biozones, defined by the first appearance of the zonal species, are distinguished (in ascending order): *Obolus ruchini*, *O. transversus*, *Ungula inornata*, *U. convexa*, *U. ingrica*, *Obolus apollinis*, "*Eurytreta*" and *Thysanotos siluricus* biozones. Co-occurrences of lingulates and conodonts permit tentative correlation between the East Baltic lingulate biozones and conodont biozones.

Closely related Cambrian-Ordovician lingulates in the Siljan District, South Bothnian submarine district and the island of Öland, Sweden, occur mostly in condensed sandstones or conglomerates referred to as "*Obolus*" beds. The Swedish "*Obolus*" beds are interpreted as having formed during several phases of reworking in the time interval from the Late Cambrian to Hunneberg.

Differences in apatite lattice parameters of fossil and Recent lingulate shells have been established by means of powder XRD. The apatite variety in Recent lingulate shells is a F-containing carbonate hydroxyapatite with a fluorine content higher than in dahllite, with the lattice parameters $a = 9.38$-9.40 and $c = 6.87$-6.89. The apatite lattice parameters for the fossil shells, $a = 9.33$-9.36 and $c = 6.87$-6.90 correspond to the apatite species between fluorapatite and carbonate fluorapatite (francolite); in many cases, more than one apatite phase is distinguished. These differences are explained by various *post mortem* processes, in particular, by microbial degradation of organic tissues and precipitation of authigenic apatite.

Key words: Brachiopoda, Lingulata, Cambrian, Lower Ordovician, systematics, biostratigraphy, taphonomy, XRD, Estonia, Russia, Sweden.

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In addition to this summary, the dissertation consists of the following papers:

I. Puura, I., in manuscript. Cambrian-Ordovician lingulate brachiopods from Estonia and northwestern Russia. 136 pp.

II. Puura, I. & Holmer, L. 1993. Lingulate brachiopods from the Cambrian-Ordovician boundary beds of Sweden. *Geologiska Föreningens i Stockholm Förhandlingar 115(3)*, 215-237.

III. Mens, K., Viira, V., Paalits, I. & Puura, I. 1993. Upper Cambrian biostratigraphy of Estonia. - *Proceedings of the Estonian Academy of Sciences. Geology 42(4)*, 148-159.

IV. Mens, K., Heinsalu, H., Jegonjan, K., Kurvits, T., Puura, I. & Viira, V. 1996. Cambrian-Ordovician boundary beds in the Pakri Cape section, NW Estonia. *Proceedings of the Estonian Academy of Sciences. Geology 45(1)*, 9-21.

V. Nemliher, J. & Puura, I., in manuscript. Shell mineralogy of lingulate brachiopods from the East Baltic Cambrian-Ordovician "*Obolus* phosphorite". Accepted for publication *in* Stouge, S. (ed.). Proceedings of the workshop of the Working Group on the Ordovician Geology of Baltoscandia. *Report Series, The Geological Survey of Denmark and Greenland.* 12 pp.

INTRODUCTION

Lingulate brachiopods (Phylum Brachiopoda, class Lingulata Goryanskij & Popov, 1985) are among the commonest fossils in the Middle Cambrian - Lower Ordovician rocks of Baltoscandia. Recent studies have demonstrated the utility of lingulates for correlation of the Cambrian-Ordovician boundary beds across the region (Popov *et al.* 1989; Holmer & Popov 1990; Puura & Holmer 1993) and in some cases, for inter- regional correlations (Popov & Holmer 1994).

Historical reviews of the study of Baltoscandian Cambrian- Ordovician lingulate brachiopods have been published by Goryanskij (1969), Holmer (1989), Puura (1990) and Puura & Holmer (1993). Goryanskij (1969), Popov *et al.* (1989) and Popov & Holmer (1994) in particular have considerably advanced knowledge of the taxonomy and distribution of these fossils. Closely related faunas have been documented from Poland (Bednarczyk 1964; Biernat 1964, 1973), Bohemia (Havlicek 1982) and the South Urals (Popov & Holmer 1994).

This dissertation examines aspects of the systematics, biostratigraphy and shell mineralogy of the Middle Cambrian - Lower Ordovician (Hunneberg) lingulate brachiopods from Estonia, Ingria (St. Petersburg district of Russia - also known by its Swedish name Ingermanland) and Sweden.

MATERIAL AND METHODS

The brachiopods on which this work is based were collected from more than 40 outcrops in Estonia and Ingria and 10 drill cores in Estonia (Fig. 1). Macroscopic lingulates were obtained by direct sampling of outcrops and core sections. From coquinas in soft sands and sandstones, brachiopod valves were extracted by wet sieving where water was available. Microscopic brachiopods were obtained mostly from sieved fractions of samples of clastic rocks processed for conodont studies and grain size analysis. The specimens from the sands and weakly-cemented sandstones were prepared mechanically with needles. The specimens from carbonate-cemented quartzose rocks were etched by weak (10%) acetic acid. The study of this newly collected material was complemented by examination of existing collections in Estonia, Sweden and Russia. The described material is deposited in the following institutions: Institute of Geology, Estonian Academy of Sciences, Tallinn, Swedish Museum of Natural History, Stockholm, Palaeontological Museum, Uppsala, Geological Survey of Sweden, Uppsala, St. Petersburg University and Central Scientific Research Geologic Exploration Museum, St. Petersburg, Russia.

Scanning electron microscopy (SEM) studies were carried out by means of a PHILIPS SEM at Uppsala University, using digital image handling. The powder XRD analysis of shell composition of the samples collected from 14 localities in Estonia and Ingria was carried out by J. Nemliher at the Mineralogical Laboratory of the University of Tartu, by means of an X-ray diffractometer DRON-0.5, using Ni-filtered Fe Kα radiation, with quartz as an internal standard. Apatite lattice parameters were calculated from the data of 25 apatite reflections in the 2 Θ interval of 12-76^{o}.

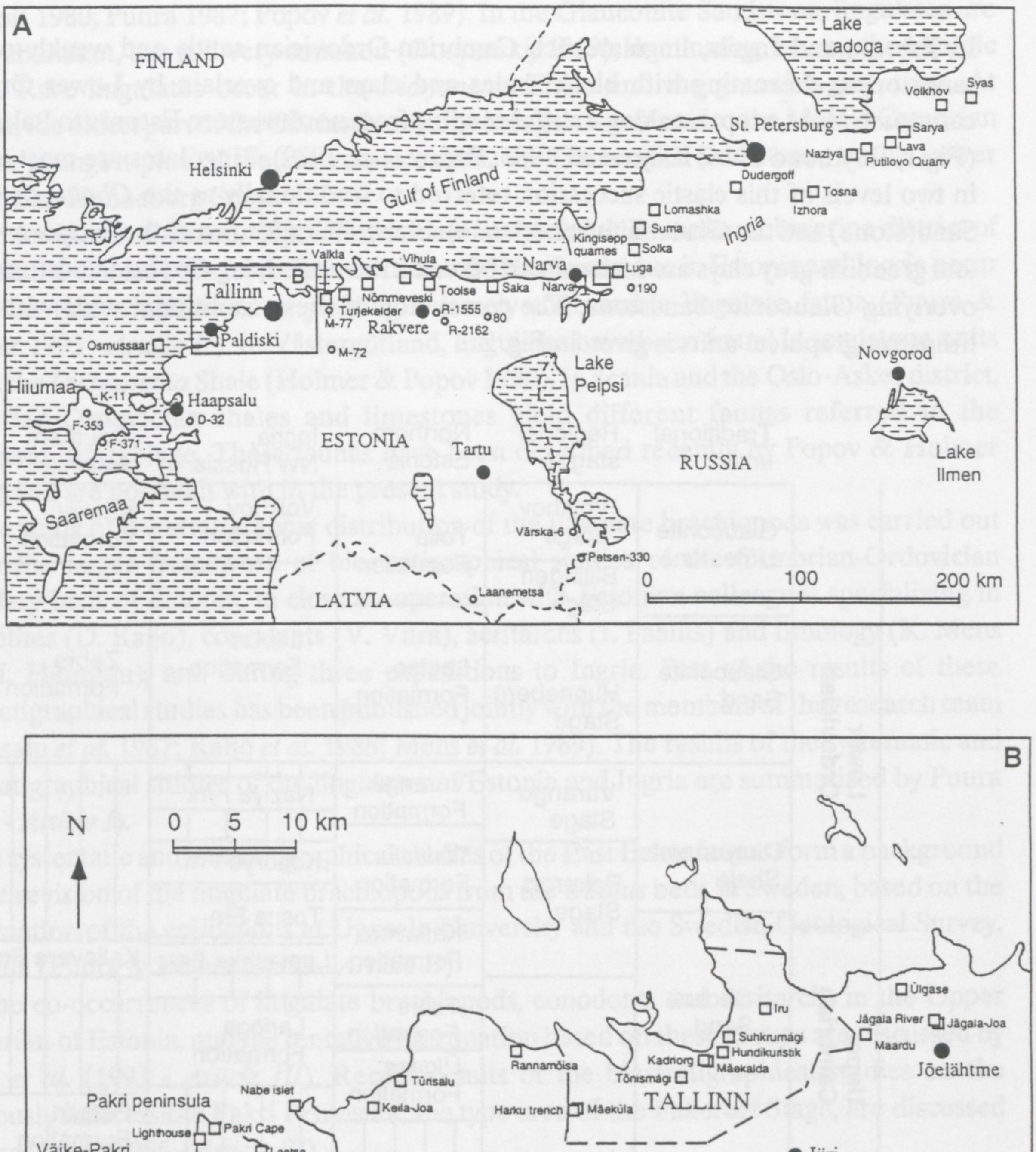


Fig. 1. Locality maps. Outcrops indicated by squares, drill core sites by open circles. []A. Map of Estonia and Ingria (St. Petersburg district of Russia). []B. Detailed locality map of northwestern Estonia.

OUTLINE OF RESEARCH

In Estonia and Ingria, lingulate-rich Cambrian-Ordovician sands and weakly-cemented sandstones, alternating with black shales and clays and overlain by Lower Ordovician carbonate rocks, crop out along a cliff extending from northwestern Estonia to Lake Ladoga (Fig.1; Raymond 1916; Kaljo *et al.* 1986; Popov *et al.* 1989). Lingulates are most abundant in two levels of this clastic succession referred to traditionally as the *Obolus* or Ungulite Sand(stone) and the Glauconite Sand(stone). Black shales, known as the *Dictyonema* Shale, and greenish-grey clays are intercalated between the underlying *Obolus* Sandstone and the overlying Glauconite Sandstone. The correlation of these traditional units with modern lithostratigraphical units is given in Fig. 2.

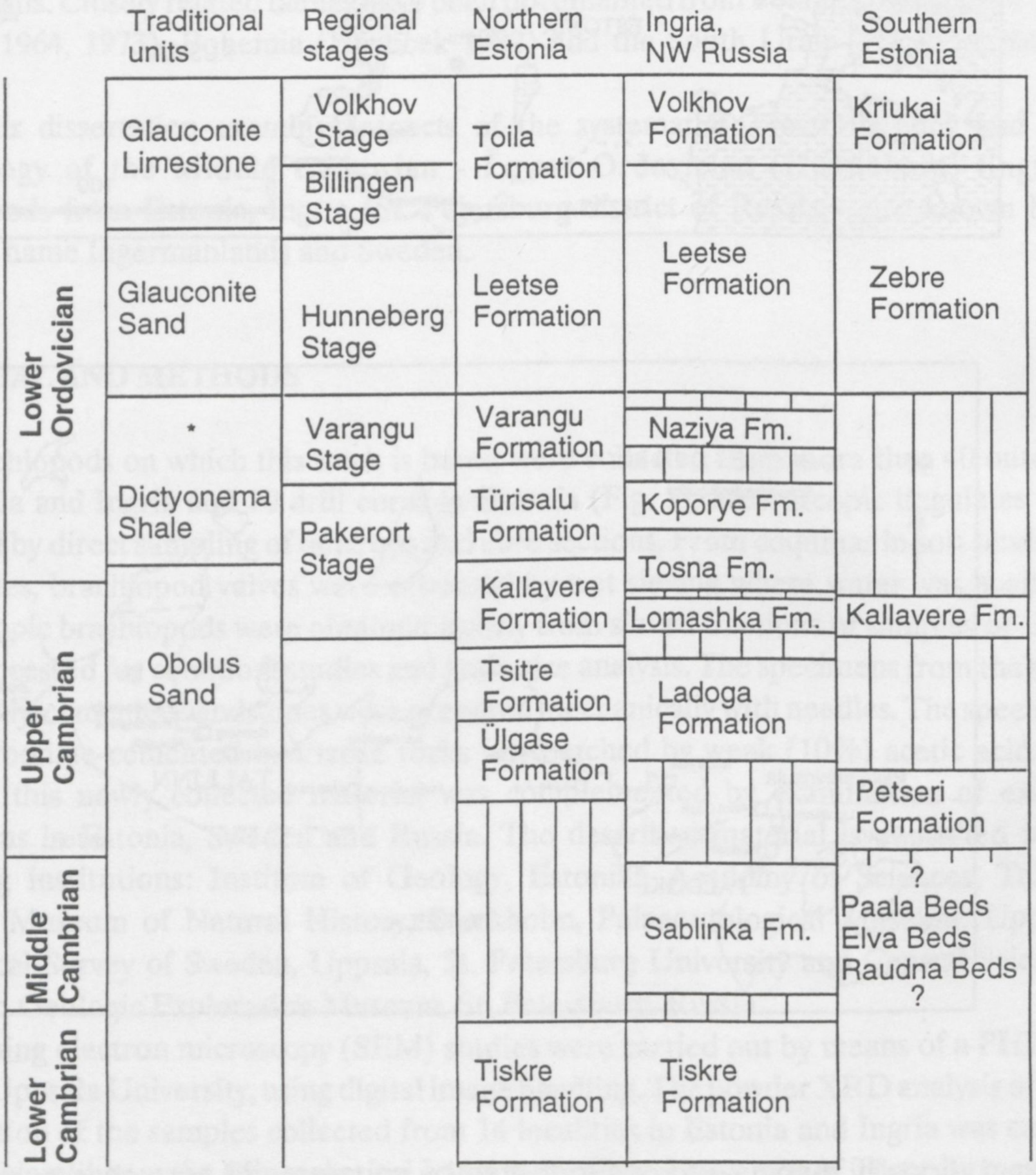


Fig. 2. Major chrono- and lithostratigraphical units of Middle Cambrian-Hunneberg in Estonia and Ingria (mainly after Popov *et al.* 1989; Mens *et al.* 1990; Mens 1992; Männil & Meidla 1994), and their correlation with traditional units.

Lingulate coquinas in the *Obolus* Sandstone form unique deposits of shelly phosphorite (Notholt 1980; Puura 1987; Popov *et al.* 1989). In the Glauconite Sandstone, lingulates are not as abundant, but still very common (Goryanskij 1969), dominating among the benthic fossils. Rare lingulates occur in the *Dictyonema* Shale and the greenish-gray clays. At present, the oldest part of the *Obolus* Sandstone in Ingria is referred to the Middle Cambrian and the youngest part of the clastic succession, the Glauconite Sandstone, to the Lower Ordovician Hunneberg Stage.

On the island of Öland, Siljan District and in the South Bothnian submarine district of Sweden, the *Obolus* beds, correlative with the *Obolus* Sandstone in Estonia and Ingria occur mostly as thin conglomerates, yielding a closely comparable lingulate fauna (Puura & Holmer 1993 - *Article II*). In Västergötland, lingulates have been found in sandstone units within the *Dictyonema* Shale (Holmer & Popov 1990). In Scania and the Oslo-Asker district, Cambrian-Ordovician shales and limestones yield different faunas referred to the *Broeggeria* assemblage. These faunas have been described recently by Popov & Holmer (1994) and are not dealt with in the present study.

The study of the stratigraphic distribution of the lingulate brachiopods was carried out within the larger framework of biostratigraphical studies of the Cambrian-Ordovician boundary beds of Estonia, in close co-operation with Estonian colleagues specializing in graptolites (D. Kaljo), conodonts (V. Viira), acritarchs (I. Paalits) and lithology (K. Mens and H. Heinsalu), and during three expeditions to Ingria. Part of the results of these biostratigraphical studies has been published jointly with the members of the research team (Heinsalu *et al.* 1987; Kaljo *et al.* 1988; Mens *et al.* 1989). The results of the systematic and biostratigraphical studies of the lingulates of Estonia and Ingria are summarized by Puura (1996 - *Article I*).

The systematic and biostratigraphical studies of the East Baltic faunas form a background for the revision of the lingulate brachiopods from the *Obolus* beds of Sweden, based on the examination of the collections at Uppsala University and the Swedish Geological Survey, Uppsala (Puura & Holmer 1993 - *Article II*).

The co-occurrences of lingulate brachiopods, conodonts and acritarchs in the Upper Cambrian of Estonia, and the tentative biozonation based on these groups are discussed by Mens *et al.* (1993 - *Article III*). Recent results of the biostratigraphical studies on the previously inaccessible Pakri Peninsula, the type area of the Pakerort Stage, are discussed by Mens *et al.* (1996 - *Article IV*).

Large samples from the outcrops in Estonia and Ingria and Recent comparative material were used for the studies of lingulate shell mineralogy by means of X-ray powder diffraction analysis (XRD) and scanning electron microscopy (SEM). Comparison of the shell mineralogy of fossil and Recent lingulates allowed the construction of diagenetic scenarios governing the mineral composition of the fossil lingulates, which form the East Baltic shelly phosphorites (Nemliher & Puura in press - *Article V*).

CAMBRIAN-ORDOVICIAN LINGULATE BRACHIOPODS FROM ESTONIA AND NORTHWESTERN RUSSIA
(Article I)

Lingulate brachiopods are described from Middle Cambrian to Hunneberg (Lower Ordovician) strata of Estonia and Ingria, traditionally known as *Obolus* Sandstone, *Dictyonema* Shale and Glauconite Sandstone. The material originates from over 40 outcrops in northern Estonia and Ingria and 10 core sections in Estonia (Fig. 1). Thirty-seven species (32 named) are described, assigned to 26 named genera, of which the obolid genus *Estoniobolus* is new. Middle Cambrian - Hunnebergian localities, lithostratigraphy and biostratigraphy are reviewed. The stratigraphical distribution of the lingulates is summarized in Fig. 3. The following seven lingulate biozones are distinguished (in ascending order).

Obolus ruchini Biozone. - The base of this zone is defined by the first appearance of *Obolus ruchini* Khazanovitch & Popov. As well as the biozonal species, the assemblage includes *Oepikites macilentus* Khazanovitch & Popov. Based on an acritarch assemblage (Borovko *et al.* 1984) and the occurrence of a bradoriid *Vojbokalina magnifica* Melnikova (*in* Khazanovitch *et al.* 1984), a Middle Cambrian age, roughly corresponding to some part of the *Paradoxides paradoxissimus* trilobite Biozone in Scandinavia has been suggested for this biozone (Popov *et al.* 1989). The fauna of this biozone is confined to the Gertovo Member of the Sablinka Formation in Ingria.

Obolus transversus Biozone. - The base of this biozone is defined by the first appearance of *Obolus transversus* Pander. As well as the biozonal species, the lingulate assemblage includes *Oepikites koltchanovi* Khazanovitch & Popov. This assemblage is restricted to the Rebrovo Member of the Sablinka Formation in Ingria. The lack of other groups of fauna makes precise age determination of this zone difficult. A tentative Middle Cambrian age has been suggested by Popov *et al.* (1989), based on the stratigraphic position of the Rebrovo Member, overlying the Gertovo Member, yielding a Middle Cambrian fauna, and underlying the Ladoga Formation of earliest Upper Cambrian age containing conodonts of the *Westergaardodina bicuspidata* Subzone in the basal part.

Ungula inornata Biozone. - The base of the biozone is defined by the first appearance of *Ungula inornata* (Mickwitz). The characteristic lingulate assemblage, including *U. inornata*, *Oepikites fragilis* Popov & Khazanovitch, 1989, and *Angulotreta postapicalis* Palmer, 1954 is confined to the Ülgase Formation in northern Estonia (Mens *et al.* 1993). In Ingria the characteristic assemblage, represented by the two latter species and *Gorchakovia granulata* Popov & Khazanovitch, is restricted to the lower subformation of the Ladoga Formation (Popov *et al.* 1989).

Tentative correlations of this biozone based on the occurrence of rare *Angulotreta postapicalis* suggest an early Late Cambrian age. In addition to its occurrence in Estonia and Ingria, this species has been recorded from the lowermost Upper Cambrian *Cedaria*/*Cedarina* Bioone in Texas, USA (Palmer 1954) and the Upper Cambrian of Novaya

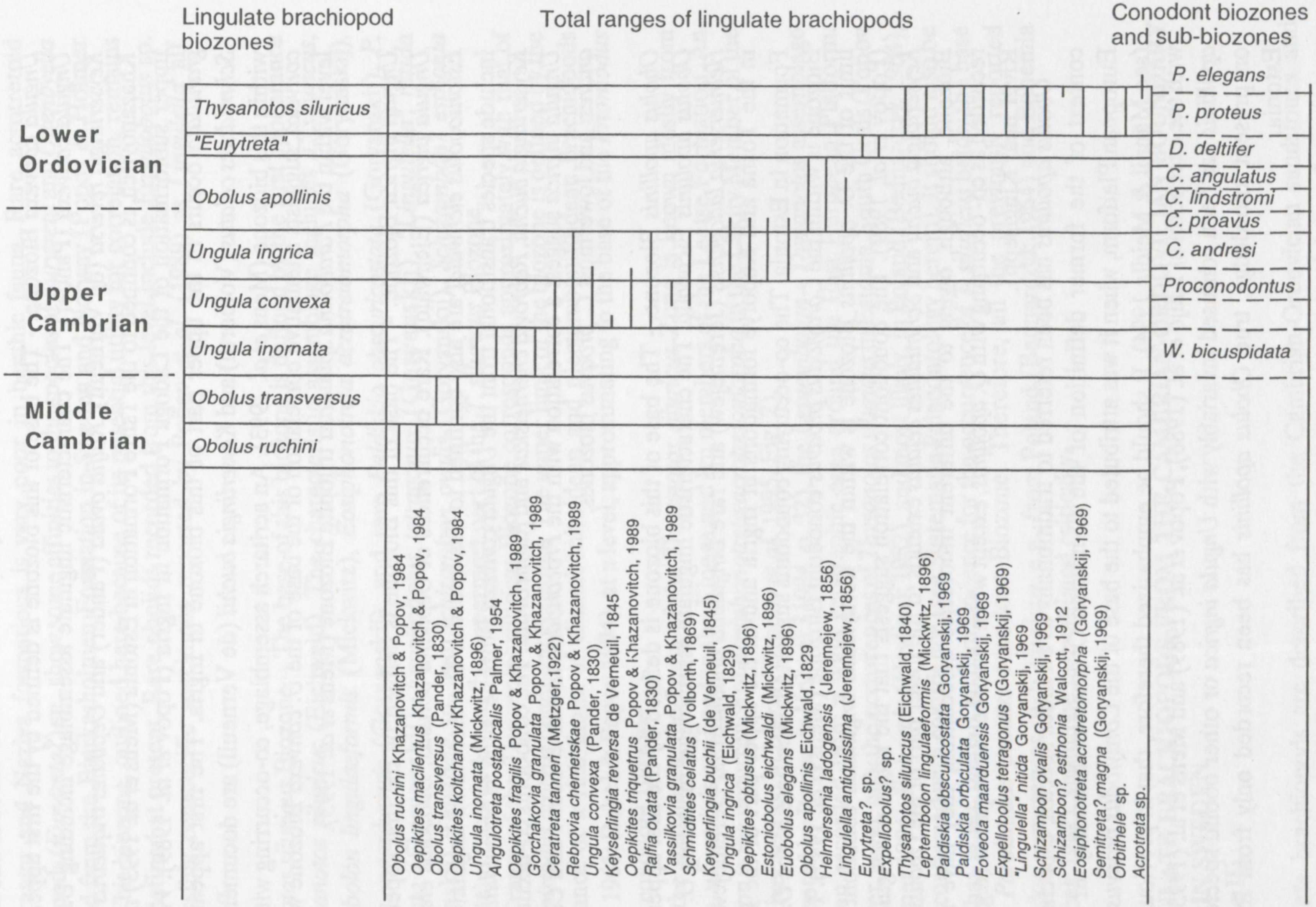


Fig. 3. Lingulate biozonation and distribution in Middle Cambrian - Hunneberg strata of Estonia and Ingria.

Zemlya, Russia (Popov 1985).

Ungula convexa Biozone. - The base of this biozone is defined by the first appearance of *Ungula convexa* (Pander). The characteristic lingulate assemblage including *U. convexa*, *Keyserlingia reversa* (de Verneuil), *Ralfia ovata* (Pander) and *Oepikites triquetrus* Popov & Khazanovitch, is confined to the Tsitre Formation in Estonia (Mens *et al.* 1993) and to the upper subformation of the Ladoga Formation in Ingria (Popov *et al.* 1989). *Vassilkovia granulata* occurs in the upper part of this biozone in Ingria. The first appearances of *Schmidtites celatus* (Volborth) and *Keyserlingia buchii* (de Verneuil) are documented from within this biozone (Mens *et al.* 1993). An acritarch assemblage, co-occurring with *Ungula convexa*, suggests a tentative correlation of the base of the *U. convexa* Biozone with some level within the *Parabolina spinulosa* trilobite Biozone (Mens *et al.* 1993).

Ungula ingrica Biozone. - The base of this Biozone is defined by the first appearance of *Ungula ingrica* (Eichwald). Rare occurrences of *Oepikites obtusus*, *Euobolus elegans* and *Estoniobolus eichwaldi* are also confined to this interval. The associated lingulates mostly include species transitional from the *Ungula convexa* Biozone, such as *Schmidtites celatus*, *Keyserlingia buchii*, *Rebrovia chernetskae* and *Ralfia ovata*. The conodonts co-occurring with *Ungula ingrica* suggest a correlation with the *Proconodontus* sub-Biozone and *Cordylodus andresi* and lowermost *C. proavus* biozones.

Obolus apollinis Biozone. - The base of this biozone is defined by the first appearance of *Obolus apollinis* Eichwald. The characteristic lingulate assemblage, including *O. apollinis*, *Helmersenia ladogensis* (Jeremejew) and rare *Lingulella antiquissima* (Jeremejew), occurs in the Tosna and Koporye formations in Ingria and in the upper part of the Kallavere Formation in Estonia. The co-occurring conodonts suggest that the base of the *O. apollinis* Biozone is within the *Cordylodus proavus* conodont Biozone (Mens *et al.* 1993). The upper limit of the *O. apollinis* Biozone is within the *Cordylodus angulatus* conodont Biozone (Popov *et al.* 1989). The conodont correlation suggests that the range of *Ungula ingrica*, *Keyserlingia buchii* and *Schmidtites celatus* extends to the lower part of the *Obolus apollinis* Biozone, although, owing to the different lithofacies association, they have not been recorded as co- occurring with *O. apollinis*, except when reworked in coquinas (e.g., in Luga River near Kingisepp).

Obolus apollinis has been referred to traditionally as an index species, especially in the context of the former definition of the Cambrian-Ordovician boundary in the East European Platform, when it was attributed to the base of the *Cordylodus proavus* Biozone (see Männil & Meidla 1994). It should be emphasized therefore, that in previous studies, with the exception of Kaljo et al. (1986), Popov *et al.* (1989) and Mens et al. (1993), *Obolus apollinis* has been confused invariably with *Ungula ingrica* or other obolid species. Based on present knowledge, true *Obolus apollinis* has been recorded only from Ingria and Estonia.

"*Eurytreta*" Biozone. - The interval between the upper limit of the *O. apollinis* Biozone and the base of the *Thysanotos siluricus* Biozone corresends approximately to the

Drepanoistodus deltifer conodont Biozone. This interval, represented by the upper part of the black shales of the Türisalu and Koporye Formations and by the greenish-grey clays of the Varangu and Naziya formations is very poor in benthic fauna. Rare acrotretoid brachiopods (*Eurytreta?*) sp., show some affinities to the species of *Eurytreta* and *Ottenbyella* recorded from the Bjørkasholmen Formation in Sweden and Norway (Popov & Holmer 1994). This biozone, outlined here because of its potential utility for correlation, remains poorly defined at present. Rare obolids recorded from this level include *Expellobolus* sp. and possibly conspecific specimens reported by Popov *et al.* (1989) as *Lingulella* aff. *tetragona*.

Thysanotos siluricus Biozone. - The base of this biozone is defined by the first appearance of *Thysanotos siluricus* (Eichwald). The characteristic assemblage includes *T. siluricus*, *Leptembolon lingulaeformis* (Mickwitz), *Eosiphonotreta acrotretomorpha* (Goryanskij), *Foveola maarduensis* (Goryanskij), and rare *Paldiskia obscuricostata* (Goryanskij), *P. orbiculata* (Goryanskij), *Expellobolus tetragonus* (Goryanskij), "*Lingulella*" *nitida* (Goryanskij), *Orbithele* sp. and *Schizambon ovalis* (Goryanskij). *Schizambon? esthonia* (Walcott) is recorded from the uppermost part of the *T. siluricus* Biozone.

The range of the *Thysanotos siluricus* Biozone corresponds approximately with that of the *Paroistodus proteus* conodont Biozone. The upper limit of the biozone is defined by the appearance of a rich fauna of clitambonitoidean and plectambonitoidean brachiopods (Rubel 1961; Rubel & Popov 1994), at a level, approximating to the base of the *Prioniodus elegans* conodont Biozone.

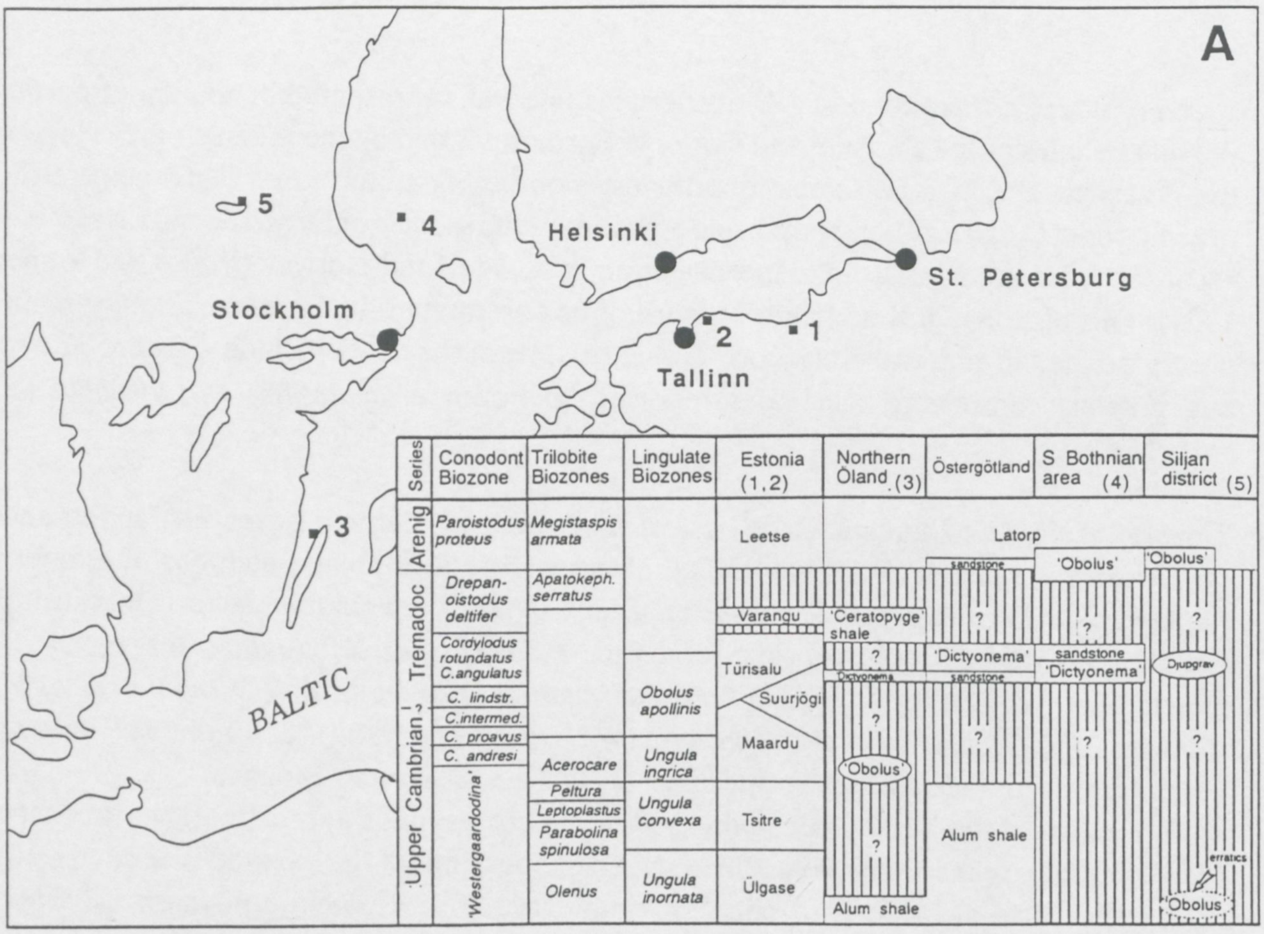
In the study area, the fauna of the *Thysanotos siluricus* Zone is known mostly from Estonia, where it is confined to the Klooga and Iru members of the Leetse Formation. An exception is the occurrence of *Eosiphonotreta acrotretomorpha* in the Lakity Member of the Lava River section in Ingria (Dronov *et al.* 1995, Fig. 2).

As noted by Popov & Holmer (1994, p. 32), the *Leptembolon - Thysanotos* assemblage has been recorded from a wide geographic area around the East European Platform. However, as yet, only the occurrences of *Thysanotos siluricus* in Estonia, South Urals (Popov & Holmer 1994), Bohemia (Havlicek 1982), and most likely, in Poland (Bednarczyk 1964), can be confirmed with confidence (see Systematic Palaeontology herein). It should also be noted that, as yet, there is no firm evidence for the occurrence of *T. siluricus* below the base of the *Paroistodus proteus* conodont Biozone. Therefore, all the previously reported Tremadoc occurrences of *T. siluricus*, e.g., from Poland (Bednarczyk 1964) and Bohemia (Havlicek 1982), should be re-evaluated critically.

LINGULATE BRACHIOPODS FROM THE CAMBRIAN-ORDOVICIAN BOUNDARY BEDS IN SWEDEN

(Article II).

Lingulate brachiopods are described from the Cambrian-Ordovician sandstones and conglomerates of Sweden, known as *Obolus* beds. The material originates from outcrops and drill cores in the Siljan District, South Bothnian submarine district and the island of



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<tr><td>Cordylodus sp</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>+</td><td></td><td></td><td>+</td></tr>
<tr><td>Cordylodus angulatus</td><td></td><td>+</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>+</td></tr>
<tr><td>Paroistodus numarcatus</td><td>+</td><td>+</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>+</td></tr>
<tr><td>Paltodus subaequalis</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>+</td></tr>
<tr><td>Drepanoistodus deltifer</td><td></td><td>+</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

B

Fig. 4. Tentative correlation of the Swedish "*Obolus*" beds with the Cambrian-Ordovician boundary beds in Estonia. []A. Localities: 1 - Saka; 2 - Ülgase, 3 - Horns Udde, Öland; 4 - Sjurberg, South Bothnian submarine district; 5 - Sjurberg, Siljan district. []B. Distribution of lingulates, conodonts and problematica in the examined samples. The approximate relative abundance is given: ++, abundant; +, present; -, rare; ?, questionable occurrence (after Puura & Holmer 1993 Figs 1, 10).

Öland (Fig. 4A).

The fauna includes *Ungula inornata*, *U. ingrica*, *Schmidtites celatus*, *Oepikites* sp., *Ceratreta tanneri* and *Keyserlingia reversa*, which are also well known in the Upper Cambrian of Estonia and Ingria. Most examined sections also include species of probable late Tremadoc to early Arenig age. The species distribution in the studied sections and erratic boulders is shown in Fig. 4B. Mainly based on lingulate correlation with the Ülgase and Saka sections in Estonia, this article suggested that the Swedish "*Obolus*" beds were formed during several phases of deposition and reworking from the Late Cambrian to early Arenig.

A more recent conodont study by Löfgren (1994) suggests that the latest phase of the formation of the "*Obolus*" beds at Sjurberg, Siljan District, was no younger than the *Drepanoistodus deltifer* Biozone. Deposition and reworking of the Cambrian-Ordovician boundary beds, in several phases in the western part of the Baltoscandian basin is corroborated by new evidence from the Orreholmen quarry, Västergötland, from where Löfgren (1996) reported reworked conodonts of the *C. lindstromi* and *D. deltifer* biozones.

UPPER CAMBRIAN BIOSTRATIGRAPHY OF ESTONIA
(Article III).

The biostratigraphy of the Upper Cambrian siliciclastic rocks of Estonia is based on co-occurrences of conodonts, lingulate brachiopods and acritarchs. The Upper Cambrian of Estonia includes four major lithostratigraphical subdivisions: Petseri, Ülgase, Tsitre and Kallavere formations. In this interval, five acritarch-, four conodont- and four lingulate biozones are distinguished. Tentative correlation with Scandinavian trilobite biozones is suggested, based mainly on acritarchs and conodonts (Fig. 5). The Petseri Formation is correlated tentatively with the *Olenus* Biozone, and the Ülgase Formation with the *Olenus* Biozone and the lower part of the *Parabolina spinulosa* Biozone. The lower part of the Tsitre Formation corresponds approximately with the *P. spinulosa* and *Leptoplastus* biozones. The uppermost part of the Tsitre Formation is correlated with the *Peltura scarabeoides* Biozone. The lower part of the Kallavere Formation corresponds with the *Acerocare* Biozone.

CAMBRIAN-ORDOVICIAN BOUNDARY BEDS IN THE PAKRI CAPE SECTION, NW ESTONIA
(Article IV)

The stratotype of the Pakerort Stage, the lowermost regional stage of the Ordovician, is located near the promontory of the Pakri Peninsula. Due to access denial by a Soviet navy base in the vicinity, these sections could not be studied from 1961 to 1993 and the concept of the Pakerort Stage was based on data derived from distant localities. These studies revealed that the lower boundary of the Kallavere Formation, usually regarded as coinciding with the base of the Pakerort Stage, is diachronous. In recent stratigraphic accounts, the base of the *Cordylodus andresi* Biozone has been preferred as the tentative

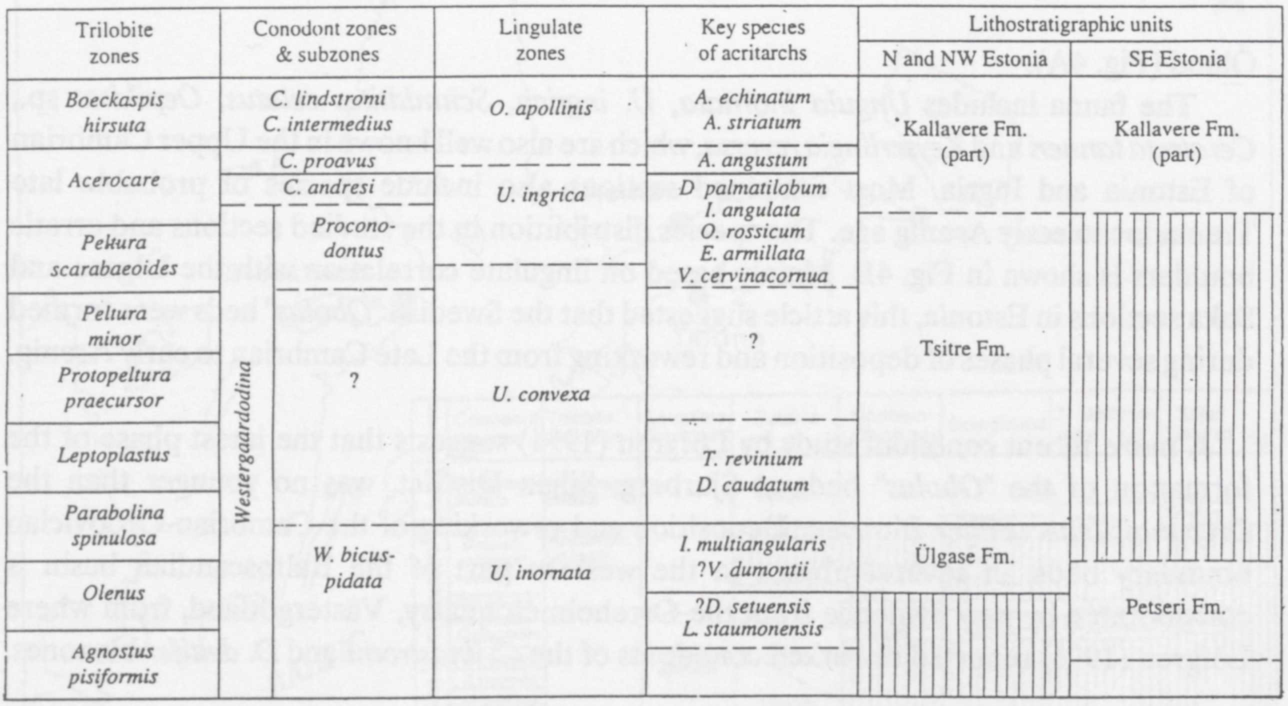

Fig. 5. Upper Cambrian biostratigraphy of Estonia based on conodont and lingulate biozones and acritarch assemblages, with a tentative correlation with Scandinavian trilobite zones (after Mens *et al.* 1993).

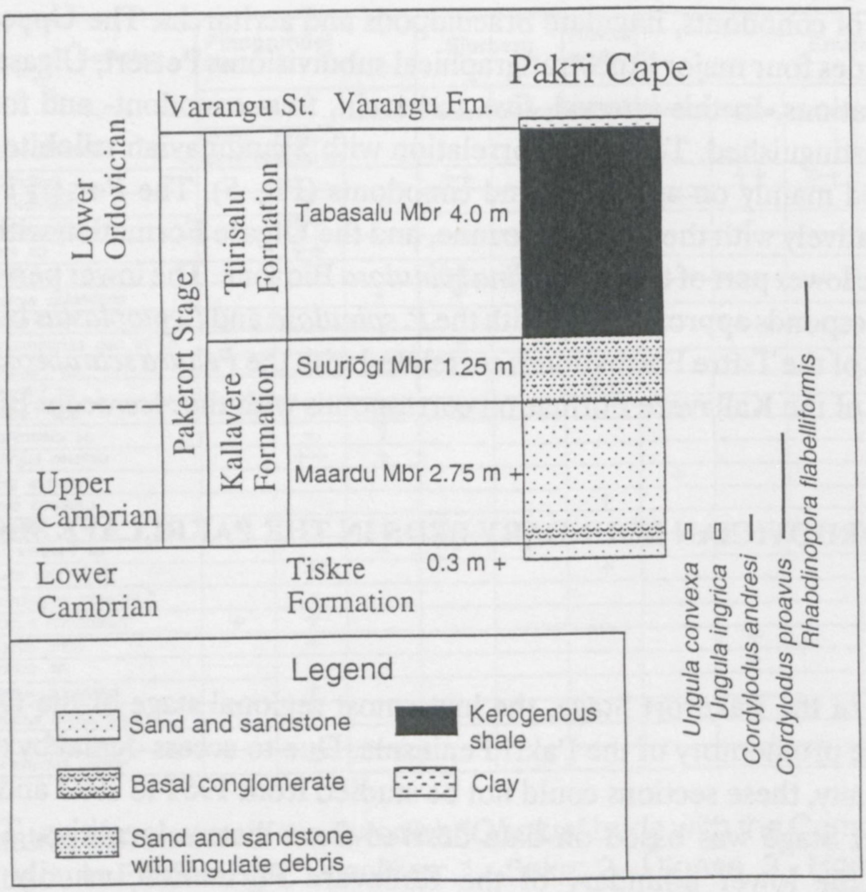

Fig. 6. Distribution of conodonts, graptolites and reworked lingulate brachiopods in the Pakri Cape section (after Mens *et al.* 1996).

lower boundary of the Pakerort Stage (Männil 1990; Männil & Meidla 1994).

The Pakri Cape section is located 1 km southeast of the promontory of the Pakri Peninsula (Figs 1B and 6), near the stratotype section of the Pakerort Stage described by Raymond (1916). The basal conglomerate of the Kallavere Formation overlying the Lower Cambrian Tiskre Formation yields the Upper Cambrian lingulate brachiopods *Ungula convexa* and *Ungula ingrica*. The age can be established only for the lower part of the Kallavere Formation, which belongs to the *Cordylodus proavus* conodont Biozone, while the *C. andresi* Biozone is missing. Younger conodont biozones cannot be recognized with confidence owing to scarcity and poor preservation of conodonts. The lower part of the overlying Türisalu Formation yields *Rhabdinopora flabelliformis* and *R.* cf. *desmograptoides*. Fig. 6 is an updated biostratigraphic interpretation of the Pakri Cape section.

SHELL MINERALOGY OF LINGULATE BRACHIOPODS FROM THE *OBOLUS* PHOSPHORITE OF ESTONIA AND INGRIA

(Article V)

Shell mineralogy of Middle and Upper Cambrian lingulate brachiopods from 14 outcrops in northern Estonia and Ingria was studied by means of XRD. The variation range of apatite lattice parameters in the commonest species, *Ungula ingrica* (Eichwald), *Schmidtites celatus* (Volborth) and *Obolus apollinis* (Eichwald), was determined, using representative material from localities representing a wide range of depositional settings. Selected specimens of *Ungula convexa*, *Oepikites macilentus*, *Oepikites koltchanovi* and *Helmersenia ladogensis* and phosphatized pebbles were used for comparative studies. In contrast to most earlier studies, the mineralogical composition of fossil and Recent lingulate brachiopod shells is shown to differ significantly (Fig. 7).

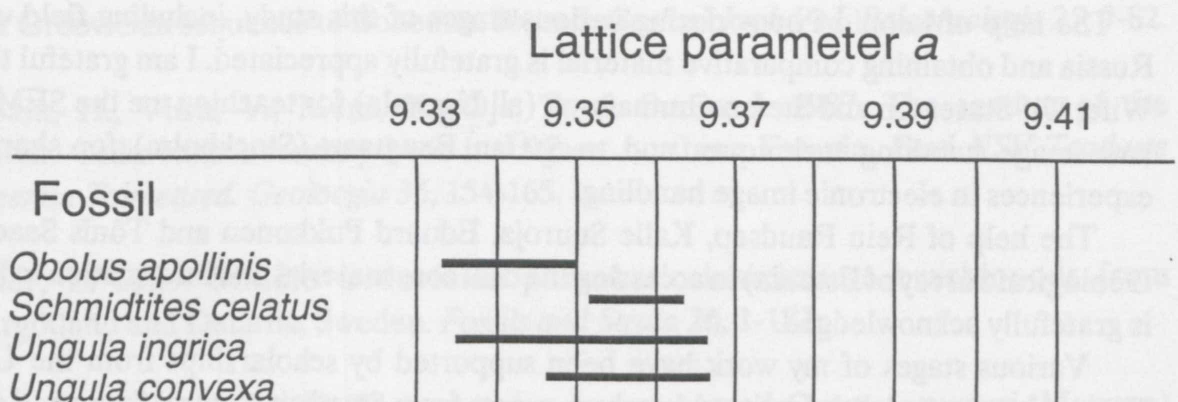

Fig. 7. Variation ranges of the apatite lattice parameter *a* (Å)in fossil and Recent lingulate brachiopod shells, based on the data from Nemliher & Puura (in press).

Recent lingulate shell mineral is a F- containing carbonate hydroxyapatite with a F-content higher than in dahllite, having the range of lattice parameters $a = 9.38$-9.40 and $c = 6.87$-6.89. The bulk composition of the studied fossil shells corresponds to the apatite species between fluorapatite and carbonate fluorapatite with the lattice parameters $a = 9.33$-9.36 and $c = 6.87$- 6.90. Previously reported lattice parameters of fossil lingulates (Ushatinskaya *et al.* 1988) also fall within this range.

The original composition of the fossil lingulate shells was possibly close to that of the Recent shells. The change in mineralogy of a fossil shell could have been caused by one or a combination of processes. These include diagenetic substitution of OH^- by F^- and $(PO_4)^{3-}$ by $(CO_3)^{2-}$ and F^-, degradation of organic tissues by bacteria and precipitation of CCP (or pyrite) in the free space.

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I

CAMBRIAN-ORDOVICIAN LINGULATE BRACHIOPODS FROM ESTONIA AND NORTHWESTERN RUSSIA

IVAR PUURA

Puura, I. 1996: Cambrian-Ordovician lingulate brachiopods from Estonia and northwestern Russia. 136 pp. Institute of Earth Sciences. Historical Geology and Palaeontology. Uppsala University.

Lingulate brachiopods are described from Middle Cambrian to Hunnebergian (Lower Ordovician) strata of Estonia and Ingria (St. Petersburg district of Russia), traditionally known as *Obolus* Sandstone, *Dictyonema* Shale and Glauconite Sandstone. The material originates from more than 40 outcrops in northern Estonia and Ingria and 10 core sections in Estonia. Thirty-seven species (32 named) are described, assigned to 26 named genera, of which an obolid genus *Estoniobolus* is new. Middle Cambrian - Hunnebergian localities, lithostratigraphy and biostratigraphy are reviewed. Seven lingulate zones, defined by the first appearance of the zonal species, are distinguished (in ascending order): *Obolus ruchini*, *O. transversus*, *Ungula inornata*, *U. convexa*, *U. ingrica*, *Obolus apollinis*, "*Eurytreta*" and *Thysanotos siluricus* zones. The implications of the taxonomical revision of the traditional index species *Obolus apollinis* Eichwald and *Thysanotos siluricus* (Eichwald) to biostratigraphical correlation in East European Platform and adjacent areas are discussed.
[]*Brachiopoda, Lingulata, Lingulida, Siphonotretida, Acrotretida, new genus, ESTONIOBOLUS, Middle Cambrian, Upper Cambrian, Lower Ordovician, Tremadoc, Arenig, biostratigraphy, Estonia, Russia.*

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DISCLAIMER

This manuscript is produced as a part of a doctoral thesis.
It is not a publication in the sense of the International Code of Zoological Nomenclature.

CONTENTS

INTRODUCTION

Lingulate brachiopods (Phylum Brachiopoda, class Lingulata Goryanskij & Popov, 1985) are among the commonest macrofossils in the Middle Cambrian - Lower Ordovician clastic rocks of Estonia and northwestern Russia. Lingulate-rich Cambrian-Ordovician sands and weakly-cemented sandstones, alternating with black shales and clays and overlain by Lower Ordovician carbonate rocks crop out along a cliff extending from northwestern Estonia to Lake Ladoga (Fig. 1; Raymond 1916; Tammekann 1940; Kaljo *et al.* 1986; Popov *et al.* 1989).

Lingulates are most abundant in two parts of this clastic succession, traditionally referred to as the *Obolus* or Ungulite Sand(stone) and the Glauconite Sand(stone) (Pander 1830;

Schmidt 1858, 1879, 1881; Mickwitz 1896; Öpik 1928a,b, 1929). Black shales, known as the *Dictyonema* Shale and greenish- grey clays rest between the underlying, *Obolus* Sandstone and the overlying, Glauconite Sandstone (Fig. 4).

Lingulate coquinas in the *Obolus* Sandstone form unique deposits of shelly phosphorite (Notholt 1980; Puura 1987; Popov *et al.* 1989; Heinsalu 1990, 1992), traditionally known as the *Obolus* phosphorite (Öpik 1928b, 1929). In the Glauconite Sandstone, lingulates are not as abundant, but they are still very common (Goryanskij 1969), and dominate among the benthic fossils. Rare lingulate brachiopods have been found recently from the *Dictyonema* Shale and the greenish-gray clays (Popov *et al.* 1989). At present, the oldest part of the *Obolus* Sandstone in Ingria (St. Petersburg district of Russia - also known by its Swedish name Ingermanland) is referred to the Middle Cambrian and the youngest part of the clastic succession, the Glauconite Sandstone, to the Lower Ordovician Hunneberg Stage. The history of stratigraphical subdivision of the Cambrian and Ordovician in Estonia and Ingria has been recently discussed in detail by Mens (1986), Männil (1986) and Popov *et al.* (1989). Recent studies have demonstrated the utility of lingulate brachiopods for the correlation of the Cambrian-Ordovician boundary beds across Baltoscandia (Popov *et al.* 1989; Holmer & Popov 1990; Puura & Holmer 1993) and, in some cases, for inter-regional correlations (Popov & Holmer 1994).

The present study examines the systematics and biostratigraphy of the Middle Cambrian - Lower Ordovician (Hunneberg) lingulate brachiopods from Estonia and Ingria. Most of the taxa described here are known since the last century as elements of the *Obolus* and *Thysanotos* faunas, including the type species of many lingulate genera. Historical reviews of the study of Baltoscandian Cambrian-Ordovician lingulate brachiopods have been published by Goryanskij (1969), Holmer (1989), Puura (1990) and Puura & Holmer (1993). Recent studies, notably by Goryanskij (1969) and Popov & Khazanovitch (1989), have considerably advanced our knowledge of the taxonomy and distribution of these fossils. Closely related faunas have been documented from approximately coeval strata in Scandinavia (Holmer & Popov 1990; Puura & Holmer 1993; Popov & Holmer 1994), Poland (Bednarczyk 1964; Biernat 1964, 1973), Bohemia (Havlicek 1982) and South Urals (Popov & Holmer 1994).

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MATERIAL AND METHODS

The brachiopods on which this work is based were collected from more than 40 outcrops in Estonia and Ingria and 10 drill cores in Estonia (Fig. 1). Many of the studied species occur in abundance in coquinas; an estimated total number of specimens collected exceeds 10000. Most of the field and laboratory work was carried out within a larger framework of biostratigraphical studies of the Cambrian-Ordovician boundary beds of Estonia, in close co- operation with Estonian colleagues specializing in graptolites (D. Kaljo), conodonts (V. Viira), acritarchs (I. Paalits), mineralogy and lithology (K. Mens, H. Heinsalu and T. Oja). Additional material was collected during three field trips to Ingria. Macroscopic lingulates were obtained by direct sampling of outcrops and core sections. From coquinas in soft sands and sandstones, brachiopod valves were extracted by wet sieving where water was available. Microscopic brachiopods were obtained mostly from sieved fractions of samples of clastic rocks processed for conodont studies and grain size analysis. The specimens from the sands and weakly-cemented sandstones were prepared mechanically with needles. The specimens from carbonate-cemented quartzose rocks were etched by weak (10%) acetic acid. The study of this newly collected material was complemented by examination of existing collections in Estonia, Sweden and Russia (see Systematic Palaeontology). Scanning electron microscopy (SEM) studies were carried out by means of a PHILIPS SEM at Uppsala University, using digital image handling.

GEOLOGICAL SETTING

The study area (Figs 1-3), including Estonia and Ingria, is situated in the northwestern part of the East European Platform. Structurally, it includes northern parts of the southeastern and southern slopes of the present Fennoscandian Shield, extending to the Moscow Syneclise in the southeast and to the northern flanks of the Baltic Syneclise and the Latvian Saddle, bordered by the Valmiera-Lokno Uplift in the south (Puura 1974; Sildvee & Vaher 1995). The boundary between the Fennoscandian Shield and its southern slope is tentatively determined by the northern limit of sedimentary rocks, and it runs through the Gulf of Finland and north of St. Petersburg towards Lake Ladoga (Fig. 2). South of this boundary, the Proterozoic crystalline basement is covered by Neoproterozoic (Vendian) to Devonian sedimentary rocks, cropping out as successively younger sublatitudinal belts, owing to a very gentle dip (0.1-0.3^{o}) to the south in Estonia (Puura & Mardla 1972; Sildvee & Vaher 1995, Figs. 5,6) and to the south-south- east in Ingria (Puura 1974; Tuuling 1988) and the Baltic

Sea floor west of Estonia (Tuuling *et al.* 1995). The Quaternary cover is of variable thickness, usually not exceeding 10 m in northern Estonia and Ingria, where the Cambrian and Ordovician rocks crop out.

Most of the outcrops of Cambrian-Lower Ordovician rocks (Fig. 1) are aligned along a cliff extending from Paldiski in northwestern Estonia to Lake Ladoga in Russia (Raymond 1916; Tammekann 1940; Kaljo *et al.* 1986; Popov *et al.* 1989). In the literature on regional geology, the cliff has been invariably referred to as 'the clint' (also glint and klint; see Martinsson (1958) for etymological discussion), and for consistency, this usage is followed here. The clint has developed into a steep and clearly marked coastal terrace along the south coast of the Gulf of Finland. In Ingria, it continues as a less distinct land- terrace observable in various places. The same escarpment continues westwards from Paldiski; it has been traced by seismostratigraphy on the sea floor and is exposed along the western coast of the island of Öland, Sweden (Martinsson 1958; Flodén 1980; Tuuling *et al.* 1995).

In general terms, the correlation of the Cambrian and Ordovician rocks of Estonia and Ingria with the coeval strata in Scandinavia is well established (Mens *et al.* 1990; Männil & Meidla 1994). This has allowed reconstructions of Cambrian- Ordovician facies distribution in successive Baltoscandian palaeobasins. Lithofacies maps have been compiled for the Vendian and Lower Cambrian (Rozanov & Lydka 1987), Upper Cambrian - Tremadoc (Heinsalu 1986) and 21 successive stages of basin development in the Ordovician (Männil 1966). Schematic reconstructions show areas of deposition in the Early and Middle Cambrian (Hagenfeldt 1989) and lithofacies distribution in the Upper Cambrian (Mens *et al.* 1993) and late Tremadoc (Erdtmann & Paalits 1994).

The deposition area of the Middle Cambrian - Tremadoc *Obolus* sands represented a shallow epicontinental basin, resting on an almost even surface of up to 150 m thick Vendian and Early Cambrian soft clastic sediments, covering the nearly horizontal surface of the Proterozoic crystalline basement (Puura *et al.* 1987). The Upper Cambrian and earliest Ordovician sandstone and siltstone facies with abundant lingulate brachiopods occur in northern Estonia and Ingria (Männil 1966, Fig. 48; Mens *et al.* 1993, Fig. 1; Heinsalu 1986, Fig. 1). The approximately coeval rocks of the western part of the basin, including the Oslo graben, Scania and southern Öland are represented mostly by alum shales (Mens *et al.* 1987; 1990; 1993), with occasional stinkstone lenses yielding trilobites and conodonts (Bruton *et al.* 1988; Müller & Hinz 1991 and references therein), and, occasionally, phosphatized poorly sclerotised arthropods (Walossek 1993 and references therein). The sandstone interbeds in the Upper Cambrian alum shales and the Ordovician basal conglomerates of Tremadoc and Early Arenig age in Scandinavia have yielded lingulate brachiopods known from the coquinas of Estonia and Ingria (Holmer & Popov 1990; Puura & Holmer 1993). The post-Tremadoc configuration of the Baltoscandian palaeobasin is expressed in the concept of confacies belts (Jaanusson 1976, 1995; Jaanusson & Bergström 1980; Fig. 3 herein). The lithofacies map for the Hunneberg time has been compiled by Männil (1966, Fig. 50). The Hunneberg *Thysanotos* fauna is confined to the facies of glauconite sand distributed in the eastern part of the palaeobasin, being mostly restricted to western Estonia.

MIDDLE CAMBRIAN - LOWER ORDOVICIAN CHRONOSTRATIGRAPHY IN BALTOSCANDIA

In the East European Platform (EEP), where the Middle Cambrian rests unconformably on the Lower Cambrian, the base of the *Eccaparadoxides oelandicus* Stage is considered as the base of the Middle Cambrian, and the base of the *Agnostus pisiformis* Biozone as the base of the Upper Cambrian (Mens *et al.* 1987, 1990).

The position of the global Cambrian-Ordovician boundary is currently being discussed by the Cambrian-Ordovician Boundary Working Group. A recent proposal supports the first appearance of *Iapetognathus* sp. n. A (*sensu* Nowlan & Nicoll 1995) in the Dayangcha section, China, as the boundary criterion (Webby 1995). This level is considered to be close to the appearance of the earliest nema-bearing graptolites of the *Rhabdinopora flabelliformis* complex, defining the base of both the Tremadoc Series and the Ordovician System in its historical type area (e.g., Rushton 1982; Fortey 1995; Fortey *et al.* 1995). In view of the ongoing discussion, the position of the Cambrian-Ordovician boundary in the sections described herein is left open. However, for consistency and clarity through this paper, the tentative Cambrian-Ordovician boundary in the EEP is drawn at the base of the *Cordylodus lindstromi* Biozone. This is the closest regionally traceable level approximating to the first appearances of *Iapetognathus* and *Rhabdinopora* (Kaljo *et al.* 1986, 1988).

The base of the *Tetragraptus approximatus* graptolite Biozone, approximating to a level near the base of the British Arenig Series (Fortey 1995; Fortey *et al.* 1995) has been approved as the base of the second Ordovician series in 1992, while the discussion on the boundary stratotype continues (Webby 1995). According to Maletz *et al.* (1995) this level coincides roughly with the base of the Baltoscandian *T. phyllograptoides* Biozone and lies within the *Paroistodus proteus* conodont Biozone.

Modern Lower Palaeozoic stratigraphic classification of Estonia and correlative sequences elsewhere in Baltoscandia follows the traditions established by Schmidt (1858, 1879, 1881, 1882, 1897) who introduced formally named and indexed chronostratigraphic units, most of which represented well-defined faunal assemblage zones. The concept of regional stages derived from Schmidt's system is consistently used in the Ordovician stratigraphy of the EEP (Männil 1990; Männil & Meidla 1994). In spite of the attempts to develop a similar stage subdivision for the Middle and Upper Cambrian on the basis of East Baltic and Ukrainian subsurface sections (e.g., Spiharskij *et al.* 1983; Volkova & Kir'yanov 1995), the only widely accepted subdivisions of this interval are the trilobite biozones of Scandinavia (e.g., Westergård 1922; Mens *et al.* 1990).

The present study deals with the stratigraphic interval including the Middle and Upper Cambrian, and the Pakerort, Varangu and Hunneberg Stages of the Lower Ordovician, as defined in Männil (1990) and Männil & Meidla (1994). Following Jaanusson (1982) and Hints *et al.* (1994), the former Hunneberg and Billingen Substages of the Latorp Stage (e.g., Jaanusson 1960; Männil 1990; Männil & Meidla 1994) are here regarded as separate stages. The current status of the boundaries of the above named Ordovician stages (Fig. 4) can be briefly summarized as follows.

The lower boundary of the **Pakerort Stage** is tentatively drawn at the base of the *Cordylodus andresi* Biozone (Männil 1987, 1990; Männil & Meidla 1994).

The base of the **Varangu Stage** is below that of the *Clonograptus sarmentosus* Biozone (Männil 1990; Männil & Meidla 1994), approximating to the base of the *Paroistodus deltifer pristinus* Biozone (e.g., Erdtmann 1995).

The base of the **Hunneberg Stage** is defined as coinciding with the base of the *Megistaspis armata* Biozone (Tjernvik 1956; Jaanusson 1982); this level approximates to the base of the *Paroistodus proteus* Biozone (Löfgren 1993a, 1994, 1996).

The base of the **Billingen Stage** approximates to the base of the *Didymograptus balticus* Biozone (Jaanusson 1982; Männil 1990).

LITHOSTRATIGRAPHY IN ESTONIA AND INGRIA

The correlation charts for the Cambrian and Ordovician of the EEP (Mens *et al.* 1987; Männil 1987) and their English editions (Mens *et al.* 1990 and Männil & Meidla 1994, respectively) include summaries of Cambrian-Ordovician lithostratigraphical units. Since the Middle Cambrian - Hunneberg stratigraphy of Estonia and Ingria has been considerably revised after the compilation of these charts (e.g., Popov *et al.* 1989; Mens 1992; Mens *et al.* 1993; Hints *et al.* 1993; Dronov *et al.* 1995), an updated review of the Middle Cambrian - Hunnebergian lithostratigraphical units (Fig. 4) is provided here.

Estonia

MIDDLE(?) CAMBRIAN

Due to the lack of biostratigraphical evidence, the occurrence of Middle Cambrian strata in Estonia remains disputable. Possible Middle Cambrian age has been suggested for the **Ruhnu Formation** in south-western Estonia (Kala *et al.* 1984; Mens 1992), tentatively correlated with Deimena Superformation in Latvia and for **Paala, Elva** and **Raudna beds** in south-eastern Estonia (Mens *et al.* 1990, p. 40; Pirrus 1991; Mens & Pirrus 1992; Mens 1992). The possible Middle Cambrian age of the latter three units is based on lithostratigraphical correlation with the upper part of the Cirma Superformation in Latvia, that has yielded Middle Cambrian acritarchs (Volkova 1983).

UPPER CAMBRIAN

Petseri Formation
(Kajak 1967)

Main lithologies. - Fine- and medium-grained sandstones and siltstones.

Stratotype. - Petseri-330 core, depth interval 446.6-457.3 m; right bank of the Piusa river (Fig. 1A), north of Petseri (Kajak 1967).

Definition. - The Petseri Formation was introduced by Kajak (1967) and described in detail by Volkova *et al.* (1981). The lower and upper boundaries of the Petseri Formation are marked by breaks in sedimentation. In Estonia, the Petseri Formation is underlain by the Paala Beds (Mens *et al.* 1990) and overlain by the Kallavere Formation or younger units. The Petseri Formation occurs in the subsurface of SE Estonia, NE Latvia (overlying the Cirma Formation) and northern part of the Pskov region, Russia (overlying the Sablinka Formation); its maximum thickness, 11 m, is documented in the stratotype core.

Fauna, flora and age. - The correlation of the upper part of the Petseri Formation with the *Olenus* trilobite Biozone has been established by acritarchs indicating a early Late Cambrian age (Volkova *et al.* 1981; Paalits 1992a). The Petseri Formation has tentatively been correlated with the uppermost *Agnostus pisiformis* and *Olenus* biozones (Mens *et al.* 1990, 1993).

Ülgase Formation
(Müürisepp 1958a)

Previously termed. - *Obolus* sandstone (in part), zone with *Acrotreta*, Ülgase Member).

Main lithologies. - Light-grey, coarse-grained siltstones and fine-grained sandstones with intercalations of greenish-grey and brownish-grey clay.

Stratotype. - An outcrop north of Ülgase village, 10 km east of Tallinn, close to the ruins of the "Eesti Vosvoriit" factory (Fig. 1B; Fig. 23, right column).

Definition. - This unit, earlier considered as a part of the *Obolus* Sandstone (Schmidt 1858, 1881), was first recognized as an independent stratigraphical subdivision by Öpik (1928a) who referred it to the zone with "*Acrotreta*" (= *Ceratreta*). The unit was introduced by Müürisepp (1958a, 1960) as the Ülgase Member, named after the Ülgase village, 10 km east of Tallinn, and given the rank of formation by Khazanovitch & Missarzhevskij (1982, p. 7). The Ülgase Formation overlies unconformably the Lower Cambrian Tiskre Formation (Mens *et al.* 1990) and is overlain by the Kallavere Formation (Figs 4, 18, 19, 23). The Ülgase Formation occurs in a restricted area in the environs of Tallinn, northern Estonia; its maximum thickness reaches 10 m.

Fauna, flora and age. - The Late Cambrian age of the Ülgase Formation was established by an acritarch assemblage tentatively correlated with the *Olenus* Biozone (Volkova 1982; Volkova & Mens 1988). Characteristic lingulate brachiopods are *Ungula inornata*, *Ceratreta tanneri*, *Oepikites fragilis* and *Angulotreta postapicalis* (Kaljo *et al.* 1986; Popov *et al.* 1989; Puura & Holmer 1993; this study).

Tsitre Formation
(Popov & Khazanovich 1985)

Previously termed. - Maardu Member (in part).

Main lithologies. - Fine-grained quartz sandstone and siltstone, with thin interbeds of shale.

Stratotype. - Outcrop at the waterfall on the Turjekelder Brook, northern Estonia (Figs 1A, 27).

Definition. - The Tsitre Formation was established by Popov & Khazanovitch (1985). It is distributed in a restricted area in northern Estonia, in the outcrops along the clint near Turjekelder Brook and Saka village (Figs 27, 30), and recorded in drill cores south of the clint (Figs 24, 31). The Tsitre Formation rests unconformably on the Lower Cambrian Tiskre Formation or Upper Cambrian Ülgase Formation and is overlain by the Kallavere Formation (Popov *et al.* 1989).

Fauna, flora and age. - Characteristic conodonts are *Furnishina* cf. *furnishi*, *Muellerodus* sp., *Prooneotodus* cf. *gallatini*, *Westergaardodina bicuspidata* and characteristic lingulate species *Ungula convexa*, *U. ingrica*, *Oepikites obtusus*, *Schmidtites celatus* (Popov *et al.* 1989, Puura & Holmer 1993; this study).

UPPER CAMBRIAN - LOWER ORDOVICIAN

Kallavere Formation

(Ulst & Gailite 1976)

Previosly termed. - A2 (in part), Packerort Formation (in part), Ungulitensand (in part), zone with obolid valves ("phosphorite"), Obolensandstein.

Main lithologies. - Sandstones and siltstones, with intercalations of kerogenous shale.

Stratotype. - Outcrop (Fig. 23, left column) at the escarpment near the ruins of the "Eesti Vosvoriit" factory, near Ülgase village, 2 km NE from the Kallavere village (Fig. 1B).

Definition. - The Kallavere Formation corresponds to the upper part of the unit A2, or Ungulitensand of Schmidt (1881), lower part of the Packerort Formation of Raymond and the zone with obolid valves, or Obolensandstein of Öpik (1928a,b, 1929). The name of the Kallavere Formation was first published by Ulst & Gailite (1976, p. 56); the name was proposed by R. Männil and A. Rõõmusoks (see Mens *et al.* 1990, p. 27) as a contribution to the stratigraphical correlation chart for the East Baltic (Grigelis 1978; Männil & Rõõmusoks 1984). As originally defined, the Kallavere Formation corresponded to the upper part of the *Obolus* Sandstone of Schmidt (1858, 1881) and the *Obolus* Sandstone of Mickwitz (1888, 1896 and Öpik 1928a) and included the Ülgase and Maardu members (Müürisepp 1958a), and the Suurjõgi and Orasoja members (Loog 1964).

Following the suggestion of Khazanovitch & Missarzhevskij (1982), the Ülgase Member was excluded from the Kallavere Formation and assigned the rank of formation.

The sandstones of the Kallavere Formation overlie the sandstones of the Ülgase and Tsitre formations or the Lower Cambrian Tiskre Formation (Mens *et al.* 1990). The lower boundary of the Kallavere Formation is marked by a discontinuity surface, often covered with a characteristic basal conglomerate composed of phosphatic pebbles and fragments of lingulate brachiopod valves. The upper boundary with the overlying kerogenous shale of the Türisalu Formation is distinct.

Subdivision. - The Kallavere Formation is subdivided into the Maardu, Suurjõgi, Orasoja, Rannu and Katela members (Heinsalu 1987; Männil & Meidla 1994, p. 25, Fig. 2).

The **Maardu Member**, introduced by Müürisepp (1958), is represented by varigrained sandstones with interbeds of lingulate brachiopod coquinas and kerogenous shale. As the stratotype in Maardu Quarry described by Loog & Kivimägi (1968) was subsequently destroyed in the course of mining, Heinsalu *et al.* (1987) introduced an outcrop near Ülgase village, 10 km east of Tallinn as a neostratotype of the Maardu Member (Fig. 23, left column).

The **Suurjõgi Member**, introduced by Loog (1964), is represented by medium-grained, cross-bedded quartz-sandstone, containing lingulate brachiopod debris, with intercalations of kerogenous shale. The stratotype of the member on the left bank of the Suurjõgi River (Fig. 28, right column), was selected by Loog & Kivimägi (1968).

The **Orasoja Member**, introduced by Loog (1964), is characterized by coarse-grained quartzose siltstones, with intercalations of kerogenous shale. The stratotype, an outcrop on the right bank of the Orasoja Brook in Puhkova village, was described by Loog & Kivimägi (1968).

The **Rannu Member**, introduced by Heinsalu (1987), is represented by sandstones with interbeds of kerogenous shale. The Saka section (Fig. 30), 1 km west of Saka village, northeastern Estonia (Fig. 1A), has been subsequently selected as the stratotype of the member (Heinsalu *et al.* 1991b).

The **Katela Member** introduced by Heinsalu (1987), is characterized by quartzose siltstones, with thin intercalations of graptolitic shale. Heinsalu (1987) selected the stratotype on the left bank of the Suurjõgi River, near the Vihula village (Fig. 28, left column).

Fauna and age. - Conodont, acritarch and graptolite data indicate that the base of the *Cordylodus lindstromi* Biozone, approximating to the Cambrian-Ordovician boundary, lies within the Kallavere Formation. The stratigraphically oldest part of the formation is the basal part of the Maardu Member, exposed in the Ülgase section, where the interval between the lower and upper coquina may correspond to the *Cordylodus andresi* Biozone or even to the *Westergaardodina* Biozone (Heinsalu *et al.* 1987). The conodonts from the Suurjõgi Member correspond to the *Cordylodus angulatus* Biozone indicating the earliest Tremadoc age. The Rannu Member is considered by Heinsalu *et al.* (1991) as roughly coeval to the Maardu and Suurjõgi members: in the stratotype, the lower part of the section is assigned to the *Cordylodus proavus* Biozone, while *Iapetognathus* sp. appears in the middle part of the section. The Orasoja Member, overlying the Rannu Member in the sequences east of Kunda, has yielded *Rhabdinopora flabelliformis flabelliformis*, *R. f. socialis*, *R. f. desmograptoides*, *R. f. anglicum* and *R. f. multithecatum* (Heinsalu 1987). According to the interpretation of Heinsalu (1987), the Katela Member, that has yielded *Rhabdinopora f. multithecatum*, is approximately coeval with the Orasoja Member.

Characteristic lingulate brachiopods occurring in the Kallavere Formation include *Ungula ingrica*, *Schmidtites celatus*, and *Keyserlingia buchii* (Kaljo *et al.* 1986; Popov *et al.* 1989; this study).

LOWER ORDOVICIAN

Türisalu Formation

(Müürisepp 1958)

Previously termed. - Alaunschiefer, A3, Dictyonema Schiefer, *Dictyonema* Shale, Türisalu Member.

Main lithologies. - Black kerogenous shale, with thin intercalations of siltstones.

Definition. - The sequence of black shale overlying the *Obolus* Sandstone (Kallavere Formation) and underlying the Glauconite Sandstone was recognized as Alaunschiefer (Schmidt 1858), unit A3, or *Dictyonema* Schiefer by Schmidt (1879, 1881). Raymond (1916) observed that the *Obolus* Sandstone and *Dictyonema* Shale are often interfingering and stratigraphically inseparable and included both units in his Packerort Formation. Müürisepp (1958) introduced the name Türisalu Member for a unit approximately corresponding to the *Dictyonema* Shale of Schmidt. The stratotype, a coastal section near Türisalu village, 25 km east of Tallinn, was subsequently described by Loog & Kivimägi (1968). Heinsalu (1987) gave the unit the rank of formation.

Subdivision. - Heinsalu (1980, 1987) subdivided the Türisalu Formation into the Tabasalu and Toolse members.

The **Tabasalu Member** is represented by a monotonous sequence of dark-brown kerogenous shale, with thin intercalations of siltstone. Heinsalu (1987) selected a coastal sequence at Rannamõisa, near Tabasalu village, 10 km east of Tallinn, as the stratotype of the member.

The **Toolse Member**, introduced by Heinsalu (1980), is represented by black shale, with intercalations of quartzose siltstones, commonly yielding concretions of pyrite and anthraconite. Heinsalu (1987) selected the interval of 19.2-21.2 m of the core 404 drilled in the area of the Toolse Deposit (stratigraphical column in Kaljo & Kivimägi 1976, Fig. 1) as the stratotype of the Toolse Member.

Fauna and age. - In the core sections of northwestern Estonia, the Tabasalu Member yielded conodonts of the *Cordylodus angulatus* and *Drepanoistodus deltifer pristinus* zones, and graptolites *Rhabdinopora flabelliformis socialis* and *R. f. flabelliformis* appearing in the upper half of the shale sequence, whilst in the eastern sections, such as Valkla, *Adelograptus* sp. has been recorded (Kaljo & Kivimägi 1970, 1976; Kaljo & Viira 1988).

The Toolse Member has yielded graptolites of *Clonograptus sarmentosus* Biozone and conodonts of the *Drepanoistodus deltifer deltifer* Biozone (Kaljo & Kivimägi 1976). Accordingly, in the western sections, the tentative Cambrian-Ordovician boundary may be below, or within the Tabasalu Member. In northeastern Estonia, the Türisalu Formation belongs to the Varangu Stage. The uppermost part of the Türisalu Formation in subsurface of northeastern Estonia (Fig. 33) has yielded rare lingulate brachiopods *Eurytreta?* sp. (this study).

Varangu Formation
(Männil *in* Aaloe *et al.* 1958)

Previously termed. - Glauconite clay, Varangu Member.

Main lithologies. - Compact, mostly greenish-grey silty clays with intercalations of glauconite sandstone.

Stratotype. - A section on a bank of the Selja River, near Varangu village, 90 km east of Tallinn (Viira *et al.* 1970, Fig. 4).

Definition. - The unit was first recognized as "strata of glauconitic clay" by Luha (1946) and named by Männil (*in* Aaloe *et al.*, 1958) as the Varangu Member. The stratotype is described in detail by Viira *et al.* (1970). The Varangu Formation, up to 3 m thick, rests on the kerogenous shales of the Türisalu Formation and is overlain by the glauconitic sand of the Leetse Formation.

Fauna and age. - The Varangu Formation has yielded the conodonts *Drepanoistodus deltifer pristinus*, *D. deltifer deltifer*, *Paroistodus numarcuatus*, "*Oneotodus*" *variabilis* and *Cordylodus angulatus* (Viira 1970; Viira *et al.* 1970; Mens & Puura 1996), and the graptolites *Clonograptus* cf. *tenellus*, *Bryograptus* cf. *broeggeri* and *Adelograptus* sp. (Kaljo & Kivimägi 1976). Rare lingulate brachiopods *Lingulella* aff. *tetragona* (= ?*Expellobolus?* sp.) have been reported (Popov & Khazanovitch, 1989). The Varangu Formation belongs to the Varangu Stage.

Leetse Formation
(Rõõmusoks 1956)

Previously termed. - Grünsand, B1, Glauconite Sand(stone), Leetse Stage.

Main lithologies. - Greyish-green glauconitic silts, sands and calcareous sandstones.

Stratotype. - A coastal section near Leetse village, Pakri Peninsula, 35 km west of Tallinn.

Definition and subdivision - The glauconitic sandstone overlying the kerogenous *Dictyonema* shale was defined as Grünsand by Schmidt (1858) and assigned to unit A2, or Glauconite Sand by Schmidt (1879, 1881). Rõõmusoks (1956) assigned this interval of glauconitic sandstones to the Leetse Stage; subsequently it has been considered as a formation (Grigelis 1978).

In the current usage, the Leetse Formation in northern Estonia includes the Klooga and Joa members, equivalent to the Glauconite Sand and the overlying strongly lithified, occasionally carbonate-cemented glauconite sandstones of the Mäeküla Member (Männil & Meidla 1994).

The **Klooga Member** was introduced by Mägi (1970), with the Klooga core No. 119 as the stratotype, where its thickness reaches 1.8 m. The member is composed of greenish-grey, very poorly lithified quartzose glauconite sands. According to Mägi (1970), the Klooga Member differs from the overlying Joa Member by higher quartz and lower glauconite content and is distributed in northwestern Estonia. The maximum thickness of the Klooga Member is 2.9 m (Männil & Meidla 1994)

The **Joa Member** corresponds in the current usage to the upper part of the Glauconite Sand. In its original usage, the Joa Substage of Männil (in Aaloe *et al.* 1958), equivalent to the Iru Substage of Rõõmusoks (1956) corresponded to the Glauconite Sand in its full extent. After Mägi (1970) introduced the Klooga Member, the name Joa Member has been used for the upper part of the Glauconite Sand. The stratotype of the Joa Member is the Keila-Joa section (FIg. 15), at the waterfall on the Keila River, 20 km west of Tallinn. The member is represented by very poorly lithified glauconite sand. The thickness is up to 1.2 m.

The Mäeküla Member, corresponding to the unit $B_{I}\beta$ of Lamansky (1905), was named by Öpik (1933, 1934) as "Mäeküla Schichten". This up to 0.5 m thick unit is composed of strongly lithified, occasionally carbonate-cemented and/or nodular glauconite sandstones with intercalations of clays. Lithologically, it represents a transition between the underlying Joa and the overlying Päite Member, and its boundaries are often indistinct. The member is composed of moderately to strongly cemented glauconitic sandstones and calcareous glauconitic sandstones. The Mäeküla cliff section near Tallinn, was selected by Rõõmusoks (1983) as the stratotype of the Mäeküla Member. The thickness is up to 0.5 m.

Fauna and age. - The faunas of the Klooga and Joa members show no notable differences. In these two members, the conodonts are represented by *Paroistodus proteus*, indicative of the *Paroistodus proteus* Biozone. The commonest lingulate brachiopods are *Thysanotos siluricus*, *Leptembolon lingulaeformis*, *Foveola maarduensis*, *Eosiphonotreta acrotretomorpha*, *Schizambon? esthonia* and *Semitreta? magna*. The Klooga and Joa members are assigned to the Hunneberg Stage. In some sections, such as Suhkrumägi (Viira 1966), Keila-Joa (Mägi & Viira 1976; Mägi *et al.* 1989) and Mäekalda (Einasto *et al.* 1996), the uppermost 0.1-0.2 m of the Joa Member has yielded conodonts of the *Prioniodus elegans* Zone, and is assigned to the Billingen Stage.

In the Mäeküla Member conodonts are represented by *Prioniodus elegans*, *Oistodus* *lanceloatus*, with *Oepikodus evae* and *Periodon flabellum* appearing in its upper part (Viira *et al.* 1970; Einasto *et al.* 1996). A rich benthic fauna of the Mäeküla Member includes trilobites (Mägi *et al.* 1989) and strophomenid, orthid and pentamerid brachiopods (Öpik 1933, 1934; Rubel 1961; Popov & Rubel 1994).

Ingria, northwestern Russia

MIDDLE CAMBRIAN
Sablinka Formation
(Rukhin, 1939)

Previously termed. - Izhora sandstone (in part).

Main lithologies. - Fine-grained quartzose sandstones with thin (less than 10 cm) intercalations of clays and siltstones, sometimes with coarse-grained sandstones near the base.

Stratotype. - Left bank of the Izhora River, near the mouth of the Sablinka Brook and Samsonovka village, 100 m upstream from the ruins of a water mill (Borovko *et al.* 1984; outcrop B-2 of Popov *et al.* 1989, Fig. 5).

Definition. - The unit was introduced by Rukhin (1939) who named it after Sablinka Brook, the left tributary of the Izhora River. It corresponds to the lower part of the Izhora Sandstone of Nekrasov (1938).

Subdivision. - Popov *et al.* (1989, p. 71) subdivided the Sablinka Formation into two unnamed subformations. In turn, the upper subformation was subdivided into the Gertovo and Rebrovo members. The **Gertovo Member**, introduced by Khazanovitch & Popov (*in* Khazanovitch *et al.* 1984) is represented by fine- to medium- grained, cross-bedded quartzose sandstones, with lingulate brachiopod debris. The stratotype, selected by Khazanovitch and Popov (in Khazanovitch *et al.* 1984), is a section on the left bank of the Tosna River, downstream of the Gertovo village (outcrop No. 789 of Popov *et al.* 1989, Fig. 4; Fig. 44 herein). The member is distributed near the clint between the Tosna and Volkhov rivers. The thickness of the member is variable, reaching 3.5 m.

The **Rebrovo Member**, introduced by Khazanovitch & Popov (*in* Khazanovitch *et al.* 1984), is represented by fine- to medium-grained, cross-bedded quartzose sandstones, with abundant lingulate brachiopod debris. The stratotype, selected by Khazanovitch & Popov (*in* Khazanovitch *et al.* 1984), is a section on the right bank of the Syas River, near the southern margin of the Rebrovo village (outcrop L-19 of Popov *et al.* 1989, Fig. 2; Fig. 49 herein). The maximum thickness of the member is 4.5 m.

West of the distribution area of the Gertovo and Rebrovo members, in the Luga River valley and in the area of the Kingisepp Quarry, up to 6.1 m thick quartzose sandstones, with quartzose gravel, are referred to the **Novolutsk Beds**, established by Popov and

Khazanovitch (1985). The stratotype selected by Popov and Khazanovitch (1985) is located on the right bank of the Luga River near Novyi Lutsk village (outcrop K-30 of Popov *et al.* 1989, Figs 11, 12; Fig. 37 herein).

Fauna, flora and age. - The Gertovo Member has yielded lingulate brachiopods *Obolus ruchini* and *Oepikites macilentus*, a bradoriid *Vojbokalina magnifica* and an acritarch assemblage including *Timofeevia phosporitica*, *T. lancarae* and *Cristallinium cambriense*; the Rebrovo Member has yielded lingulate brachiopods *Obolus transversus* and *Oepikites kolchanovi* (Popov *et al.* 1989). The Gertovo and Rebrovo members have been tentatively assigned to the Middle Cambrian. No fossils have been found from the Novolutsk Member.

UPPER CAMBRIAN

Ladoga Formation

(Rukhin 1939)

Main lithologies. - Light grey weakly cemented quartzose sandstones, with glauconitic nodules, quartz gravel and phosphatic pebbles.

Stratotype. - Left bank of the Izhora River, near the ruins of Samsonovka village, 100 m upstream of the ruins of a water mill; selected by Borovko *et al.* (1984); outcrop B-3 of Popov *et al.* (1989, Fig. 5; Fig. 42 herein).

Definition. - The Ladoga Formation was introduced by Rukhin (1939, p. 152); its Late Cambrian age was established by Borovko *et al.* (1980, 1984). The Ladoga Formation is underlain by the Sablinka Formation and overlain by the Tosna Formation. The Ladoga Formation is distributed as a narrow sublatitudinal belt near the clint from the Dudergoff Heights in the West to the Syas River in the East, reaching its maximum thickness, 3.8 m, in the valley of the Volkhov River.

Subdivision. - Popov *et al.* (1989) subdivided the Ladoga Formation into two unnamed subformations, lower and upper.

Fauna and age. - The lower subformation of the Ladoga Formation has yielded the conodonts *Furnishina alata*, *F. furnishi*, *Prooneotodus tenuis* and *Westergaardodina bicuspidata* and the lingulate brachiopods *Oepikites fragilis*, *Rebrovia chernetskae*, *Ceratreta tanneri*, *Gorchakovia granulata* (Popov *et al.* 1989; this study).

The upper subformation has yielded *Oepikites triquetrus*, *Rebrovia chernetskae*, *Ungula convexa*, *Ralfia ovata*, *Keyserlingia reversa*, and in its upper part, *Oepikites elongatus*, *Vassilkovia granulata* and *Keyserlingia buchii* (Popov *et al. 1989; this study). Two conodont assemblages have been distinguished from the upper subformation: the lower includes Furnishina furnishi*, *Problematoconites perforata*, *Proconodontus rotundatus*, *Prooneotodus* aff. *gallatini*, *P. tenuis*, *P. terashimai*, *Prosagittodontus dahlmani*, *Westergaardodina bicuspidata*, *W.* cf. *fossa* and *W. moessebergensis*, and the upper *Furnishina furnishi*, *F. alata*, *Proconodontus primitivus*, *P. rotundatus*, *Prooneotodus* aff. *gallatini*, *P. tenuis*, *Westergaardodina* fossa and *W. bicuspidata* (Popov *et al.* 1989).

Lomashka Formation
(Kaljo *et al.* 1986)

Main lithologies. - Fine-grained sandstones, occasionally with thin intercalations of kerogenous shale. Basal part characterized by coarse-grained quartz sandstones with accumulation of lingulate valves.

Stratotype. - Right bank of the Lomashka River, downstream of the Lomaha village (outcrop L-34 of Popov *et al.* 1989, figured as L-32 on Fig. 6; Fig. 40 herein).

Definition. - The Lomashka Formation introduced by Kaljo *et al.* (1986) rests on the Lower Cambrian Tiskre or Lükati formations and is overlain by the Tosna Formation. The Lomashka Formation, distributed in the western part of Ingria, reaches its maximum thickness, 2.2 m, in the stratotype.

Fauna and age. - The Lomashka Formation has yielded conodonts *Furnishina furnishi*, *Prooneotodus tenuis*, *Westergaardodina bicuspidata* and *Cordylodus andresi*, indicative of *C. andresi* Biozone. Lingulate brachiopods are represented by *Oepikites obtusus*, *Schmidtites celatus*, *Ungula ingrica* and *Rebrovia chernetskae* (Popov *et al.* 1989; this study).

UPPER CAMBRIAN - LOWER ORDOVICIAN
Tosna Formation
(Rukhin 1939)

Main lithologies. - Fine- to medium-grained quartzose sandstones containing lingulate valves and debris, with rare thin intercalations of greenish-grey silty clays.

Stratotype. - Outcrop on the left bank of Tosna River, upstream of the mouth of Sablinka Brook (outcrop L-11 of Popov *et al.* 1989, Fig. 4; Figs 43, 44 herein).

Definition. - The formation was introduced by Rukhin (1939); the stratotype was selected by Popov *et al.* (1989, p. 74). The eastern border of the distribution area of the Tosna Formation is the Syas River; in the West, it extends to the Narva River. According to Popov *et al.* (1989), the same beds extend westwards to Estonia, reaching the Orasoja Brook. However, for consistency, in Estonian territory these beds have been assigned to the Kallavere Formation. The Tosna Formation overlies the Ladoga Formation and underlies the Koporye Formation. Popov *et al.* (1989) have suggested the subdivision of the Tosna Formation into two unnamed subformations.

Fauna and age. - The lower subformation of the Tosna Formation has yielded lingulate brachiopods *Obolus apollinis* and *Helmersenia ladogensis* and conodonts of the *Cordylodus proavus* and *C. lindstromi* biozones, together with older species (Popov *et al.* 1989; this study). The trace fossil *Skolithos* is very common. The upper subformation has yielded conodonts of the *Cordylodus angulatus* Biozone and *Oneotodus altus*, together with older species (Popov *et al.* 1989).

LOWER ORDOVICIAN

Koporye Formation

(Balashova & Balashov 1959)

Previously termed. - Alum Shale, Koporye Substage.

Main lithologies. - Fine-grained sandstones and kerogenous shales.

Stratotype. - An outcrop on the right bank of the Lomashka river, downstream of the Lomaha village, 5 km SW of the Koporye village (outcrop L-34 of Popov *et al.* 1989, figured as L- 32 on Fig. 6; Fig. 40 herein).

Definition. - Pander (1830) regarded this interval as a separate unit, referring to it as Alum Shales. Balashova & Balashov (1959) assigned this unit to Koporye Substage. Borovko *et al.* (1983) elevated this unit in rank to a formation. The Koporye Formation is distributed as a narrow sublatitudinal belt along the clint, from the Luga River to the Syas River, reaching its maximum thickness, 5.4 m, in the valley of the Koporka River.

Popov *et al.* (1989) have suggested a subdivision of the Koporye Formation into two subformations. The lower subformation, represented by intercalating fine-grained sandstone, siltstone and kerogenous shale, is distributed between the Solka River and Gostilitsy village and in the Syas River valley. The upper subformation, represented by monotonous sequence of kerogenous shale with anthraconite and pyrite concretions, is distributed between the Solka and Syas rivers.

Fauna and age. - The Koporye Formation has yielded the conodonts *Cordylodus angulatus*, *C. lindstromi*, *C. prion* and *Oneotodus altus* (Popov *et al.* 1989) and graptolites *Rhabdinopora desmograptoides*, *R. multithecata*, *R. bryograptoides*, *R. rossica* and *Anisograptus* sp. (Kaljo & Kivimägi 1976). The lingulate brachiopods *Obolus apollinis* and *Helmersenia ladogensis* occur in the easternmost part of the distribution area of the formation (Popov *et al.* 1989).

Naziya Formation

(Borovko *et al.* 1983)

Main lithologies. - Greyish-green silty glauconitic clays, with thin intercalations of fine-grained glauconitic sandstones in the basal part.

Stratotype. - An outcrop on the right bank of the Naziya River, near the ruins of the Novyi village (outcrop L-10 of Popov *et al.* 1989, Fig. 4; Kaljo *et al.* 1986, Fig. 3; Fig. 45 herein).

Definition. - Introduced by Borovko *et al.* (1983). The Naziya Formation overlies the Koporye Formation and is overlain by glauconitic sandstones of the Hunneberg Stage. The Naziya Formation occurs in the area of Naziya and Lava rivers; its thickness reaches 0.4 m.

Fauna and age. - The Naziya Formation has yielded conodonts of the *Drepanodus deltifer pristinus* and *D. d. deltifer* Biozones, together with older species (Borovko *et al.* 1983; Popov *et al.* 1989). It is correlated to a part of the Varangu Formation in Estonia.

Leetse Formation

Definition and subdivision in Ingria. - The concept of the Leetse Formation in Ingria differs from that in Estonia. In Ingria, the Päite Member usually has been included within the Leetse Formation (Männil & Meidla 1994). The Leetse Formation is subdivided into the Lakity, Mäeküla, Vassilkovo and Päite members (Dronov *et al.* 1995, Fig. 2; Fig. 46 herein).

The **Lakity Member**, named after the nearby Lakity village, was introduced by Rubel & Popov (1994, p. 195); the stratigraphical column is provided by Dronov *et al.* (1995, Fig. 2; Fig. 46 herein). The member is represented by glauconitic sandstones and clays. In the Lava River section, the Lakity Member has yielded conodonts of the *Paroistodus proteus* and *Prioniodus elegans* zones, a lingulate brachiopod *Eosiphonotreta* cf. *acrotretomorpha*, and rare poorly preserved orthoid brachiopods *Ranorthis* sp. and *Paurorthis* sp. (Dronov *et al.* 1995, Fig. 2; L. Popov, pers. comm. 1996).

The fauna of the overlying **Mäeküla Member** in Ingria is similar to that in Estonia (Rubel 1961; Rubel & Popov 1994; Dronov *et al.* 1995, p. 319).

LOCALITIES

All localities are described from the base to the top. For the locality map, see Fig. 1. Legend for all stratigraphical columns and faunal logs is given in Fig. 5.

ESTONIA

Subsurface of Hiiumaa island and western Estonia

The presence of the Cambrian-Ordovician boundary beds in the subsurface of Hiiumaa island (previously known as Dagö) was recently discovered in cores drilled for the study of the Kärdla meteorite crater of Middle Ordovician (Idavere) age (Puura & Suuroja 1992) and geological mapping of Hiiumaa carried out by the Geological Survey of Estonia. Some cores outside the Kärdla crater rim (K-11 and Kidaste F-353) penetrated the sandstones of the Kallavere Formation yielding the lingulate brachiopods *Helmersenia ladogensis* and *Obolus apollinis*. The Kallavere Formation is overlain by kerogenous shales of the Türisalu Formation, distributed in northern Hiiumaa and reaching a thickness of 1 m. The overlying clays of the Varangu Formation, up to 0.6 m thick, have been recorded in the subsurface of southeastern Hiiumaa. The glauconitic sandstones of the Leetse Formation, eroded in most of the subsurface of Hiiumaa, have been recorded only in the cores drilled in southeastern part of the island. The thickness of the Leetse Formation increases southward, from 0.2 to 4 m (K. Suuroja, pers. comm., 1995). As yet, the only record of macrofossils from the Leetse Formation in the subsurface of the Hiiumaa region is a ventral valve of *Thysanotos siluricus* from the Kassari core No F-371, depth 168.3-168.35 m. This core has been drilled on the Kassari islet near the southeastern coast of Hiiumaa. The occurrence of *Thysanotos siluricus* is also documented in the core D-32 drilled SE of Haapsalu, in the western part of the mainland of Estonia.

Kidaste core No F-353. - The core (Fig. 6) drilled during the geological mapping of Hiiumaa reached the crystalline basement at the depth of 242 m. The sandstones of the Kallavere Formation overlie unconformably the greenish-grey siltstones and silty clays of the Lower Cambrian Irbeni Formation (depth interval 120.5-126.5) occurring at the top of an about 120 m thick sequence of Lower Cambrian clastic rocks.

UPPER CAMBRIAN

Pakerort Stage. Kallavere Formation.

Depth interval 114.5-120.5 m. Fine-grained sandstone, with intercalations of kerogenous argillite and fine lingulate brachiopod debris. The lower part of the formation, depth interval 118.7-120.5 m, yielding *Eoconodontus notchpeakensis* and *Cordylodus andresi*, has been referred to the *C. andresi* Biozone (Mens *et al.* 1993). The upper part of the formation, depth interval 114.5-118.7 m has yielded *Cordylodus proavus*. Complete valves of *Obolus apollinis* were found at the level 115.8 m.

UPPER CAMBRIAN AND/OR LOWER ORDOVICIAN

Pakerort Stage. Türisalu Formation.

Depth interval 114.0-114.5 m. Black kerogenous argillite.

The Türisalu Formation is overlain unconformably by the limestones of the Kunda Stage, while the Latorp and Volkhov stages are missing.

Core K-11, Kärdla airport. - The 86.4 m deep core (Fig. 7) drilled near Kärdla airport during the studies of the Kärdla crater has reached the lower Cambrian siltstones and clays of the Irbeni Formation (at the depth interval of 83.5-86.4 m), that are overlain by the sandstones of the Kallavere Formation. Conodonts from this core have not been studied as yet.

UPPER CAMBRIAN AND/OR LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation.

Depth interval 77.7-83.5 m. Light-grey fine-grained quartz sandstone with fine lingulate debris. Up to 10 cm thick intercalations of brownish-grey kerogenous argillite occur in the lower 2 m of the formation. The valves of a lingulate brachiopod *Helmersenia ladogensis* are very common in the depth interval 78.7-81.6 m.

Pakerort Stage. Türisalu Formation.
Depth interval 77.1-77.7 m. Dark-brown kerogenous argillite. The lower boundary is sharp, with pyrite concretions at the base. Anthraconite lenses occur in the uppermost 10 cm of the interval.

The Türisalu Formation is overlain unconformably by the limestones of the Kunda Stage, while the Latorp and Volkhov Stages are missing. Up-section follows the sequence of Middle and Upper Ordovician limestones, with the Nabala Stage in the uppermost part, overlain by 4 m thick Quaternary cover.

Core D-32 - The drilling site is located in western part of the mainland of Estonia, 15 km SE of the town of Haapsalu. The core (Fig. 8) has reached the sandstones of the Lower Cambrian Tiskre Formation in the depth of 211.2-217 m, which are overlain by the sandstones of the Kallavere Formation (depth interval 210.7-211.2 m) and the black shales of the Türisalu Formation (207.8-210.7 m). The overlying quartzose glauconite sandstone of the Leetse Formation (206.2-207.8 m) has yielded lingulate brachiopods *Thysanotos siluricus* at the level 207.3 m. Overlying are the limestones and dolomites of the Toila Formation (Volkhov Stage).

Osmussaar island

Osmussaar island (previously known as Odinsholm) is located about 90 km west of Tallinn. Lower Ordovician localities of Osmussaar were studied already by Eichwald (1860). The lower Ordovician sequence exposed along the eastern coast of the island has been described by Öpik (1927) and Puura & Tuuling (1988).

Osmussaar 410 core. - The geology of the subsurface of the island has been studied in this core drilled by Estonian Geological Survey under supervision of E. Kala in 1970 (Fig. 10). According to the description of L. Põlma published by Puura & Tuuling (1988), the core reached the crystalline basement at the depth of 169.7 m. Vendian (depth 111.3-169.7) and Lower Cambrian siltstones and sandstones (depth 18.8-111.3) are overlain by the pyritized quartzose sandstones of the Kallavere Formation occurring in the depth interval 18.6-18.8 m. In the depth interval 13.0-18.6 m follow kerogenous shales of the Türisalu, and in the depth interval 8.5-13 m green glauconitic sandstones of the Leetse Formation. The overlying beds contain clastic material, associated with the clastic dikes described by Öpik (1927) and Puura & Tuuling (1988).

The uppermost part of the Joa Member of the Leetse Formation is accessible in sections along the coastal cliff in the eastern part of the island when the sea water level is low. In a section on the eastern coast of Osmussaar, about 1 km south of the lighthouse (Figs 9, 10), the uppermost 0.4 m of the Joa Member has yielded lingulate brachiopods *Thysanotos siluricus* and *Leptembolon lingulaeformis*.

Pakri peninsula and Pakri islands

On Pakri peninsula, 50 km west of Tallinn, the Cambrian- Ordovician, the total thickness of the exposed Cambrian- Ordovician sequence, ranging from the Lower Cambrian Tiskre Formation to the Middle Ordovician Uhaku Stage reaches 24 m (Mens & Puura 1996). Inaccessible since the early 1960s because of military restrictions, Pakri peninsula became available for geological studies after August 1993, after the withdrawal of the Soviet troops from the navy base at Paldiski. Since then, some studies of the Pakerort Stage in the Pakri Cape section have been completed (Mens *et al.* 1996; Nemliher & Puura 1996; Mens & Puura 1996; Puura & Viira 1996), while the biostratigraphical study of the Hunneberg Stage is currently in progress.

The exposures of the Pakerort Stage are located near the promontory of the Pakri peninsula (Fig. 1B). A section at the lighthouse, described by Raymond (1916, p. 186, Plate 2) as "the most instructive section" for his Packerort Formation (sic!) is now considered as the stratotype of the Pakerort Stage (Hints *et al.* 1993; Männil & Meidla 1994).

Pakri Cape Section. - This section is located in the northeastern side of the Pakri peninsula, about 1 km east of its promontory (Fig. 12). The section has been described in detail by Mens *et al.* (1996); a concise description is given below.

LOWER CAMBRIAN
Tiskre Formation.
Exposed thickness 4 m. Light-grey sandy siltstones with intercalations of argillaceous siltstones and clays. Lower boundary not exposed.

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 2.75 m. Yellowish-grey, very fine to fine-grained quartzose sandstone, with intercalations of kerogenous argillite, occasionally cross-bedded, containing lingulate brachiopod debris. This interval has yielded the conodonts *Westergaardodina bicuspidata, Proconodontus rotundatus*, *Cordylodus andresi*, *C. primitivus*, *C. proavus*, *Cordylodus* sp. and *Eoconodontus notchpeakensis* and is considered to correspond to the *Cordylodus proavus* Biozone (Mens *et al.* 1996). The lower boundary is sharp, marked by the appearance of up to 0.25 m thick kerogenous argillite layer at the base. The basal part of the interval is varying along the coastal exposure: 200-300 m eastward of the described section, up to 0.5 m thick lenses of basal conglomerate (Fig. 11) containing sandstone cobbles, phosphatic pebbles and fragments of lingulate brachiopods (*Ungula ingrica* and *U. convexa*) have been observed

at the base of this interval (Nemliher & Puura 1996).

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 1.25 m. Yellowish-brown, fine to medium-grained, cross-bedded sandstone with very rare tiny shell fragments of lingulate brachiopods. Strongly pyritized sandstone lenses (referred to as "pyrite layer") occur in the uppermost 0.15 m of the interval. No conodonts have been found from this part of the section.

Pakerort Stage. Türisalu Formation. Tabasalu Member.

Thickness 4.5 m. Dark brown kerogenous argillite yielding *Rhabdinopora f. flabelliformis* and *R.* cf. *desmograptoides* in the basal part.

Paldiski. - The continuous coastal cliff section (Fig. 13) along the western side of the Pakri peninsula from the lighthouse towards the Paldiski port is about 2 km long. Descriptions of the composite section have been published by Raymond (1916), Öpik (1928a) and Müürisepp & Orviku (*in* Männil *et al.* 1958, p. 35); for the Varangu and Hunneberg stages by Mens & Puura (1996).

The siltstones and sandstones of the Tiskre Formation (4 m) and the Kallavere Formation (4.15 m) underlie the Türisalu Formation (Fig. 14).

LOWER ORDOVICIAN

Pakerort Stage. Türisalu Formation. Tabasalu Member.

Thickness 4.15 m. Dark-brown kerogenous argillite.

Varangu Stage. Varangu Formation.

Thickness 0.4 m. Greenish-grey, fine-grained sandstone and clay, with pyrite concretions and glauconite grains. This interval has yielded the conodonts *Drepanoistodus deltifer pristinus*, *Paroistodus numarcuatus*, *Cordylodus angulatus* and *Drepanoistodus deltifer* cf. *D.d. deltifer* (V. Viira *in* Mens & Puura 1996).

Hunneberg Stage. Leetse Formation. Joa Member.

Thickness 3.9 m. Greenish-grey, fine-grained glauconitic sandstone, with intercalations of light-grey clays. The lower part of the unit contains numerous pyrite concretions. This interval yields the lingulate brachiopods *Thysanotos siluricus*, *Leptembolon lingulaeformis* and *Lingulella? nitida*. *Schizambon esthonia* occurs in the interval 10-20 cm below the top of this unit. The holotypes of the species *Schizambon? esthonia* (Walcott 1912), *S. ovalis* (Goryanskij 1969) and *Paldiskia obscuricostata* (Goryanskij 1969) originate also from this interval.

Billingen Stage. Leetse Formation. Mäeküla Member.

Thickness 0.1 m. Green glauconite sandstone, strongly cemented with carbonate minerals.

A lingulate brachiopod *Acrotreta subconica* has been reported from this level (Goryanskij 1969, p. 67; Holmer & Popov 1994).

Billingen Stage. Toila Formation. Päite Member.
Thickness 0.1 m. Greenish-grey limestone, with rare glauconite grains.

Up-section follow the limestones of the Volkhov (1.3 m), Kunda (0.95 m) and Aseri Stages (0.15 m). The overlying Lasnamägi Stage is exposed in full thickness (4.85 m) in a quarry NW of Paldiski, and is overlain by the Uhaku Stage (exposed thickness about 1.5 m).

Environs of Leetse. - The glauconitic sandstones of the Leetse Formation crop out in several sections along the sea coast in the area of the former Leetse manor, between Leetse and Kersalu villages. A generalized profile of the Leetse section has been provided by Raymond (1916, Plate 2). A section about 1 km NW of the Kersalu village is the stratotype of the Leetse Formation (Männil & Rõõmusoks 1984).

In general terms, the sections in the environs of Leetse are closely similar to those in the environs of Paldiski. The Leetse Formation at Leetse has yielded *Thysanotos siluricus* and *Leptembolon lingulaeformis* and a specimen of the trace fossil *Rusophycus* sp. (S. Jensen, pers. comm., 1995). Goryanskij (1969) has selected the lectotype of *Leptembolon lingulaeformis* from the Leetse Formation at Leetse.

Pakri islands. - The Väike-Pakri island, used as a training bombing polygon by Soviet air forces until 1992, remains presently inaccessible for civilians until the bomb clearing is completed. Thus, the remarks on the geology and fossils of this island are based on the collection of Armin Öpik from the 1930s and his early study (Öpik 1927). According to the generalized description of the Lower Ordovician sequence at Vesternäs, northern coast of Väike-Pakri island (Öpik 1927, p. 38), the section is closely similar to that of the Paldiski section on the Pakri peninsula. The collection of Armin Öpik from 1930s includes a well-preserved ventral valve of *Thysanotos siluricus* (Fig. 67A) from the Leetse Formation of the Väike- Pakri island. Other lingulate species reported by Öpik (1927, p. 40) include *Leptembolon lingulaeformis* and *Schizambon? esthonia*. According to Öpik (1927, p. 40), erratic blocks, but no exposures, of the glauconitic sandstone of the Leetse Fm. were observed on the neighbouring Suur-Pakri island.

Outcrops between Lohusalu and Rannamõisa

The most representative outcrops between Lohusalu and Rannamõisa are Türisalu and Rannamõisa, where the complete sequence of the Pakerort Stage is exposed, and Keila-Joa, a key section for the Hunneberg Stage. The basal part of the Kallavere Formation crops out on the Nabe islet and at Tiskre Brook (Müürisepp 1958). Temporary artificial exposures of parts of the Pakerort Stage have been also observed at Vääna-Viti and Suurupi (Öpik 1928b, 1929), but they are not accessible at present.

Nabe Islet. - The basal part of the Kallavere Formation is exposed in the eastern side of the Nabe Islet united by a causeway with the promontory of the Lohusalu Peninsula when the water is low. The basal conglomerate of the Kallavere Formation in this locality was observed by Müürisepp (1958b). In this locality, the quartzose sandstones of the Lower Cambrian Tiskre Formation are overlain by the sandstones of the Maardu Member of the Kallavere Formation exposed with a thickness of 0.2 m. The up to 10 cm thick basal conglomerate at the base of this interval yields pebbles from 1 to 10 cm in diameter, and rounded fragments of lingulate brachiopods, *Ungula* sp. The conglomerate matrix includes quartzose sand grains and carbonate cement. A bed of medium-grained yellow sandstone, up to 0.1 m thick occurs above the conglomerate; its upper boundary is eroded and overlain by Quaternary sediments.

Türisalu section. - The coastal section is located near Türisalu village, 25 km east of Tallinn. This section, already noted by Helmersen (1838) is the stratotype of the Türisalu Formation (Loog & Kivimägi 1968). A stratigraphical column and conodont data for this section have been published by Popov *et al.* (1989, Fig. 10).

LOWER CAMBRIAN
Tiskre Formation.
Exposed thickness 0.3 m. Light grey sandy quartzose siltstone. Lower boundary not exposed.

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 3.5 m. Fine-grained sandstone, with intercalations of kerogenous argillite. Lower boundary marked by the appearance of a kerogenous argillite layer. The lower 0.5 m of this interval has yielded the conodonts *Cordylodus andresi*, *C. proavus*, *Phakelodus tenuis*, *Furnishina furnishi* and *Prooneotodus* aff. *gallatini*, indicative of the *Cordylodus proavus* Biozone (Popov *et al.* 1989).

LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Suurjõgi Member.
Thickness 1.3 m. Medium-grained sandstone containing fine debris of lingulate brachiopods, with thin intercalations of kerogenous argillite. The uppermost 20 cm of the Member is cemented with pyrite.

Pakerort Stage. Türisalu Formation. Tabasalu Member.
Thickness 4.7 m. Dark-brown kerogenous argillite, with very thin (up to 3 mm) intercalations of light grey quartz-siltstone. This interval is the stratotype of the Türisalu Formation (Loog & Kivimägi 1968, p. 381).

Keila-Joa section. - The section (Fig. 15) is located at the Keila- Joa waterfall on the Keila River, about 500 m downstream of Keila-Joa village, 30 km east of Tallinn. Exposures of parts of the Türisalu and Kallavere Formations can be observed on the banks of the Keila river 200-300 m downstream of the waterfall.

This section is the stratotype of the Joa Member, first defined as a regional substage by Männil (*in* Aaloe *et al.* 1958). The section has been described by Kleesment & Mägi (1975) and Mägi (1991a). The fauna and biostratigraphy have been discussed by Mägi & Viira (1976) and Mägi *et al.* (1989) and the conodont correlation of this section with sequences at Hunneberg, Sweden by Löfgren (1993a). The conodont data of Mägi and Viira (1976) are reinterpreted according to the multielement taxonomy (Mägi *et al.* 1989; V. Viira, written communication, 1996). In the wall of the Keila- Joa waterfall, the following sequence is exposed.

LOWER ORDOVICIAN

Varangu Stage. Varangu Formation.

Exposed thickness 0.7 m. Grey silty clay, containing small pebbles and pyrite concretions, with thin intercalations of dark- brown kerogenous argillite. This interval has yielded the conodonts *Drepanoistodus deltifer pristinus*, *D. d. deltifer*, *Oneotodus variabilis*, *Paroistodus proteus*, *Cordylodus prion* and *C. angulatus*.

Hunneberg Stage. Leetse Formation. Klooga Member.

Thickness 1.1 m. Greyish-green glauconitic quartzose siltstone. The conodonts *Drepanoistodus forceps*, *Paroistodus proteus*, *Acodus deltatus deltatus*, *Acodus erectus* and *Drepanodus arcuatus* appear at the base of this level. *Drepanoistodus deltifer pristinus*, *Cordylodus prion*, *C. angulatus*, *Oneotodus variabilis* and *Paroistodus parallelus* are present. Lingulate brachiopods are represented by *Thysanotos siluricus*, *Leptembolon lingulaeformis* and *Lingulella? nitida* (this study).

Hunneberg Stage. Leetse Formation. Joa Member.

Thickness 1.15 m. Greyish-green glauconitic siltstone, with intercalations of greenish-grey viscous glauconitic clay. Lower boundary marked by a wavy discontinuity surface. This interval mostly yields the transitional conodonts occurring in underlying beds, except *Drepanodus arcuatus* and *Drepanoistodus conulatus* which make their first appearance near the base of this interval. Lingulate brachiopods are represented by *Thysanotos siluricus*, *Leptembolon lingulaeformis*, *Foveola maarduensis*, *Eosiphonotreta acrotretomorpha*, *Schizambon esthonia* and *Lingulella? nitida* (this study).

Billingen Stage. Leetse Formation. Mäeküla Member.

Thickness 0.25 m. Strongly cemented greenish-grey glauconitic siltstone. Except for transitional conodont species, this interval yields *Oistodus lanceloatus*, *Acodus deltatus deltatus*, here making their first appearance.

Billingen Stage. Toila Formation. Päite Member.

Thickness 0.15 m. Light-grey limestone containing glauconite grains, with many discontinuity surfaces and abundant fragments of trilobites and brachiopods.

Up-section follow greenish-grey glauconitic limestones of the Volkhov Stage (2 m) and light-grey oolitic limestones of the Kunda Stage (0.6 m exposed; Mägi 1991a, p. 77).

Rannamõisa section. - The Rannamõisa section near Tabasalu village has been suggested by Heinsalu (1987) as the stratotype of the Tabasalu Member. Here, the quartzose siltstones and sandstones of the Lower Cambrian Tiskre Formation, exposed with a thickness of 0.2 m underlie the quartzose sandstones of the Kallavere Formation, 4.2 m thick. The overlying sequence of brown kerogenous argillites of the Tabasalu Member of the Türisalu Formation, 5.1 m thick, has yielded the graptolites *Rhabdinopora* ex. gr. *flabelliformis* and *R. f. cf. norvegicum* near the base (Kaljo & Kivimägi 1976). Up-section follow the glauconitic sandstones of the Leetse Formation.

Tallinn and environs

The outcrops of Cambrian-Ordovician boundary beds in Tallinn and environs are mostly related to the remains of the clint and temporary excavations at various construction sites.

Harku trench. - The Harku trench (Figs 16, 17) is located close to the western boundary of Tallinn, 4 km west of the Tallinn Zoo by Tallinn-Keila road, 500 m south of the entrance to the Harku limestone quarry, near former Mäeküla. In a deep unfinished trench-like excavation for a water pipe construction, a section from the uppermost Türisalu Formation to the lowermost Lasnamägi Stage is exposed.

LOWER ORDOVICIAN

Pakerort Stage. Türisalu Formation. Tabasalu Member.

Exposed thickness 0.15 m, reaching 3 m in the deeper part of the trench. Dark-brown kerogenous argillite.

Varangu Stage. Varangu Formation.

Thickness 0.2 m. Greenish-grey glauconitic clay.

Hunneberg Stage. Leetse Formation. Joa Member.

Thickness 0.9 m. The basal 0.25 m is composed of green medium-grained glauconitic quartzose sandstone, with tiny fragments of lingulate brachiopods (up to 3 mm in diameter). The upper 0.65 m is composed of greyish-green medium-grained glauconitic quartzose sandstone, with up to 1 cm thick intercalations of grey clay. The Joa Member has yielded *Semitreta? magna* and shell fragments of *Thysanotos siluricus*.

Billingen Stage. Leetse Formation. Mäeküla Member.
Thickness 0.35 m. Strongly cemented greenish-grey glauconitic sandstone. The basal 0.05 m of this interval is composed of massive sandstone. The overlying 0.25 m is represented by nodular sandstone with up to 0.02 m thick intercalations of clay. A 0.05 m thick layer of greenish-grey clay occurs at the top of the interval.

Billingen Stage. Toila Formation. Päite Member.
Thickness 0.3 m. Greenish-grey glauconitic limestone.

Overlying are the limestones of Hunneberg, Volkhov (2.6 m), Kunda (0.5 m), Aseri (0.4 m) and Lasnamägi (1 m exposed) stages.

Mäeküla. - Öpik (1929, p. 18) described the temporary artificial outcrop at Mäeküla, 9 km west of Tallinn. This locality, situated very close to the Harku trench (V. Jaanusson, pers. comm., 1996), is not accessible at present. The collection of Armin Öpik from the Mäeküla locality includes *Ungula ingrica* from the Kallavere Formation and *Thysanotos siluricus* from the Leetse Formation. A collection at the University of Tartu included a specimen of a rare species *Lingulella* aff. *tetragona* from the Tabasalu Formation.

In this section, Öpik (1933) defined a unit corresponding to the B$_I\beta$ interval of Lamansky (1905) as Mäeküla Schichten. Thus, this section has has been further considered as the stratotype of the Mäeküla Member (Rõõmusoks 1983). A sample from the Mäeküla Member has yielded *Acrotreta subconica* (Holmer & Popov 1994).

Tõnismägi section. - The Tõnismägi section (Fig. 18) at the Tõnismägi hill in the centre of Tallinn was exposed in 1986 in an excavation related to the construction of the Estonian National Library building. The detailed description by Kaljo *et al.* (1988) includes conodont, graptolite and lingulate distribution; the acritarch data have been published separately by Paalits (1995). Aspects of global correlation of this section related to the Cambrian-Ordovician boundary problem have been discussed by Norford (1991), Miller & Stitt (1995) and Miller & Taylor (1995).

LOWER CAMBRIAN
Tiskre Formation.

Exposed thickness 1.5 m. Light grey coarse-grained quartz- siltstone intercalated with about 0.1 m thick layers of greenish- grey clay.

UPPER CAMBRIAN
Ülgase Formation.
Thickness 0.25 m. Light yellow quartz-siltstone intercalated with greenish-grey clay. This interval has yielded a lingulate brachiopod, *Ungula inornata*.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Maardu Member.

Thickness 1.45 m. Yellowish-grey fine-grained quartz-sandstones, with intercalations of the dark-brown kerogenous argillite. A brachiopod coquina (0.12 m) at the base yielded fragments of lingulates, mostly *Ungula ingrica*. The conodonts from the coquina have been interpreted as characteristic of the *Cordylodus proavus* Biozone (Kaljo *et al.* 1988) or, alternatively, as indicative of the *C. lindstromi* Biozone (Norford 1991). A 5 cm thick layer of argillite 0.18 cm above the base of the interval yielded *Rhabdinopora flabelliformis flabelliformis*, *R. f. cf. socialis* and *R. f. cf. desmograptoides* (Kaljo *et al.* 1988).

Iapetognathus preaengensis appears in a sandstone intercalation immediately above this argillite. *Cordylodus lindstromi?* and *C. intermedius* appear in the next sampled interval.

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 0.5 m. Brownish-grey, cross-bedded quartz sandstone, containing lingulate debris. Uppermost 5-15 cm strongly pyritized. Conodonts *Cordylodus angulatus* and *Oistodus altus* appear at the base of this interval and *Cordylodus drucei* in the upper part of the interval.

Pakerort Stage. Türisalu Formation. Tabasalu Member.

Exposed thickness 3 m. Dark-brown, kerogenous argillite. Upper boundary eroded and overlain by Quaternary sediments.

Kadriorg. - Near the stadium in Kadriorg Park, east of the centre of Tallinn, Öpik (1929, p. 18) observed a section in a temporary water canal exposed in 1920s.

According to Rõõmusoks *et al.* (1975, p. 5), an unpublished description by A. Öpik reports up to 3.15 m thickness of the light-grey sandstones of the Ülgase Formation. A collection of Armin Öpik from this locality housed at the Institute of Geology, Tartu University, includes sandstone slabs with lingulate brachiopods *Ungula inornata*, *Oepikites fragilis* and *Ceratreta tanneri*.

Up-section, Öpik (1929, p. 18) observed the 1.5 thick Maardu Member, with an up to 0.25 thick lingulate coquina at the base and the up to 0.95 m thick Suurjõgi Member, with an up to 0.15 m thick pyritized layer ("Markasitschicht") at the top. On the basis of these data, the Kadriorg section appears to be closely similar to the Mäekalda section, located not farther than 500 m from this locality.

Mäekalda. - In 1986, a Cambrian-Ordovician sequence from the Lower Cambrian Tiskre Formation to the Middle Ordovician Uhaku Stage was opened in a road-cut (Fig. 19) for the speedway connecting the Lasnamäe district of Tallinn to the centre of the city. The description of the lower part of the sequence, which was exposed until 1995 about 500 m SW of the Kadriorg Stadium, is given after Mens *et al.* (1989).

LOWER CAMBRIAN

Tiskre Formation.
Exposed thickness 1 m. Greenish-grey argillaceous siltstones with lenses of light grey coarse-grained siltstones.

UPPER CAMBRIAN
Ülgase Formation.
Thickness 3.2 m. The lower 1.6 m of this formation, composed of light-grey coarse-grained siltstones, intercalated with grey clays or argillaceous siltstones, is overlain by 1 m thick cross-bedded coarse-grained and sandy siltstones. Uppermost 0.6 m is composed of fine-grained sandstones and coarse-grained siltstones.

The lower boundary of the Ülgase Formation is sharp, marked by the appearance of phosphatic pebbles and fragments of lingulate brachiopods. The pebbles yield lingulate brachiopods *Ungula* sp. The lingulate brachiopods *Ungula inornata* and *Oepikites fragilis* can be observed on bedding plains of siltstones throughout the unit. A sample 1 m above the base has yielded a single specimen of *Ceratreta tanneri* and a conodont *Phakelodus tenuis*. A sample 0.6 m below top of the formation has yielded two specimens of ?*Proconodontus*. Fragments of a hyolithelminth *Torellella* sp. have been found from samples from many levels throughout the unit.

Four clay beds sampled for microfossils yielded a uniform acritarch assemblage including *Stelliferidium cortinulum*, *Vulcanisphaera turbata*, *Leiofusa stoumonensis*, *Cristallinium cambriense*, *C. randomense* and *Veryhachium dumontii* and representatives of the genera *Impluviculus*, *Timofeevia* and *Cymatiogalea* (Mens *et al.* 1989).

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 1.5 m. Light-yellow quartz-sandstones and siltstones, with thin intercalations or films of dark-brown kerogenous argillites. Lower boundary marked by a 0.2 m thick lingulate coquina containing valves of *Ungula ingrica*. *U. ingrica* occurs throughout this interval. *Rhabdinopora* ex. gr. *flabelliformis* occurs 1.2 m above the base of this interval.

Pakerort Stage. Kallavere Formation. Suurjõgi Member.
Exposed thickness 0.7 m. Brownish-grey cross-bedded fine- to medium grained sandstones. Upper boundary is eroded and overlain by Quaternary sediments.

The upper part of the section is exposed about 500 m eastwards. The description is given after Mägi (1990) and Einasto *et al.* (1996).

Pakerort Stage. Türisalu Formation. Tabasalu Member.
Exposed thickness 1.5 m. Dark-brown kerogenous argillite.

Varangu Stage. Varangu Formation.
Thickness 0.25 m. Beige argillite, yielding *Paroistodus numarcuatus*.

Hunneberg Stage. Leetse Formation. Klooga Member.

Thickness 0.2 m. Dark-green glauconitic quartzose siltstone. Lower and upper boundaries marked by limonitized smooth discontinuity surfaces with rounded phosphatic pebbles. This interval has yielded the conodonts *P. numarcuatus* and *Drepanoistodus deltifer*. The first chitinozoans, including *Lagenochitina esthonica*, *Cyathochitina primitiva* and *Eremochitina* sp. appear above the base (J. Nõlvak, pers. comm., 1996).

Hunneberg Stage. Leetse Formation. Joa Member.

Thickness 1.15 m. Clayey and silty glauconitic sand. Lower part dark-green, coarse-grained, with fragments of lingulate brachiopods. The lingulate brachiopods *Thysanotos siluricus* and *Semitreta? magna* occur. The conodonts *Paroistodus proteus* and *Tropodus comptus* characteristic of the *P. proteus* Biozone appear in the middle and the conodonts *Prioniodus elegans* and *Oistodus lanceolatus*, indicative of the *Prioniodus elegans* Biozone, in the upper part of this interval.

Billingen Stage. Leetse Formation. Mäeküla Member.

Thickness 0.4 m. Greenish-grey glauconitic sandstone. Basal 0.15 m of the interval composed of silty and fine-grained nodular glauconitic sandstone with thin intercalations of clay. Overlying 0.15 m characterized by strong carbonate cementation. A 0.1 m thick bed of greenish-grey clay occurs at the top of this interval. The Mäeküla Member has yielded a lingulate brachiopod *Acrotreta subconica* Kutorga (Holmer & Popov 1994). The conodonts *Oepikodus evae* and *Periodon flabellum* appear in the middle of this interval.

Billingen Stage. Toila Formation. Päite Member.

Thickness 0.35 m. Grey, partly semi-nodular fine-grained limestone. Basal 10 m contains abundant glauconite and quartz grains and is characterized by many phosphatized discontinuity surfaces and intercalations of clay. *Acrotreta subconica* has been isolated from this interval (Holmer & Popov, 1994).

Hundikuristik. - In this locality, 4 km east of the centre of Tallinn by Tallinn-Narva road, a sequence from the upper part of the Ülgase Formation to the Türisalu Formation is exposed (Fig. 21). Early references to this section include Kupffer (1870) and Öpik (1928b, 1929). A brief description of the Ülgase Formation is provided by Rõõmusoks *et al.* (1975, p. 6). Lingulate brachiopod data are provided by Popov *et al.* (1989) and Holmer & Popov (1990). The conodont data for the Suurjõgi Member are reported by Mens *et al.* (1989).

UPPER CAMBRIAN

Ülgase Formation.

Exposed thickness 3.6 m. Light-grey coarse-grained siltstones. *Ungula inornata* occurs in upper 2 m of this this interval. A sample from the uppermost 40 cm has yielded *Ceratreta tanneri*, *Oepikites fragilis*, *Angulotreta postapicalis* and *Ungula inornata* (Popov *et al.* 1989; Holmer & Popov 1990).

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 1.5 m. Light-grey quartzose sandstone, yielding poorly preserved *Ungula ingrica*.

Pakerort Stage. Kallavere Formation. Suurjõgi Member.
Thickness 0.9 m. Brownish-grey cross-bedded fine- to medium- grained sandstones, with abundant rounded lingulate debris. Angular pieces of kerogenous argillite occur at the base of the interval. By conodonts, this unit is assigned to the *Cordylodus angulatus* Biozone. The zonal species and *Cordylodus prion* are very common, co-occurring with *C. intermedius*. Rare *C. drucei*, *Iapetognathus* sp., *Oneotodus altus*, and *Drepanodus deltifer pristinus* also appear (Mens *et al.* 1989).

Pakerort Stage. Türisalu Formation. Tabasalu Member.
Exposed thickness 2 m. Dark-brown kerogenous argillite. Upper boundary eroded and overlain by Quaternary sediments.

Suhkrumägi section. - At Suhkrumägi, 3 km east of the centre of Tallinn, the sequence from the Upper Cambrian Ülgase Formation to the Middle Ordovician Lasnamägi Stage is exposed (Fig. 20). The section has been described by Põlma & Mägi (1984) and Heinsalu (1990). The Cambrian-Ordovician boundary beds have been studied for graptolites (Kaljo & Kivimägi 1976), conodonts (Viira 1974; Kaljo *et al.* 1986), acritarchs (Volkova & Mens 1988) and lingulate brachiopods.

UPPER CAMBRIAN
Ülgase Formation.
Exposed thickness 2.1 m. Light-grey fine-grained quartzose sandstones and siltstones, with rare intercalations of dark-grey clay. This interval has yielded a conodont *Phakelodus tenuis* (Kaljo *et al.* 1986), a lingulate brachiopod, *Ungula inornata*, and a hyolitheliminth *Torellella sulcata*. Two clay samples from different levels have yielded a uniform acritarch assemblage including *Leiofusa stoumonensis*, *Veryhachium dumontii*, *Vulcanisphaera turbata*, *Timofeevia lancarae*, *T. phosphoritica* and the representatives of the genera *Cristallinium*, *Cymatiogalea*, *Leiosphaeridia*, *Micrhystridium* and *Stelliferidium* (Volkova & Mens 1988).

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 1.5 m. Light-grey fine-grained quartzose sandstones, with up to 2 cm thick intercalations of dark-brown kerogenous argillite. The lower part of the interval yields conodonts *Cordylodus proavus* and *Eoconodontus notchpeakensis*; *Cordylodus lindstromi* and *C. prion* appear in the uppermost 40 cm (Kaljo *et al.* 1986). Fragments and rare complete valves of *Ungula ingrica* have been found at the base of this interval. Two samples from the intercalating kerogenous argillite beds at the base and 0.55 m above the base of the Maardu Member yield a uniform acritarch assemblage including *Acanthodiacrodium angustum*, *Baltisphaeridium capillatum*, *Buedingisphaeridium tremadocum*, *Cymatiogalea multarea*, *C.*

cuvillieri, *Dasydiacrodium ornatum*, *Goniosphaeridium uncinatum*, *Ladogella rotundiformis* and *Priscotheca tumida* (Volkova & Mens 1988). The sample 0.55 m above the base of the Maardu Member has yielded the graptolites *Rhabdinopora f. flabelliformis* and *Rhabdinopora f. sociale* (Kaljo & Kivimägi 1976).

The acritarchs *Acanthodiacrodium echinatum*, *A. striatum*, *Lunulida lunula*, *Stelliferidium simplex* and *Vulcanisphaera* sp. appear in the sample from thin kerogenous argillite bed 1.1 m above the base of the member. From this level, *Rhabdinopora f. norvegicum* has been reported by Kaljo & Kivimägi (1976). Directly above this level, the conodonts *Cordylodus lindstromi*, *C. intermedius* and *C. prion* appear (Kaljo *et al.* 1986).

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 1 m. Yellowish-grey fine- to medium-grained cross- bedded sandstones, containing lingulate brachiopod debris. A 5-10 cm thick pyritized layer ("pyrite layer") occurs at the top of the interval. The conodonts *Cordylodus angulatus*, *Acodus firmus*, *Oneotodus altus* and *Iapetognathus* sp. appear in this interval assigned to the *Cordylodus angulatus* Biozone (Kaljo *et al.* 1986).

Pakerort Stage. Türisalu Formation. Tabasalu Member.

Thickness 4 m. Dark-brown kerogenous argillite, with occasional very thin intercalations of siltstone.

Varangu Stage. Varangu Formation.

Thickness 0.15 m. Dark-grey clay. *Bryograptus* cf. *broeggeri* and *Clonograptus* sp. have been reported from this interval (Kaljo & Kivimägi 1976).

Hunneberg Stage. Leetse Formation. Klooga Member.

Thickness 0.85 m. Dark green glauconitic silt, with intercalations of clay, yielding the conodonts *Cordylodus angulatus*, *Acodus deltatus deltatus* and *A. erectus*.

Hunneberg Stage. Leetse Formation. Joa Member.

Thickness 0.55 m. Green, sandy-clayey glauconitic silt with dark phosphatized debris of lingulate brachiopods, with intercalations of light grey clay. This interval has yielded the conodonts *Drepanoistodus forceps* and *Cordylodus angulatus*.

Billingen Stage. Leetse Formation. Mäeküla Member.

Thickness 0.2 m. Greyish-green silty quartzose glauconitic sandstone, dolomitized in the upper part.

Billingen Stage. Toila Formation. Päite Member.

Thickness 0.3 m. Grey thin- to medium-bedded calcareous dolomite with dispersed grains of glauconite and limonitic, phosphatic and pyritic discontinouity surfaces.

Up-section follow the limestones of Volkhov Stage (2.5 m), Kunda Stage (0.7 m), Aseri

Stage (0.5 m) and Lasnamägi Stage (exposed thickness 2.7 m).

Iru section. - The Iru section (Fig. 22) is located at the eastern margin of Tallinn, near ancient Iru stronghold. The section has been described by Öpik (1928a, 1929) and briefly discussed by Popov *et al.* (1989, p. 61).

UPPER CAMBRIAN
Ülgase Formation.
Exposed thickness 2 m. Light-grey quartz-sandstone yielding a lingulate brachiopod *Ungula inornata.*

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 2.3 m. The lower 0.7 m is represented by a light grey medium-grained quartzose sandstone, with abundant lingulate brachiopods forming a coquina. The amount of brachiopod valves decreases in the uppermost 20 cm. The coquina is mainly composed of the valves of *Ungula ingrica* and *Schmidtites celatus*, yielding also *Keyserlingia buchii* and redeposited valves of *Ungula inornata. Marcusodictyon priscum*, attached to a valve of *Schmidtites celatus*, has been found. No conodonts have been recorded from this interval.

The overlying 0.4 m is represented by light-grey medium- to coarse-grained quartz-sandstone with intercalations of kerogenous argillite. This interval yields abundant *Ungula ingrica* and redeposited rounded fragments of *Ungula inornata*. *Cordylodus proavus* appears at the base of this interval.

The upper 1.2 m is composed of light-grey fine-grained sandstone, with intercalations of the kerogenous argillite.

LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation, Suurjõgi Member.
Thickness 0.7 m. Brownish-grey cross-bedded fine- to medium- grained quartz-sandstones, with intercalations of kerogenous argillite.

Pakerort Stage. Türisalu Formation. Tabasalu Member.
Exposed thickness 1.5 m. Dark-brown kerogenous argillite. Upper boundary eroded and overlain by Quaternary sediments.

About 500 m upstream, on the right bank of the Pirita river is another outcrop, where the upper part of the Ülgase Formation, reaching 4.4 m in thickness, has yielded *Ungula inornata*, *Ceratreta tanneri* and *Oepikites fragilis* (Holmer & Popov 1990).

Ülgase. - Cambrian-Ordovician boundary beds are exposed in two sections (Fig. 23) along the clint near the ruins of the phosphate- processing factory of the "Eesti Vosvoriit" company, near Ülgase village, about 10 km east of the Iru section.

The sections at Ülgase have been previously described and discussed by Rõõmusoks, *et al.* (1975), Heinsalu *et al.* (1987), Popov *et al.* (1989), Heinsalu (1990) and Puura & Holmer (1993).

The Upper Cambrian Ülgase Formation is exposed in a wall of abandoned mineworks in a phosphorite mine exploited during 1921-1938. This exposure, selected as the stratotype of the Ülgase Formation by Müürisepp (1958), has been previously described and discussed by Loog & Kivimägi (1968), Rõõmusoks *et al.* (1975) and Puura & Holmer (1993). In this section, the sandstones of the Lower Cambrian Tiskre Formation are overlain by the Ülgase Formation, reaching 6.5 m in thickness. The Ülgase Formation has yielded lingulate brachiopods *Oepikites fragilis*, *Ungula inornata*. A single valve of *Ceratreta tanneri* has been reported from 1.5 m below the top of the formation (Popov & Holmer, 1990). *Ungula* sp. occurs in the basal 0.1 m of the formation. Khazanovitch and Missarzhevskij (1982) have reported a hyolithelminth *Torellella sulcata* from this interval.

Another section, 200 m westwards, has been briefly discussed by Öpik (1928b, 1929) and Müürisepp (1958), and described as a neostratotype of the Maardu Member by Heinsalu *et al.* (1987), after the stratotype in the Maardu Quarry had been destroyed in the course of phosphorite mining. Aspects of the stratigraphy of this section have been also discussed by Popov *et al.* (1989), Heinsalu (1990) and Puura & Holmer (1993). The conodont data (Heinsalu *et al.*, 1987) suggest that in this section, the lower part of the Maardu Member belongs to the *Westergaardodina* Biozone. Accordingly, this part is considered to be older than the Pakerort Stage. The description is given after Heinsalu *et al.* (1987).

UPPER CAMBRIAN

Ülgase Formation.

Exposed thickness 0.5 m. Light-grey siltstones and sandstones. *Torellella sulcata* has been found from this interval.

Kallavere Formation. Maardu Member (lower part).

Thickness 2.5 m. Brownish to yellowish-grey sandstones. The lower 1.6 m is represented by a brownish-grey to light-grey sandstone with abundant lingulate brachiopods forming a 0.3 m thick coquina at the base of the interval. The coquina, dominated by *Ungula ingrica* and *Schmidtites celatus*, also yields *Keyserlingia buchii* and *Oepikites obtusus*. Above the coquina, the content of *Ungula ingrica* decreases and that of *Schmidtites celatus* increases gradually; this is well correlated with the gradual upward decrease in grain size (Heinsalu *et al.* 1987, Fig. 1). A sample taken 0.7 m above the base of the Maardu Member has yielded the poorly preserved conodonts *Furnishina furnishi*, *Westergaardodina* cf. *bicuspidata* and *Problematoconites perforata*.

The upper 0.9 m is composed of yellowish-grey fine-grained quartzose sandstone. This interval has yielded *Estoniobolus* gen. nov. *eichwaldi* and a single conodont specimen identified as *Prooneotodus? sp.*

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Maardu Member (upper part).

Thickness 1.0 m. Basal 0.25 m represented by coarse- grained sandstones, with abundant lingulate brachiopod valves forming a coquina. As in the lower coquina, the brachiopod assemblage is dominated by *Ungula ingrica* and *Schmidtites celatus*, accompanied by rare *Keyserlingia buchii* and *Estoniobolus eichwaldi*. The well-preserved conodonts *Cordylodus proavus* and *Eoconodontus notchpeakensis* appear in the coquina. The overlying 0.6 m are composed of fine- grained sandstone and siltstone with *Schmidtites celatus*; the grain size decreases gradually upwards. The uppermost 0.15 m is represented by a kerogenous argillite bed, with thin intercalations of siltstone. *Cordylodus lindstromi* appears 0.4 below the top of the Maardu Member.

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 1.3 m. Reddish-brown fine- to medium-grained, cross- bedded sandstone, containing lingulate brachiopod debris. A sample from the basal 0.25 m has yielded the conodonts *Cordylodus angulatus*, *C. prion*, *Oneotodus altus*, *Iapetognathus* sp., *Cordylodus lindstromi* and *C. drucei*.

Maardu quarries and subsurface south of Maardu

Maardu quarries. - During 1964-1992, shelly phosphorite was mined in the Maardu open pit quarries covering an extensive area in environs of Maardu. At present, the quarries cover the area on many localities west of Ülgase reported by Öpik (1928b, 1929). In the process of mining and reclamation, the configuration of the quarries has been in continuous change. Thus, unfortunately, the outcrops in the Maardu quarries, from where Gorjansky (1969) collected and described many new species of lingulate brachiopods, have been destroyed.

The Upper Cambrian - Lower Ordovician sequence in Maardu quarries is closely similar to that in Ülgase sections discussed above. A profile from the north-eastern part of the Maardu quarry has been provided by Heinsalu (1990). In this section, the quartzose sandstones of the Maardu Member, 2.9 m thick, and the Suurjõgi Member, 1.05 m thick, are overlain by 2.6 m thick kerogenous argillites of the Türisalu Formation. In some sections in Maardu quarries, the Türisalu Formation is overlain by an up to 0.2 m thick layer of dark-grey clay of the Varangu Formation. The thickness of overlying greyish-green glauconitic sandstones of the Leetse Formation varies from 1.5 to 2 m (Raudsep 1991).

The Kallavere Formation in Maardu quarries has yielded *Ungula ingrica*, *Schmidtites celatus*, *Oepikites obtusus* and *Keyserlingia buchii*.

From the Leetse Formation in Maardu quarries, Gorjansky (1969) has reported *Thysanotos siluricus*, *Leptembolon lingulaeformis*, *Paldiskia obscuricostata*, *P. orbiculata* (holotype), *Foveola maarduensis* (holotype), *Lingulella tetragona* (holotype), *L. (?) nitida* (holotype) and *Semitreta? magna*. The samples from the Leetse Formation in the Maardu quarry have also yielded *Acrotreta* sp.

A generalized sequence of the Cambrian-Ordovician boundary beds based on numerous cores drilled south of Maardu has been illustrated by Popov *et al.* (1989, Figs 1, 13, 14, 15). Holmer & Popov (1990, p. 260, Fig. 8A) described the core M-77, drilled at a site 12 km south-west of the Turjekelder section. In this core, the Ülgase Formation, depth interval 29.3-38.8 m, has yielded *Ceratreta tanneri*, *Angulotreta postapicalis* and *Oepikites fragilis*. The overlying Tsitre Formation has yielded *Ungula ingrica*, *Schmidtites celatus*, *Oepikites triquetrus* and *Oepikites obtusus*.

Another core section of palaeontological interest is the core M-72.

Core M-72. - The drilling site is located about 30 km south-east of Tallinn (Figs. 1A, 24).

LOWER CAMBRIAN

Tiskre Formation.

Depth interval 119.6-121 m. Light-grey siltstone, with intercalations of greenish-grey clay.

UPPER CAMBRIAN

Tsitre Formation.

Depth interval 112.8-119.6 m. Light-grey fine-grained sandstone, with lingulate brachiopod debris and valve fragments. The Tsitre Formation has yielded the lingulate brachiopods *Ungula convexa* and *Schmidtites celatus*. From this interval, Paalits (1992b) has described an acritarch assemblage including *Veryhachium dumontii*, *Vulcanisphaera turbata*, *Trunculumarinium revinium*, *Timofeevia phosphoritica*, *T. estonica*, *Dasydiacrodium caudatum*, *D. obsonum*, *Stelliferidium cortinulum* and *Cymatiogalea wironia*.

Pakerort Stage. Kallavere Formation.

Depth interval 102.2-112.8 m. The basal part, depth interval 111.2-112.8, is represented by medium- and coarse-grained sandstone, with abundant rounded shells of a lingulate brachiopod *Ungula ingrica*, forming a coquina. The depth interval 102.2-111.2 m is composed of light-grey siltstones and fine- grained sandstones, with up to 1 cm thick intercalations of kerogenous argillite.

The Kallavere Formation is overlain by the kerogenous shales of the Türisalu Formation, depth interval 98.7-102.26 m.

Outcrops between the Jägala River and Narva

Jägala River. - The sandstones of the Ülgase and Kallavere formations are exposed in many outcrops along the Jägala River (Fig. 25), downstream of the Jägala Falls, 25 km east of Tallinn. The lower part of the Ülgase Formation is exposed in an outcrop 400 m downstream of a former children summer camp. In this locality, the yellowish-grey siltstones and sandstones of the Lower Cambrian Tiskre Formation occur in the basal part of the sequence; the exposed thickness above the river water level was 1.8 m. Overlying are light-grey coarse-grained siltstones of the Ülgase Formation, exposed with a thickness of 1.5 m. A 0.03 m thick conglomerate containing phosphatized and pyritized pebbles and

fragments of lingulate brachiopods *Ungula inornata* and *Ungula* sp. occurs at the base of the Ülgase Formation.
The upper boundary of the formation is eroded and overlain by Quaternary sediments. In another locality, 100 m downstream of the mouth of the Jõelähtme Brook, the Ülgase Formation is exposed with a thickness of 4 m (Rõõmusoks *et al.*, 1975, p. 7).

The following section of the Kallavere Formation is exposed on the left bank of the Jägala River, downstream of the mouth of the Jõelähtme Brook.

UPPER CAMBRIAN
Ülgase Formation.
Exposed thickness above the water level 0.8 m. Light-grey coarse- grained siltstones yielding *Ungula inornata* and *Oepikites fragilis*.

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Maardu Member.
Thickness 2.9 m. Light-grey fine- to medium-grained sandstone, with intercalations of kerogenous argillite. An up to 0.15 m thick coquina at the base yields *Schmidtites celatus, Ungula ingrica, Oepikites obtusus* and redeposited *U. inornata*. A 0.1 m thick conglomerate bed occurs 1.6 m above the base.

LOWER ORDOVICIAN
Pakerort Stage. Kallavere Formation. Suurjõgi Member.
Thickness 0.9 m. Medium-grained sandstone with lingulate brachiopod fragments.

Pakerort Stage. Türisalu Formation.
Exposed thickness 1 m. Dark-brown kerogenous argillite. The upper boundary is eroded and overlain by Quaternary sediments.

An early description of this section is provided by Mickwitz (1896, p. 38). A footnote on the same page indicates that most of the obolid specimens described in his monograph, came from his Bed 7, corresponding to the basal conglomerate of the Kallavere Formation.

Jägala-Joa. - A sequence from the uppermost Türisalu Formation to the Kunda Stage is exposed in the wall of the Jägala waterfall (Mägi, 1991b, p. 79). Here, the dark-brown kerogenous argillite of the Türisalu Formation (exposed thickness 0.75 m) is overlain by grey clay of the Varangu Formation, 0.2 m thick. The overlying greyish-green glauconitic sandstone of the Joa Member of the Leetse Formation is 1 m thick. The Joa Member has yielded the conodonts *Drepanoistodus deltifer pristinus* and *Acodus erectus* (Viira, 1974) and a lingulate brachiopod, *Thysanotos siluricus*. Directly above the Joa Member follow the Mäeküla Member, 0.3 m thick, represented by glauconitic carbonate-cemented quartz-sandstone and the Päite Member, 0.3 m thick, composed of glauconitic limestone. Up- section follow the glauconitic limestones of the Volkhov Stage (2.7 m) and Kunda Stage (exposed thickness 2.6 m).

Valkla River. - On the left bank of the Valkla river, where the river cuts the lower part of the clint, the upper part of the Ülgase Formation and lower part of the Kallavere Formation are exposed (Fig. 26). The section has been briefly discussed by Rõõmusoks *et al.* (1975) and Popov *et al.* (1989), who provide the lithological column and palaeontological data. Here, the yellowish-grey coarse-grained quartz-siltstones of the Ülgase Member, exposed with a thickness of 2 m, have yielded *Ceratreta tanneri*, *Oepikites fragilis* and *Ungula inornata*. The overlying sandstones of the Maardu Member, 4.7 m thick, have yielded *Schmidtites celatus*, *Ungula ingrica*, *Keyserlingia buchii* and redeposited *Ungula inornata*. Overlying are the cross-bedded sandstones of the Suurjõgi Member (0.8 m) and siltstones and argillites of the Katela Member, exposed in thickness of 1 m. The upper boundary of the Katela Member is eroded and overlain by Quaternary sediments.

Turjekelder. - This outcrop (Fig. 27), located near Tsitre village at a waterfall on Turjekelder rivulet, is the stratotype of the Tsitre Formation (Khazanovitch & Popov, 1985; Popov *et al.*, 1989).

The stratigraphy of this section has been discussed by Rõõmusoks *et al.* (1975), Kaljo *et al.* (1986) and Popov *et al.* (1989). Conodont and lingulate brachiopod distribution has been discussed by Kaljo *et al.* (1986), Popov *et al.* (1989) and Holmer & Popov (1990). Volkova (1982, 1989) has studied acritarchs and Märss (1988) hadimopanellids, now known as fragments of palaeoscolecid worms (Hinz *et al.*, 1990).

A detailed description of the section is provided by Popov *et al.* (1989, p. 56); a generalized description is given here.

UPPER CAMBRIAN

Ülgase Formation.

Thickness 5.4 m. Light-grey coarse-grained quartzose siltstone, with thin interbeds of silty clay. Throughout all this interval, the lingulate brachiopods *Oepikites fragilis*, *Angulotreta postapicalis* and *Ceratreta tanneri* occur, together with the conodonts *Prooneotodus tenuis* and *Furnishina* cf. *furnishi* (Kaljo *et al.*, 1989; Popov *et al.*, 1989; Holmer & Popov, 1990).

Tsitre Formation.

Thickness 1.6 m. Light-grey fine-grained quartz-sandstone and siltstone, with lingulate brachiopod debris and intercalations of dark-grey clay. This interval has yielded a lingulate brachiopod, *Schmidtites celatus*, and the conodonts *Phakelodus tenuis*, *Prooneotodus* cf. *gallatini*, *Furnishina* cf. *furnishi* and *Westergaardodina bicuspidata* (Kaljo *et al.*, 1986; Popov *et al.*, 1989). A problematic net- like epibiont *Marcusodictyon priscum* (Bassler) has been found (see Taylor 1984; Popov *et al.* 1989), attached to a valve of *Schmidtites celatus*. Microscopic sclerites of palaeoscolecid worms, described as the hadimopanellids *Kaimenella reticulata* and *Hadimopanella collaris* (Märss 1988) have been found from this interval.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Maardu Member.

Thickness 3 m. The lower 1.9 m of the member is composed of brownish-yellow fine- to medium-grained quartz-sandstone, with lingulate brachiopod valves and fragments. A 0.25 m thick lingulate coquina at the base of this interval yields the lingulate brachiopods *Schmidtites celatus*, *Ungula ingrica* and *Keyserlingia buchii* and a conodont *Prooneotodus* cf. *gallatini*.

From a sample taken 1.35-1.8 m above the base, the conodonts *Cordylodus andresi*, *Eoconodontus notchpeakensis*, *Furnishina* cf. *furnishi*, *Phakelodus tenuis* and *Prooneotodus* cf. *gallatini* have been found.

The upper 1.1 m of the Maardu Member is represented by dark- to light-yellow fine-grained quartz-sandstone. The lower part of this interval contains lingulate brachiopod debris, the upper part is intercalated by thin kerogenous argillite beds. A sample 0.25-0.55 above the base of the interval has yielded the conodonts *Cordylodus proavus*, *C. intermedius*, *C. lindstromi* and *C. drucei*.

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 0.6 m. Brownish-yellow fine-grained quartz-sandstone, with abundant debris of lingulate brachiopods. This interval has yielded the conodonts *Cordylodus angulatus*, *C. intermedius*, *C. lindstromi* and *Oneotodus altus*. The upper boundary is eroded and overlain by Quaternary sediments.

Nõmmeveski. - On the right bank of the Valgejõgi River, 500 m downstream of the Nõmmeveski waterfall, the Cambrian- Ordovician boundary beds are exposed. The basal part of the Maardu Member, exposed with a thickness of 5.2 m above the water level, has yielded *Schmidtites celatus*. The overlying yellowish-brown cross-bedded sandstones of the Suurjõgi Member, 2.2 m thick, have yielded conodonts *Cordylodus lindstromi C. prion* and *C. intermedius*. Overlying are the Katela Member, 1 m thick, composed of siltstones with kerogenous argillite intercalations, and the Türisalu Member, 2 m thick, represented by a monotonous sequence of kerogenous argillites, with siltstone intercalations in the lower part.

Vihula. - Two sections (Fig. 28) are situated on the banks of the Suurjõgi River, near the Vihula village. The lower part of the Cambrian- Ordovician sequence is exposed in an outcrop on a right bank of the river, downstream from the Vihula manor.

LOWER CAMBRIAN

Tiskre Formation.

Exposed thickness 0.8 m. Light-grey siltstone, with intercalations of greenish-grey clay. Lower boundary not exposed.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Maardu Member.

Exposed thickness 5.8 m. Brownish-grey sandstones and siltstones, with intercalations of dark-brown kerogenous argillites. In the basal 0.3 m occur the lingulate brachiopods *Ungula ingrica*, *Schmidtites celatus*, *Oepikites obtusus* and *Keyserlingia buchii*. The interval 0.6-0.9 m above the base of the member has yielded the conodonts *Furnishina alata*, *Prooneotodus* aff. *gallatini*, *Westergaardodina bicuspidata*, *Prooneotodus tenuis*, *Cordylodus andresi*, and *Eoconodontus notchpeakensis*. The latter three species also occur in the interval 0.9-2.5 m above the base of the Maardu Member. *Cordylodus proavus* appears in the interval 2.6-3.1 m above the base of the member.

The upper boundary of the Maardu Member is eroded and overlain by the Quaternary sediments.

Another outcrop on the left bank of the Suurjõgi River, 500 m downstream of the Vihula village, is the stratotype of the Suurjõgi Member (Loog & Kivimägi 1968) and the Katela Member (Heinsalu 1987) of the Kallavere Formation. For consistency, the lithostratigraphy in this section follows that of Heinsalu (1987); an alternative interpretation has been suggested by Popov *et al.* (1989, p. 52; see also Heinsalu & Raudsep, 1992). The upper part of the Maardu Member (1.4 m exposed) is overlain by light-grey fine- to medium-grained cross-bedded sandstones of the Suurjõgi Member (5.1 m). The Suurjõgi Member has yielded *Cordylodus proavus* (Viira *et al.* 1987). The overlying Katela Member, 0.6 m thick, is composed of light-grey sandstones with intercalations of kerogenous argillite. The Katela Member is overlain by kerogenous argillite of the Toolse Member. Its exposed thickness is 0.5 m; the upper boundary is eroded and overlain by Quaternary sediments.

Toolse River. - An outcrop of Cambrian-Ordovician boundary beds (Fig. 29) is located on the left bank of the Toolse River, 50 m downstream of the bridge on the road between Selja village and Kunda. The section has been studied by Kaljo *et al.* (1986) and Popov *et al.* (1989).

LOWER CAMBRIAN

Tiskre Formation.

Exposed thickness 0.3 m. Light-yellow sandstone.

UPPER CAMBRIAN

Pakerort Stage. Kallavere Formation. Maardu Member.

Thickness 0.6 m. Light-grey fine-grained sandstone. A lingulate brachiopod coquina containing *Schmidtites celatus* and *Ungula* sp. occurs in the basal 0.3 m of the member. The coquina has yielded the conodonts *Cordylodus andresi*, *Eoconodontus notchpeakensis*, *Phakelodus tenuis* and *Westergaardodina bicuspidata*.

The upper 0.3 m of the member has yielded the conodonts *Cordylodus proavus* and *C. andresi*.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Suurjõgi Member.

Thickness 4.5 m. Yellowish-grey fine- to medium-grained cross- bedded sandstone containing fragments and rounded valves of *Schmidtites celatus* and *Ungula ingrica*. In the basal 1 m, the conodonts are represented by *Cordylodus proavus*, *C. andresi* and *Eoconodontus notchpeakensis* and *C. intermedius*. *C. lindstromi* appears 3 m above the base of the member.

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Katela Member.

Exposed thickness 1 m. Light brownish-grey fine-grained sandstone. The basal 0.2 m has yielded lingulate debris and the conodonts *Cordylodus angulatus*, *C. lindstromi*, *C. prion*. *Rhabdinopora flabelliformis* aff. *multithecatum* appears above the base of the member (Kaljo *et al.* 1986). The upper boundary is eroded and overlain by Quaternary sediments.

Saka. - The Saka section (Fig. 30), 2 km west of the Saka village, has been exposed since 1984, as a result of construction of a waste water pipe. Previous descriptions of this section include Kaljo *et al.* (1986), Popov *et al.* (1989), Heinsalu *et al.* (1991a,b) and Puura & Holmer (1993).

LOWER CAMBRIAN

Tiskre Formation.

Exposed thickness 3 m. Yellowish-grey sandstone with intercalations of greenish-grey clay.

UPPER CAMBRIAN

Tsitre Formation.

Thickness 0.4 m. Light-grey siltstones and fine-grained sandstones, with intercalations of dark brown kerogenous shales. The Tsitre Formation has yielded *Ungula convexa* and the conodonts *Westergaardodina* cf. *bicuspidata*, *Prooneotodus* cf. *gallatini* and *Furnishina* sp. Lenses of the Tsitre Formation are distributed only locally; they thin out in the northern and southern parts of the Saka outcrop.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Rannu Member.

Thickness 1.8 m. This interval is represented by two transgressive sequences, starting with brachiopod coquinas and coarse- to medium-grained, light-grey sandstones, and terminating with fine-grained sandstones. *Ungula ingrica* and *Schmidtites celatus* occur in the coquinas at the base of the formation and 0.5 m above it. The interval corresponds to the *Cordylodus proavus* and *C. lindstromi* conodont biozones (Kaljo *et al.*, 1986; Heinsalu *et al.* 1991a).

LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation. Orasoja Member.

Thickness 2.2 m. Light-grey siltstones with the intercalations of thin layers of black kerogenous shale, which become more common in the topmost 40 cm of the member. A graptolite *Rhabdinopora flabelliformis* cf. *multithecata* has been found near the base of this interval (Kaljo *et al.*, 1986). *Cordylodus angulatus* appears 1.2 m below the top of the member (Heinsalu *et al.*, 1991a).

Pakerort and Varangu stages. Türisalu Formation. Toolse Member.
Thickness 2.3 m. Black kerogenous shale, with intercalations of light-grey siltstones. The thin siltstone layers have yielded conodonts *Cordylodus angulatus* and *Iapetognathus* sp. *Drepanoistodus deltifer pristinus* appears 0.4 m below the top of the member (Heinsalu *et al.*, 1991a). Accordingly, the topmost 0.4 m of the Toolse Formation belonging to the *D. deltifer pristinus* Biozone are assigned to the Varangu Stage.

Hunneberg Stage. Leetse Formation. Joa Member.
Thickness 1 m. Dark-green glauconitic sandstone, with greyish- green intercalations of clay.

Billingen Stage. Leetse Formation. Mäeküla Member.
Thickness 0.5 m. Dark-green nodular glauconitic sandstone, with dolomitized carbonate cement.

Overlying are the limestones of the Päite Member (0.35 m), and the Volkhov, Kunda and Aseri stages.

Subsurface of Rakvere Phosphorite Deposit and NE Estonia

During the geological survey of the Rakvere Phosphorite Deposit (see Puura, 1987), extensive drilling was carried out in this region. Based on the core data, the lithostratigraphy of the Cambrian- Ordovician boundary beds in the subsurface of the environs of the town of Rakvere has been discussed by Raudsep (1987), Heinsalu & Raudsep (1993) and Heinsalu *et al.* (1994). Unfortunately, in most cases these cores are not suitable for biostratigraphical studies, as weakly cemented sandstones have not been preserved in their original sequence, and the corresponding core intervals are often represented by slurry. Rare exceptions are some sufficiently well preserved cores where clayey and carbonate cementation occurs. Holmer & Popov (1990, p. 261, Fig. 8B) provide a description of the core R-1653, drilled at a site 12 km south-east of Rakvere. In this core, the Ülgase Formation (depth 88.4-89.65) has yielded *Ceratreta tanneri* and the Kallavere Formation (depth 85.85- 88.4) *Ungula ingrica* and *Schmidtites celatus*.

Core R-2162. - This core (Fig. 31), drilled at a site 15 km south-east of Rakvere, has reached the sandstones of the Lower Cambrian Tiskre Formation at the depth of 115.6 m, which is overlain by the Upper Cambrian Tsitre Formation (depth interval 114.1-115.6 m). The basal 20 cm of the overlying sandstones of the Kallavere Formation (104.7-114.1 m) has yielded *Obolus apollinis*. An interval in the upper part of the Kallavere Formation (107.6-108.2 m) has yielded conodonts *Cordylodus proavus* and *C. lindstromi* (Heinsalu *et al.* 1994), and a single specimen of a lingulate brachiopod, *Euobolus elegans*. The Kallavere Formation is overlain by the Leetse Formation, represented by glauconite sandstone.

Core R-1555. - The site of this core drilled in 1979, is about 15 km east of Rakvere. The core (Fig. 32) penetrated the Ordovician and Upper Cambrian rocks and reached the uppermost part of the Lower Cambrian Tiskre Formation. The core yield for the Pakerort Stage was 89% (Raudsep *et al.*, 1981).

LOWER CAMBRIAN

Tiskre Formation.

Depth interval 103.1-106.3 m. Light-grey fine-grained sandstones, with intercalations of clay.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Kallavere Formation.

Depth interval 95-103.1 m. The lower part, depth interval 99.1- 103.1 m, is represented by light-grey fine-grained quartzose sandstones, strongly cemented by carbonate cements. Valves of a lingulate brachiopod *Obolus apollinis* occur throughout this interval.

The upper part, depth interval 95-99.1 m, is composed of brownish-grey medium- to coarse-grained sandstones, with lingulate brachiopod debris and strongly rounded shell fragments of *Ungula ingrica*.

LOWER ORDOVICIAN

Hunneberg Stage. Leetse Formation. Joa Member.

Depth interval 94.2-95 m. Greyish-green glauconitic sandstone.

The Leetse Formation is overlain by the limestones of the Volkhov Stage (depth 91.7-94.2 m).

Core 80. - The drilling site is located in NE Estonia, about 10 km south of the town of Püssi (Fig. 1A). In the depth of 78.8-80.4 m, the core (Fig. 33) has reached the Kallavere Formation, represented by the sandstones with lingulate debris. The Kallavere Formation is overlain by a thin layer of grey shale, representing Türisalu Formation (78.7-78.8 m). This interval has yielded lingulate brachiopods referred to *Eurytreta?* sp. According to I. Paalits (pers. comm., 1995), this interval has yielded acritarchs characteristic of *Drepanoistodus deltifer pristinus* conodont Biozone. The overlying interval of glauconite sandstone (78.3-78.7 m) belongs to the Leetse Formation. Overlying are the limestones of the Toila Formation.

Subsurface in southern Estonia

In the subsurface of central Estonia, approximately along the Pärnu-Mustvee line (Fig. #) occurs a hiatus corresponding to the Upper Cambrian and the Pakerort Stage; in this area the Upper Cambrian and earliest Ordovician rocks have been possibly eroded (Mens *et al.* 1993, Fig. 1; Heinsalu 1986, Fig. 1). The distribution of the Upper Cambrian Petseri Formation in south-eastern Estonia and adjacent areas of Russia and Latvia has been discussed by Volkova *et al.* (1981); acritarchs from the Petseri Formation have been described by Paalits (1992a). Lingulate brachiopods assigned to the genera *Oepikites*, *Ungula* and *Angulotreta* have been reported from the Petseri Formation (Mens *et al.* 1987, 1990); unfortunately, these identifications could not be verified, as no core samples were available for examination. The fossils from the overlying Kallavere Formation in south-eastern Estonia remain poorly studied; available samples from two drill cores have yielded lingulate brachiopods. In the Laanemetsa and Värska-6 cores, the overlying Kallavere Formation has yielded lingulate brachiopods.

Core Värska-6. - The drilling site is located in the environs of Värska village, south-eastern Estonia (Fig. 1A). In this core (Fig. 34), the Middle Cambrian Paala Beds are overlain by dark- grey sandstones of the Kallavere Formation, occurring in the depth interval 455.2-494 m. At the base of the Kallavere Formation occurs lingulate brachiopod coquina composed of abundant valves of *Schmidtites celatus* and rare *Ungula ingrica*. Given the lack of conodont data, the age of the Kallavere Formation in this section remains open: it could be Upper Cambrian and/or Lower Ordovician. The Kallavere Formation is overlain by glauconitic sandstone of the Leetse Formation.

Laanemetsa core. - The drilling site is near Laanemetsa village, close to the southern border of Estonia (Fig. 1A). The Middle Cambrian Paala Beds are overlain by the fine-grained sandstones and siltstones of the Upper Cambrian Petseri Formation, occurring in the depth interval 405.5-416.1 m (Volkova *et al.* 1981). The overlying Kallavere Formation occurs in the depth interval 399.6-405.5 m and is composed of light-grey fine- to medium- grained sandstones. A sample from the depth 399.65 m contains abundant valves of *Schmidtites celatus*. As in the case with the Värska core, the age of the Kallavere Formation remains open.

INGRIA, NORTHWESTERN RUSSIA

Narva River. - On the east bank of the Narva River, 350 m upstream of the dam of the Narva hydroelectric power station, a section of the Cambrian-Ordovician boundary beds is exposed (Fig. 36). The description, from the base to the top, follows Popov *et al.* (1989). The Lower Cambrian Tiskre Formation, composed of light-yellow to white siltstones is overlain by the Tosna Formation.

UPPER CAMBRIAN AND/OR LOWER ORDOVICIAN

Pakerort Stage. Tosna Formation. Lower subformation.
Thickness 0.8 m. Brownish-grey fine to medium-grained cross-bedded quartzose sandstone, with lingulate debris, dolomitized. Lower boundary sharp. In some places occur flattened pebbles of phosphatized sandstone, up to 20 cm long.

In the upper 30 cm of this interval, rare valves of *Obolus apollinis*, *Helmersenia ladogensis* and redeposited valves of *Schmidtites celatus* and *Ungula ingrica* occur.

Pakerort Stage. Tosna Formation. Upper subformation.
Thickness 2.1 m. Reddish-brown to brownish-grey cross-bedded quartzose sandstone. This interval has yielded redeposited valves of *Obolus apollinis*, *Schmidtites celatus*, *Ungula ingrica* and *Keyserlingia buchii*. A 0.03 m thick layer of light-brown pelitic phosphorite occurs in the top of this interval.

Hunneberg Stage. Leetse Formation. Joa Member.
Thickness 0.2 m. Greenish-grey glauconitic sandstone and sandy clay.

Luga River. - Outcrops along the Luga River near Yamburg (Kingisepp) were studied by Eichwald (1825), who described *Obolus apollinis* and *Obolus ingricus* from one of these localities (Eichwald 1829). The Cambrian-Ordovician boundary beds are exposed in numerous outcrops between the bridge in Kingisepp town to the Novyj Lutsk village along the river (e.g., Rukhin 1939; Popov *et al.* 1989).

An outcrop (Fig. 37), 100 m upstream of the old bridge, opposite of the Yekaterina Church (locality K-20 of Popov *et al.* 1989) is the best studied from a palaeontological perspective. In this section, the lower 3.5 m of the sandstone sequence, represented by light-yellow quartzose sandstone have been assigned by Popov *et al.* (1989) to the Novolutsk Beds of tentative Middle Cambrian age. Overlying is the 1.7 m thick Tosna Formation, represented by brownish-grey sandstone, yielding fragments of *Obolus apollinis* and redeposited valves of *Ungula ingrica*, *Schmidtites celatus* and *Keyserlingia buchii*. The first appearance of the conodont *Cordylodus proavus* has been documented 0.1 m above the base of the Tosna Formation. The uppermost 0.1 m of the Tosna Formation has yielded the conodonts *Cordylodus angulatus*, *C. lindstromi* and *C. prion*. Overlying are the glauconitic sandstones of the Leetse Formation.

Solka River. - On the left bank of the Solka River (a tributary of the Luga River), near the Killi village, 30 m upstream of the ruins of a mill, the fine-grained sandstones of the Lower Cambrian Tiskre Formation are overlain by the Tosna Formation (Popov *et al.* 1989, outcrop L-35; Fig. 38 herein).

LOWER ORDOVICIAN
Pakerort Stage. Tosna Formation. Upper subformation.
Thickness 0.15 m. Brownish-grey sandstone, containing lingulate debris. At the base of this interval, up to 10 cm long phosphatized sandstone pebbles occur, along with an up to 2 cm

thick limonitized layer and large ferriferous ooids, up to 1.5 cm in diameter. This interval yields fragments of valves and debris of *Obolus apollinis*, *Schmidtites celatus*, *Ungula ingrica* and *Keyserlingia buchii*. Conodonts are represented by *Cordylodus angulatus* and *C. rotundatus*.

Koporye Formation.
Thickness 0.17 m. Dark-brown to black kerogenous argillite, with thin intercalations of siltstone and silty clay, yielding graptolite debris.

Overlying is the Leetse Formation composed of greenish-grey glauconitic sandstone.

Suma River. - An outcrop of the Cambrian-Ordovician boundary beds (Fig. 39) is located on the right bank of the Suma River, 500 m downstream of the bridge on the road connecting the Kaibolovo village with the R-35 road. This outcrop has been described by Rukhin (1939) and Popov *et al.* (1989, outcrop L-31).

The Tiskre Formation (0.3 m exposed) is overlain by the Tosna Formation.

UPPER CAMBRIAN
Pakerort Stage. Tosna Formation. Lower subformation.
Thickness 3 m. Reddish-brown cross-bedded fine- to medium-grained sandstone. *Obolus apollinis* is characteristic of this interval. The basal 0.05 m yields a coquina of valves of *Schmidtites celatus*, *Ungula convexa* and *Keyserlingia buchii*.

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Tosna Formation. Upper subformation.
Thickness 1 m. Reddish-grey cross-bedded quartzose sandstone, with debris of lingulates *Obolus apollinis*, *Schmidtites celatus* and *Ungula ingrica*. Near the top of this interval, the conodonts *Cordylodus lindstromi* and *C. prion* appear.

LOWER ORDOVICIAN
Pakerort Stage. Koporye Formation.
1.9 m - Black kerogenous argillite, with the 1-2 cm thick intercalations of brownish-grey siltstones. The basal part of this interval is represented by a 0.15 m thick reddish clayey siltstone. A sample 0.7 above the base of this interval has yielded the conodonts *Cordylodus angulatus*, *C. lindstromi* and *C. prion*.

Overlying is the greenish-grey glauconitic sandstone of the Leetse Formation.

Lomashka River. - On the right bank of the Lomashka River, 2.3-2.5 km downstream from the bridge in the Lomaha village, and 2 km upstream of the mouth of the river, a sequence of Cambrian-Ordovician boundary beds is exposed (Fig. 40). This section has been suggested by Popov *et al.* (1989, outcrop L-34) as the stratotype for Lomashka and Koporye formations. In this section, the siltstones and clays of the Lower Cambrian Lükati Formation are overlain by 2.2 m of the fine-grained sandstones of the Upper Cambrian Lomashka Formation. The 0.1 m thick coquina et the base of the Formation has yielded *Schmidtites celatus*, *Oepikites obtusus* and *Ungula* sp. The conodonts *Cordylodus andresi*, *Furnishina furnishi*, *Prooneotous tenuis* and *Westergaardodina bicuspidata* and a lingulate brachiopod *Rebrovia chernetskae* appear 0.8 m below the top of the Lomashka Formation. From the intercalations of clay in the lower part of the lower part of the Lomashka Formation, N.I. Golub (in Popov *et al.* 1989) reported an acritarch assemblage including *Acanthodiacrodium* sp., *Stelliferidium* aff. *stelligerum*, *Stelliferidium* sp., *Cymatiosphaera* sp. *C.* aff. *columelliferae*, *Baltisphaeridium capillatum* and *Acanthodiacrodium* aff. *ubui*.

Overlying is the 2.0 m thick Tosna Formation, composed of reddish-brown sandstones. The lower 1.3 m is rich in the valves of *Helmersenia ladogensis*. *Obolus apollinis* occurs in the basal 0.4 m, but is not common. The uppermost 0.5 m of the Tosna Formation yields valves and fragments of *Helmersenia ladogensis*, *Schmidtites celatus* and *Keyserlingia buchii*. A sample from the lower 0.4 m has yielded a conodont species *Cordylodus lindstromi* and a sample from the upper 0.2 m *C.lindstromi* and *C. prion*.

The lowest 2.4 m of the overlying Koporye Formation is represented by intercalating fine-grained sandstones and black kerogenous argillites; the upper 2.2 m consists of a monotonous sequence of black kerogenous argillites. *Cordylodus lindstromi* and *C. prion* occur in the basal 0.6 m of the *Koporye Formation*; a graptolite *Rhabdinopora flabelliformis rossicum* has been reported 0.4 m above the base of the Formation (Kaljo *et al.* 1986). The interval from 2.5 to 3 m above the base of the Koporye Formation has yielded the conodonts *Cordylodus angulatus* and *C. prion*.

Dudergoff Heights. - The most complete sequence of Cambrian- Ordovician boundary beds in the region of Dudergoff Heights, SSE of St. Petersburg is exposed in a wall of an old quarry on *Kirchoff Hill*, 250-300 m north of the western border of Karvala village (Fig. 41). The Ladoga Formation (0.45 m exposed), composed of fine- grained yellowish-white quartzose sandstones, has yielded numerous valves of *Keyserlingia reversa*. The overlying Tosna Formation (3 m) is represented by yellowish-red quartzose sandstone with thin intercalations of kerogenous argillite containing lingulate brachiopod debris dominated by fragments of *Schmidtites celatus*. The top of the formation is marked by a 0.1 m thick pyritized sandstone bed. The overlying Koporye Formation (0.6 m) is composed of the dark-grey to black kerogenous argillites. The Koporye Formation is overlain by the glauconitic sandstones of the Leetse Formation.

Izhora River. - Outcrops of the Cambrian-Ordovician boundary beds in Izhora River (Fig. 42) have been described and discussed by Rukhin (1939), Borovko *et al.* (1980, 1984), Borovko & Sergeyeva (1981) and Popov *et al.* (1989).

An outcrop on the left bank of the Izhora River 8 km south of the town of Pavlovsk 3.5 km NE of the Fedorovskij village and downstream of the ruins of a water-mill, is the stratotype of the Ladoga Formation. In this section, the sandstones of the Sablinka Formation overlie the blue clay of the Lower Cambrian Lontova Formation, exposed at or slightly above the water level of the river. The description follows Borovko *et al.* (1984).

MIDDLE CAMBRIAN

Sablinka Formation.

Thickness 3.5 m. Yellowish-grey to light-yellow fine- to medium- grained sandstones, with the intercalations of greyish-green clay. The acritarch assemblage includes *Lophomarginata corollata*, *L. glumacea*, *L. izhorica* and *Leiosphaeridia bicrura*.

UPPER CAMBRIAN

Ladoga Formation.

Thickness 1.4 m. Brownish-grey fine- to medium-grained cross- bedded sandstone, with intercalations of greenish-grey and brownish-grey clays. The basal 0.3 m of the formation has yielded fragments and rare valves of lingulate brachiopods *Ungula convexa* and *Keyserlingia reversa* and a conodont assemblage including *Westergaardodina moessebergensis*, *W. bicuspidata*, *W.* cf. *fossa*, *Prooneotodus* aff. *gallatini*, *Problematoconites perforata*, *Proconodontus rotundatus*, *Hertzina americana* and *Prooneotodus terashimai*. Fragments of *Torelella* sp. and *Rukhinella spinosa* also occur in this interval. The topmost 0.65 m of the formation has yielded a different conodont assemblage, including *Westergaardodina fossa*, *W. bicuspidata*, *Furnishina furnishi*, *F. alata*, *Proconodontus primitivus* and *Prooneotodus tenuis*.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Tosna Formation.

Thickness 3 m. Brownish yellow and light-grey cross-bedded sandstones containing lingulate brachiopod debris. The lowermost 10 cm consists of light-grey coarse-grained sandstone, with rare pebbles. The basal 1 m of the formation has yielded lingulate brachiopods *Obolus apollinis*, *Keyserlingia buchii* and *Helmersenia ladogensis*. The interval 0-0.5 m above the base of the formation has yielded *Cordylodus proavus*. *Cordylodus lindstromi* and *C. angulatus* appear 0.7 and 2 m above the above the base of the formation, respectively.

LOWER ORDOVICIAN

Pakerort Stage. Koporye Formation.

Thickness 0.8 m. Black kerogenous shale, with anthraconite concretions and thin intercalations of siltstone. The siltstone lenses have yielded *Cordylodus angulatus*.

The Koporye Formation is overlain by glauconitic sandstones of the Leetse Formation.

Another outcrop on the left bank of the Izhora River, located 700 m upstream, has been described by Popov *et al.* (1989). In this section, the exposed thickness of the yellowish-grey to light- yellow fine- to medium-grained sandstones of the Sablinka Formation is 2 m. The upper 0.75 m of the formation is assigned to the Gertovo Member. *Obolus transversus* occurs in the basal 0.05 m of this member. The overlying Ladoga Formation, 1.4 m thick, is represented by brownish-grey and yellowish-grey cross-bedded sandstones with intercalations of greenish-gray clays. The Ladoga Formation has yielded the lingulate brachiopods *Ungula convexa*, *Ralfia ovata*, *Rebrovia chernetskae* and *Keyserlingia* sp., and the conodonts *Westergaardodina moessebergensis* and *Prooneotodus* aff. *gallatini*. Overlying are the medium-grained sandstones of the Tosna Formation. The basal 0.3 m of the formation has yielded lingulate brachiopods *Obolus apollinis* and *Helmersenia ladogensis*, and a conodont *Cordylodus proavus*.

Tosna River. - Many outcrops of the Cambrian-Ordovician boundary beds occur on the banks of the Tosna River, downstream of the Gertovo village and on the banks of the Sablinka Brook, a tributary of the Tosna River. Many of these outcrops were described by Rukhin (1939); a recent account has been provided by Popov *et al.* (1989, p. 32).

A section on the left bank of the Tosna River, upstream of the Sablinka Brook (outcrop L-11 of Popov *et al.*, 1989; Figs 43, 44 herein) is the stratotype of the Sablinka and Tosna Formations. In this section, the Middle Cambrian Sablinka Formation (15.5 m), composed of yellowish-grey cross-bedded quartzose sandstones with intercalations of clay, overlies blue clays of the Lower Cambrian Lontova Formation. The section above the Sablinka Formation is described as follows.

UPPER CAMBRIAN

Ladoga Formation.

Thickness 0.2 m. Light-grey fine- to medium-grained cross-bedded quartzose sandstone, containing up to 8 cm long sandstone pebbles in the basal part. Lingulate brachiopods are represented by *Ungula convexa*, *Keyserlingia reversa* and conodonts by *Prooneotodus* aff. *gallatini* and *Problematoconites perforata*.

UPPER CAMBRIAN - LOWER ORDOVICIAN

Pakerort Stage. Tosna Formation.

Thickness 3 m. Light-brown and grey medium-grained cross-bedded quartzose sandstones. The lowest 1.5 m, considered by Popov *et al.* (1989) as the lower subformation, has yielded lingulate brachiopods *Obolus apollinis* and rounded valves of *Schmidtites celatus*, *Ungula convexa* and *Keyserlingia* sp. A conodont *Cordylodus proavus* appears 1.05 m above the base of the formation. *Cordylodus angulatus* appears 0.2 m below the top of the Tosna Formation.

LOWER ORDOVICIAN

Pakerort Stage. Koporye Formation.

Thickness 0.25 m. Black kerogenous argillite, with thin intercalations of siltstone.

The Koporye Formation is overlain by the glauconitic sandstones of the Leetse Formation.

Another locality (outcrop No. 789 of Popov *et al.* 1989) on the right bank of the Tosna River, 200 m upstream of the southern margin of the Pustynka village, is the stratotype of the Gertovo Member of the Sablinka Formation. Here, the lower part of the section is represented by light-grey fine-grained quartzose sandstones of the lower subformation of the Sablinka Formation (exposed thickness 1.8 m). The overlying Gertovo Member of the upper subformation of the Sablinka Formation (2.8 m) is composed of light-grey fine- to medium-grained sandstone, with intercalations of clay. The lower 2.3 m of the Gertovo Member contains rare complete valves of the lingulate brachiopod *Oepikites macilentus* and fragments of *Obolus ruchini*. The Sablinka Formation is overlain by the Tosna Formation.

Naziya River. - A section on the left bank of the Naziya River 400 m downstream of the ruins of Novaya village is the stratotype of the Naziya Formation (Fig. 45). The section has been described by Borovko *et al.* (1983) and Popov *et al.* (1989).

UPPER CAMBRIAN

Ladoga Formation. Upper subformation.

Exposed thickness 2.9 m. Light-grey fine-grained quartzose sandstone, with intercalations of greenish-grey clay. The formation has yielded rare lingulate brachiopods *Ungula convexa* and conodonts *Furnishina furnishi*, *Prooneotodus* aff. *gallatini*, *P. tenuis*, *Westergaardodina bicuspidata* and *W. moessebergensis*.

LOWER ORDOVICIAN

Pakerort Stage. Tosna Formation.

Thickness 1.4 m. Pinkish-brown fine- to medium-grained cross- bedded sandstone. The lingulate brachiopod assemblage includes *Obolus apollinis* and *Helmersenia ladogensis*, and debris and rounded valves of *Ungula convexa*, *Ralfia ovata* and *Keyserlingia* sp. Among the conodonts, *C. lindstromi* and *C. proavus* appear near the base and *C. angulatus* 0.05 m below the top of the formation.

Pakerort Stage. Koporye Formation.

Thickness 0.25 m. Black kerogenous argillite intercalated with reddish-brown fine-grained sandstone. The formation has yielded conodonts of the *Cordylodus angulatus* Biozone (Borovko *et al.* 1983).

Varangu Stage. Naziya Formation.

Thickness 0.25 m. Greenish-grey glauconitic sandstones and clays yielding fragments of lingulate brachiopod *Eosiphonotreta* aff. *acrotretomorpha*. The conodont assemblage (Borovko *et al.* 1983, Fig. 1) corresponds to the *Drepanodus deltifer deltifer* Biozone.

The Naziya Formation is overlain by glauconitic sandstones of the Leetse Formation.

Lava River. - On the right bank of the Lava River, a section from the Upper Cambrian Ladoga Formation to the Lower Ordovician Kunda Stage is exposed (Fig. 46). Raymond (1916) gave a generalized description of the section; the Cambrian-Ordovician boundary beds have been described by Popov *et al.* (1989) and the Lower Ordovician part above the

Naziya Formation by Dronov *et al.* (1995).

UPPER CAMBRIAN

Ladoga Formation.

Exposed thickness 0.4 m. Light-grey fine-grained quartzose sandstone. The lingulate brachiopods *Ungula convexa*, *Vassilkovia granulata*, and the conodonts *Furnishina alata*, *F. furnishi*, *Prooneotodus* aff. *gallatini*, *P. tenuis* and *Westergaardodina bicuspidata* occur in this interval. Phosphatic fragments of a small skeletal fossil *Rukhinella spinosa* have been found.

UPPER CAMBRIAN AND/OR LOWER ORDOVICIAN

Pakerort Stage. Tosna Formation.

Thickness 3.55 m. Light grey to reddish-brown cross-bedded fine- to medium grained quartzose sandstone. The lower 0.6 m yields rounded valves of *Ungula convexa* and rare sponge spicules. In the middle and upper part of the interval, *Obolus apollinis* is abundant and rare *Lingulella antiquissima* and *Vassilkovia granulata* occur. Rare conodonts are represented by *Prooneotodus* aff. *gallatini*.

LOWER ORDOVICIAN

Pakerort Stage. Koporye Formation.

Thickness 0.6 m. Reddish-brown quartzose sandstone with intercalations of greenish and reddish clays and black kerogenous argillites. The lower 0.3 m has yielded the lingulates *Obolus apollinis* and *Helmersenia ladogensis* and a conodont *Cordylodus angulatus*. The uppermost 0.1 m of the interval comprises black kerogenous argillite, with thin intercalations of the fine-grained quartzose sandstone.

Varangu Stage. Naziya Formation.

Thickness 0.05 m. Greenish-grey clay, with 1-2 cm thick glauconitic quartzose sand at the base. This interval has yielded a lingulate brachiopod *Eosiphonotreta* aff. *acrotretomorpha* and the conodonts *Drepanodus arcuatus*, *Drepanoistodus deltifer deltifer* and *D. d. pristinus*, *Cordylodus angulatus*, *C. intermedius*, *C. lindstromi* and *C. prion*.

The overlying glauconitic siltstones and sandstones of the Hunneberg Stage (1.2 m) have been recently assigned to the Lakity Beds by Dronov *et al.* (1995), who reported the occurrence of *Eosiphonotreta* aff. *acrotretomorpha* 0.3-0.5 m above the base of this interval. The Lakity Beds are overlain by the Mäeküla Member, 0.5 m thick, represented by glauconitic sandstones and limestones.

Sarya River. - The sections of Cambrian-Ordovician boundary beds on the banks of the Sarya River (Fig. 47), near Vojbokalo village, have been described by Rukhin (1939) and Popov *et al.* (1989). The lower part of the Gertovo Member is exposed in an outcrop 700 m downstream of Vojbokalo village (outcrop L-6 of Popov *et al.*, 1989). In this section, the Gertovo Member overlies the lower subformation of the Sablinka Formation, composed of white medium- grained quartzose sandstone. The exposed thickness of the Gertovo

Member is 3.5 m; it is composed of light-grey and brownish-grey fine- to medium-grained cross- bedded sandstones. Lingulate brachiopods are represented by complete valves of *Oepikites macilentus* and fragments of *Obolus ruchini*; the latter occur in the basal part of the member. The upper boundary of the Gertovo Member is eroded and overlain by Quaternary sediments.

The Ladoga and Tosna Formations are exposed in another section, located on the right bank of the Sarya River, 550 m upstream of the previous locality, near a bridge in Vojbokalo village. In this locality, the Sablinka Formation is overlain by the Ladoga Formation (up to 0.6 m thick) and composed of light-grey sandstones. Conodonts in the Ladoga Formation are represented by *Problematoconites perforata* and lingulate brachiopods by the valves of *Ralfia ovata* and fragments of *Ungula convexa*. The overlying Tosna Formation, reaching 3.8 m in thickness, is composed of brownish-gray medium- grained cross-bedded quartzose sandstone. The upper part of the formation has yielded the lingulate brachiopods *Obolus apollinis* and *Helmersenia ladogensis*.

Volkhov River. - Outcrops along the Volkhov River (Fig. 48) have been described by Rukhin (1939) and Popov *et al.* (1989). An exposure of the Cambrian-Ordovician boundary beds is situated on the right bank of the Volkhov River, upstream of the southern margin of the Gorchakovskaya village (outcrops L-40 and L-41 of Popov *et al.*, 1989).

MIDDLE CAMBRIAN

Sablinka Formation. Lower subformation.

Exposed thickness 2.3 m. Light-grey fine- to medium-grained sandstone, with 1-3 mm thick intercalations of light-brown clay. Lower boundary not exposed.

Sablinka Formation. Upper subformation. Gertovo Member.

Thickness 0.4 m. Light-grey fine- to medium-grained quartzose sandstone, cross-bedded in upper 0.2 m of the Member. Lingulate brachiopods are represented by *Obolus ruchini*, occurring throughout the Member and *Oepikites macilentus*, occurring in the uppermost 20 cm of the Member.

Sablinka Formation. Upper subformation. Rebrovo Member.

Thickness 1.25 m. Light-grey fine- to medium-grained cross-bedded sandstone, with up to 3 mm thick intercalations of light-grey clay. Lingulate brachiopods are represented by rare *Oepikites koltchanovi* and *Obolus transversus*.

UPPER CAMBRIAN

Ladoga Formation. Lower subformation.

Thickness 3.9 m. Light-grey siltstone, with intercalations of greyish-green and brown clay. Lingulate brachiopods are represented by *Gorchakovia granulata* and *Angulotreta* cf. *postapicalis*, and conodonts by *Furnishina furnishi* and *Prooneotodus tenuis*. This interval has also yielded *Rukhinella spinosa*.

Ladoga Formation. Upper subformation.

Thickness 0.25 m. Brownish-grey to light brown fine-grained quartzose sandstone, yielding rare valves of a lingulate brachiopod *Ungula convexa*, and the conodonts *Proconodontus rotundatus*.

Pakerort Stage. Tosna Formation.

Exposed thickness 0.7 m. Reddish-brown fine- to medium-grained cross-bedded sandstone, with lingulate debris. Lingulate brachiopods are represented by *Obolus apollinis* and rounded specimens and fragments of *Oepikites triquetrus*, *Schmidtites celatus* and *Ungula convexa*. One conodont species *Cordylodus proavus* occurs in this interval. The upper boundary of the Tosna Formation is eroded and overlain by Quaternary sediments.

A more complete section of the Tosna Formation is located on the right bank of the Volkhov River, across the river from the northern margin of Staraya Ladoga village (outcrop L-42 of Popov *et al.*, 1989). In this section, the Tosna Formation reaches 4.6 m in thickness. The lower 0.6 m of the formation is composed of reddish-brown medium- to coarse-grained cross-bedded sandstone. The basal coquina contains the valves of *Obolus apollinis* and rounded valves of *Oepikites triquetrus* and *Schmidtites celatus*. The upper 4 m of the Tosna Formation is composed of brownish-grey fine-grained quartzose sandstone. Lingulate brachiopods are represented by *Helmersenia ladogensis* and conodonts by *Cordylodus proavus*. The upper boundary of the Tosna Formation is eroded and overlain by Quaternary sediments.

Syas River. - The Cambrian-Ordovician sections on the banks of the Syas River (Fig. 49) have been described by Rukhin (1939) and Popov *et al.* (1989).

A section on the right bank of the Syas River, near the southern margin of the Rebrovo village (outcrop L-19 of Popov *et al.* 1989), is the stratotype of the Rebrovo Member of the Sablinka Formation. In this section, the exposed thickness of the Rebrovo Member is 4.4 m; the lower boundary is not exposed. The Rebrovo Member is composed of light-grey fine- to medium- grained sandstone, with intercalations of greenish-grey clay, cross-bedded in the upper 3.6 m. Lingulate brachiopods are represented by *Oepikites koltchanovi* and *Obolus transversus*. The Rebrovo Member is overlain by the fine- grained sandstones of the Ladoga Formation yielding *Oepikites fragilis*.

Another section (outcrop L-17 of Popov *et al.* 1989) is situated 200 m upstream of the previous one. In this section, the Sablinka Formation is overlain by the Ladoga Formation.

UPPER CAMBRIAN

Ladoga Formation. Lower subformation.

Thickness 1.3 m. Light-grey siltstones and fine-grained sandstones, with intercalations of greyish-brown clays. The lingulate brachiopods *Oepikites fragilis*, *Rebrovia chernetskae*, *Ungula* sp., *Acrotreta* cf. *postapicalis* and *Ceratreta* cf. *tanneri* occur in the interval 0.05-0.65 m above the base of the formation. Conodonts are represented by *Furnishina furnishi*, *Prooneotodus tenuis*, *Westergaardodina bicuspidata*. Fragments of *Rukhinella spinosa* have been found from the upper 0.65 m of the subformation.

Ladoga Formation. Upper subformation.

Thickness 1.75 m. The basal 0.15 m of this interval, composed of light-brown fine- to medium-grained cross-bedded sandstone, with lingulate brachiopod debris, yields the conodonts *Proconodontus rotundatus* and lingulate brachiopods *Oepikites triquetrus*, *Schmidtites celatus* and *Ungula convexa*. This bed is overlain by 1.5 m thick light-grey fine-grained sandstone, with thin intercalations of greyish-green and brown clays, yielding rare valves of *Ungula convexa*. The uppermost 0.1 m of the formation is composed of greyish-green clay, intercalated with quartzose sandstone layers.

UPPER CAMBRIAN - LOWER ORDOVICIAN
Pakerort Stage. Tosna Formation.

Thickness 4.9 m. Basal 0.3 m of the formation iscomposed of greyish-brown medium-grained quartzose sandstone. Lingulate brachiopods are represented by *Obolus apollinis* and rounded valves of *Schmidtites celatus*, *Oepikites triquetrus* and *Ungula convexa*. The conodonts *Cordylodus proavus* and *Phakelodus tenuis* have been found.

The upper 4.6 m is composed of light-grey fine-grained cross-bedded quartzose sandstone. Lingulate brachiopods are represented by *Helmersenia ladogensis* and rare *Obolus apollinis*; *Lingulella antiquissima* occurs in the interval 1.8-2.2 m above the base of the Tosna Formation. The conodont *Cordylodus lindstromi* appears 3.2 m above the base of the Tosna Formation.

The Tosna Formation is overlain by the Koporye Formation, composed of black shales, intercalating with fine-grained quartzose sandstones.

SYSTEMATIC PALAEONTOLOGY

The illustrated and/or discussed material is deposited in the following institutions: Institute of Geology, Estonian Academy of Sciences, Tallinn (GT Br), Swedish Museum of Natural History, Stockholm (RM Br), St. Petersburg University (SPU) and Central Scientific Research Geologic Exploration Museum, St. Petersburg, Russia (CNIGR). The descriptive terminology follows Williams & Rowell (1965), Holmer (1989, p. 30) and Popov & Holmer (1994, p. 34).

Morphometric studies were not included within the scope of the present work, as a study of the variability of selected Cambrian and Lower Ordovician species and genera, with the application of outline and landmark methods (Rohlf & Bookstein 1990), represents a potential separate research project. For previous conventional morphometric studies applying sets of linear measurements, the reader is referred to Popov & Khazanovitch (1989), Holmer & Popov (1990) and Popov & Holmer (1994).

Phylum Brachiopoda Duméril, 1806
Class Lingulata Goryanskij & Popov, 1985
Order Lingulida Waagen, 1885
Superfamily Linguloidea Menke, 1828
Family Obolidae King, 1846

Genus *Obolus* Eichwald, 1829

Synonymy. - []1829 *Obolus* gen. nov. - Eichwald, p. 274. [] 1969 *Obolus* (*Obolus*) Eichwald (in part) - Goryanskij, p. 19. []1984 *Obolus* Eichwald - Khazanovitch & Popov *in* Khazanovitch *et al.*, p. 27. []1989 *Obolus* Eichwald - Popov & Khazanovitch, p. 97.

Type species. - Original designation by Eichwald (1829, p. 274); *Obolus apollinis* Eichwald, 1829; Tosna Formation, Luga River near Kingisepp, St. Petersburg Region, Russia.

Diagnosis. - Shell subcircular to rounded subtriangular, dorsibiconvex to subequally biconvex. Ventral pseudointerarea triangular, with well-defined flexure lines. Pedicle groove deep and narrow. Dorsal propareas narrow and high, lacking flexure lines. Dorsal median ridge vestigial or absent. Visceral area of both valves slightly thickened, extending to mid-valve. *Vascula lateralia* of both valves submarginal, arcuate (modified after Popov & Khazanovitch, 1989, p. 97).

Species assigned. - *Obolus apollinis* Eichwald, 1829; *Obolus ruchini* Khazanovitch & Popov, 1984; *Ungula transversa* Pander, 1830.

Discussion. - The genus *Obolus* (Eichwald), as revised by Popov & Khazanovitch (1989) includes the type species and two species from the Middle Cambrian of Ingria, Russia. *Ungula* Pander, 1830, was previously considered to be a junior synonym of *Obolus* Eichwald, 1829, but Popov & Khazanovitch (1989) have demonstrated the distinctness of these two genera. *Obolus* differs from *Ungula* Pander by having subcircular, thinner and flatter shell, a lack of a heart- shaped depression in ventral visceral area and a lack of flexure lines in dorsal propareas.

In many early studies (e.g., Mickwitz 1896; Walcott 1898, 1912) *Obolus apollinis* Eichwald was confused with *Ungula ingrica* (Eichwald), and the latter species was often illustrated as the type species of the genus *Obolus* (see the discussion of *Obolus apollinis* below). It should be also noted that Mickwitz (1896) and Walcott (1912) applied a very wide generic concept of *Obolus* introducing many subgenera. Walcott (1912) included in *Obolus* 77 species and 11 subspecies, among which the only true representative of *Obolus* is a variety, discussed on p. 383 as "*O. apollinis* in the narrower sense", conspecific with *Obolus apollinis*. Most of Mickwitz's and Walcott's subgenera of *Obolus* have been assigned to separate linguloid genera (Rowell 1965; Goryanskij 1969; Popov & Khazanovitch 1989).

Occurrence. - Middle Cambrian - Lower Ordovician (Tremadoc), Ingria, Russia, and Estonia.

Obolus apollinis Eichwald, 1829

Fig. 50

Synonymy. - []1829 *Obolus apollinis* sp. nov. - Eichwald, p. 274, Pl. 4: 5a,b. []1830 *Ungula plana* sp. nov. - Pander, p. 59, Pl. 28: 5a, b. []1840 *Obolus apollinis* Eichwald - Eichwald, p. 194. [in part]. []1845 *Obolus apollinis* Eichwald - de Verneuil *in* Murchison et al., p. 290 [in part], Pl. 19: 3. []1848 *Aulonotreta polita* n. sp. - Kutorga, p. 278; Pl. 7:10a-e; not Pl. 7:10f. []1853 *Obolus apollinis* Eichwald - Davidson, p. 135 [in part]; Fig. 51, 52; Pl. 9: 280, 282, 283;not Pl. 9: 281, 285. []1860 *Obolus apollinis* Eichwald - Eichwald, p. 925 [in part]. []1861a *Obolus apollinis* Eichwald - Eichwald, p. 264 [in part]. []1892 *Obolus apollinis* Eichwald - Hall & Clarke, p. 80 [in part], Fig. 33, not Fig. 34. []1896 *Obolus apollinis* Eichwald - Mickwitz, p. 133 [in part]. []not 1896 *Obolus Apollinis* Eichwald - Mickwitz, p. 133, Pl. 1:1-14. []not 1896 *Obolus Apollinis* Eichwald var. *ingricus* n. var. - Mickwitz, p. 137, Pl. 1:15-28. []not *Obolus Apollinis* Eichwald var. maximus n. var. - Mickwitz, p. 140, Pl. 1: 29-38. []not 1896 *Obolus Apollinis* var. *Quenstedti* Mickwitz - Mickwitz, p. 143, Pl. 2:1-6. []not 1898 *Obolus apollinis* Eichwald - Walcott, Pl. 26:3-6. []not 1902 *Obolus apollinis* Eichwald var. Quenstedti - Matthew, p. 93, Pl. 1:10. []not 1905 *Obolus Apollinis* Eichwald - Wiman, p. 62, Pl. 3:1-11. []not 1906 *Obolus Apollinis* Eichwald - Moberg & Segerberg, p. 65, Pl. 3:1-3. []1912 *Obolus apollinis* Eichwald - Walcott, p. 381 [in part], not Figs 4, 15, Pl. 7:1-8, 10-17; 14:6, 6a. []not 1912 *Obolus apollinis ingricus* (Eichwald) - Walcott, p. 384. []not 1912 *Obolus apollinis maximus* Mickwitz - Walcott, p. 384, Pl. 7:9; 14:7, 7a. []not 1912 *Obolus apollinis quenstedti* (Mickwitz) - Walcott, p. 384, Fig. 34a, b. []not 1964 *Obolus apollinis* Eichwald - Biernat, p. 73, Pl. 1: 1- 7. []not 1965 *Obolus apollinis* Eichwald - Rowell, p. H263; Fig. 159a-d. []1969 *Obolus (Obolus) apollinis* Eichwald - Goryanskij, p. 20, Pl. 1:1-9, not Pl. 1:10-11. [] 1986 *Obolus apollinis* Eichwald - Kaljo *et al.*, Pl. 1: 4-7. [] 1989 *Obolus apollinis* Eichwald - Popov & Khazanovitch, p. 98, Pl. 1: 1-11; Pl 8: 1; Pl. 1: 17.

Lectotype. - Selected by Popov & Khazanovitch, 1989, p. 98; SPU 1/3534, Luga river near Kingissepp (Yamburg), Lower Ordovician, Tosna Formation.

Figured material. - Ventral valves: GT Br 1703; GT Br 1705; GT Br 3512; GT Br 3514. Dorsal valves: GT Br 1704; GT Br 1706; GT Br 3513.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - Shell flattened, slightly dorsibiconvex, subcircular in outline. Ventral pseudointerarea narrow and triangular, with well-defined flexure lines and narrow deep pedicle groove. Dorsal pseudointerarea narrow, with wide, slightly concave median groove. Propareas high, reduced, without flexure lines. Ventral visceral area slightly elevated, extending to about mid-valve. Dorsal visceral area large, with narrow median ridge and strongly impressed elongate oval central muscle scars.

Description. - Shell gently biconvex, subcircular in outline. Shell surface smooth, with fine growth lines and widely and unevenly spaced growth lamellae, often with abraded margins. Ventral pseudointerarea triangular, with well-defined flexure lines and deep, narrowly triangular pedicle groove. Propareas flat, elevated, lacking flexure lines. Ventral visceral area extending to about mid-valve, with two distinct triangular composite scars of central, middle and outside lateral muscles. Transmedian and anterior lateral muscles forming two narrow, arcuate scars posterolateral of visceral area.

Dorsal pseudointerarea with wide, slightly concave median groove. Propareas high, reduced and lacking flexure lines. Dorsal central muscle scars large, elongate oval, strongly impressed, slightly elevated.

Discussion. - From the sandstone of the Tosna Formation, at the Luga River, Eichwald (1829, p. 274) described two species: *Obolus apollinis* and *O. ingricus*. The original description and drawing of *Obolus apollinis* Eichwald (1829, p. 274; Pl. 4:5) shows a distinctive thin-shelled oval form; the same page includes also the description of a thick-shelled *O. ingricus*.

The latter species was not figured and the holotypes for neither of the two species were originally assigned. Popov & Khazanovitch (1989) selected lectotypes from the Eichwald's collection at the State University of St. Petersburg and assigned *O. ingricus* to the genus *Ungula* Pander, 1830.

In his later works, Eichwald (1840, 1841, 1860, 1861a) did not illustrate *Obolus apollinis*. Although he was consistent in distinguishing *O. apollinis* and *O. ingricus*, it can be assumed by his descriptions and listed localities from western Estonia, where *O. apollinis* does not occur according to our present knowledge, that he apparently included some specimens of *Ungula ingrica* in *Obolus apollinis*.

As briefly discussed by Popov & Khazanovitch (1989) and Puura & Holmer (1993), in most former studies, *Obolus apollinis* has been almost invariably confused with *Ungula ingrica* and sometimes with other obolids (see the synonymy).

Mickwitz (1896, p. 133) considered Eichwald's distinctive form as *O. apollinis* in the narrower sense, but included the forms presently known as *Ungula ingrica* within the variation range of *Obolus apollinis*. All the specimens illustrated by Mickwitz as *Obolus apollinis* come from the Jägala-Joa outcrop and actually belong to *Ungula ingrica* and *Ungula inornata*. Basing his detailed description of the genus *Obolus* on *Ungula ingrica*, Mickwitz (1896) illustrated the undivided umbonal muscle scars as diagnostic for the genus *Obolus*. According to the present generic concept, in all known species of *Obolus*, umbonal muscle scars are clearly divided in both valves. Also, a heart-shaped depression indicated as a diagnostic feature of the genus *Obolus* and the type species in the previous diagnoses of *Obolus* (e.g. Rowell, 1965, Goryanskij, 1969) is lacking in the type species and other species of *Obolus*.

Goryanskij (1969) attempted to restore Eichwald's original concept of *Obolus apollinis*; however, he unfortunately figured some specimens of *Ungula ingrica* (Eichwald) as *Obolus apollinis* Eichwald (Goryanskij, 1969, Pl. 1: 10-11).

The presently accepted concept of *Obolus apollinis* has been applied recently by Popov in Kaljo et al. (1986), Popov & Khazanovitch (1989) and Puura & Holmer (1993).

Obolus transversus differs from *Obolus apollinis* by having a more transverse outline of the shell, wider ventral pseudointerarea with wider, triangular, pedicle groove and wider dorsal pseudointerarea with wider median groove. *Obolus ruchini* differs from *Obolus apollinis* by having a wider triangular pseudointerarea with triangular pedicle groove and a dorsal median sulcus in posterior half of the dorsal valve.

Occurrence. - *Obolus apollinis* ranges from the *C. proavus* to the *C. rotundatus* conodont Biozone. This species is very common in Ingria, Russia, where it occurs in the Tosna Formation in the following localities: Narva River, Solka River, Luga River, Suma River, Lomashka River, Izhora River, Tosna River, Naziya River, Putilovo quarry, Lava River, Sarya River, Volkhov River and Syas River. In Estonia, it occurs in the Kallavere Formation, ranging from the *C. proavus* to the *C. lindstromi* Biozone in the subsurface of the Rakvere Phosphorite Deposit.

Obolus ruchini Khazanovitch & Popov, 1984

Fig. 51

Synonymy. - []1984 *Obolus ruchini* sp. nov. - Khazanovitch & Popov in Khazanovitch et al., p. 27, Pl. 3: 21-30. []1989 *Obolus ruchini* Khazanovitch & Popov - Popov & Khazanovitch, p. 101, Pl. 1: 12-17.

Holotype. - Original designation by Khazanovitch and Popov in Khazanovitch *et al.*, 1984, p. 37; specimen CNIGR 5/11916, left bank of the Tosna river downstream of Gertovo village, Middle Cambrian, Sablinka Formation, Gertovo Member.

Figured material. - Ventral valves: GT Br 3515; GT Br 3516; GT Br 3517; GT Br 3521; GT Br 3522; GT Br 3523. Dorsal valves: GT Br 3518; GT Br 3519; GT Br 3520.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - Shell gently biconvex. Ventral valve subtriangular. Ventral pseudointerarea triangular, with narrow, triangular, pedicle groove. Ventral propareas with well defined flexure lines, accentuated by narrow grooves. Ventral visceral area slightly elevated, extending to about mid-valve. Dorsal valve transversely suboval, with narrow and low sulcus. Dorsal pseudointerarea with wide concave median groove and high, reduced propareas, lacking flexure lines. Dorsal visceral area slightly elevated, with a low median ridge.

Description. - Shell thin, gently biconvex. Shell surface smooth, with fine concentric growth lines. Ventral valve gently convex, subtriangular, about as long as wide. Ventral pseudointerarea with narrow, triangular pedicle groove. Propareas with well-defined flexure lines, accentuated by narrow grooves. Ventral visceral area slightly elevated, extending to about mid-valve, with two triangular composite scars of central, middle and outside lateral muscles. Transmedian and anterior lateral muscles forming two large, elongate suboval composite scars, placed posterolaterally.

Dorsal valve gently convex, subcircular to tranversely suboval, with an indistinct narrow low sulcus in the posterior part of the valve. Dorsal pseudointerarea narrow, with wide concave median groove. Propareas high, reduced, lacking flexure lines. Dorsal visceral area slightly elevated, with a low median ridge. Dorsal central muscle scars elongate oval, subparallel.

Discussion. - *Obolus ruchini* differs from *O. transversus* in having narrower outline of both valves and dorsal median sulcus. In the outline of both valves, *O. ruchini* somewhat resembles *Ungula inornata*, differing in the lack of the heart-shaped depression in the ventral visceral area and deep rugae on the shell surface.

Occurrence. - Middle Cambrian, Gertovo Member of the Sablinka Formation in the environs of St. Petersburg and eastward. Localities: Tosna River, Sarya River and Volkhov River.

Obolus transversus (Pander, 1830)

Fig. 52

Synonymy. - []1830 *Ungula transversa* sp. nov. - Pander, p. 59, Pls 3:28; 28:7a,7b,8a,8b. []1984 *Obolus rebrovi* Khazanovitch & Popov - Khazanovitch *et al.*, p. 39, Pl. 3:14-20. []1989 *Obolus transversus* (Pander, 1830) - Popov & Khazanovitch, p. 101, Pl. 1: 18-22.

Neotype. - Selected by Popov & Khazanovitch, 1989, p. 101; Specimen CNIGR 21/12348, dorsal valve, left bank of the Izhora river, 3.5 km NE from the Fedorovskiy village, Sablinka Formation, Rebrovo Member.

Figured material. - Ventral valves: GT Br 3524; GT Br 3525; GT Br 3528; GT Br 3529. Dorsal valves: GT Br 3526; GT Br 3527.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - Shell gently biconvex. Ventral valve transversely subtriangular. Ventral pseudointerarea with triangular pedicle groove. Propareas with well-defined flexure lines, accentuated by narrow grooves. Ventral visceral area slightly elevated, extending to about one-third of the valve length. Dorsal pseudointerarea low and narrow, with wide concave median groove and reduced propareas.

Description. - Shell thin, subequibiconvex. Shell surface smooth, with fine concentric growth lines. Ventral valve transversely subtriangular. Ventral pseudointerarea with narrow, triangular pedicle groove. Propareas with well-expressed flexure lines, accentuated by narrow grooves. Ventral visceral area slghtly elevated, extending to about one third of the valve length. Dorsal pseudointerarea low and narrow, with slightly concave median groove. Propareas reduced, lacking flexure lines. Dorsal visceral area slightly elevated, with long median depression.

Discussion. - This species was described by Khazanovitch & Popov (in Khazanovitch *et al.* 1984) as *Obolus rebrovi*. Popov & Khazanovich (1989) found it to be a junior synonym of

Ungula transversa Pander and, after revising the genera *Obolus* Eichwald and *Ungula* Pander, assigned this species to the genus *Obolus*.

Occurrence. - Middle Cambrian, the Rebrovo Member of the Sablinka Formation south of Lake Ladoga, Ingria, Russia. Localities: Syas River and Volkhov River.

Genus *Ungula* Pander, 1830

Synonymy. - []1830 *Ungula* gen. nov. - Pander, p. 57. []1896 *Obolus (Euobolus)* - Mickwitz, p. 133 [in part]. []1898 *Obolus* Eichwald - Mickwitz [in part]. []1912 *Obolus* Eichwald - Mickwitz, p. 370 [in part]. []1965 *Obolus* Eichwald - Rowell, p. H283. []1969 Obolus (Obolus) Eichwald - Goryanskij, 1969 [in part]. []1989 *Ungula* Pander - Popov & Khazanovitch, p. 116. []1993 *Ungula* Pander - Puura & Holmer, p. 216.

Type species. - By original designation, *Ungula convexa* Pander, 1830; Upper Cambrian, Ladoga Formation, Ingria, Russia.

Diagnosis. - Shell dorsibiconvex, subcircular to transversely suboval or subtriangular in outline, smooth or with concentric rugae. Pseudointerareas of both valves with flexure lines. Ventral pseudointerarea with narrow, deep pedicle groove. Dorsal pseudointerarea high, wide, with somewhat concave median groove. Ventral visceral area elevated anteriorly, forming a low platform with heart-shaped, median depression. Dorsal visceral area slightly thickened. Ventral and dorsal *vascula lateralia* arcuate, marginal. Dorsal *vascula media* short, widely divergent (modified after Popov & Khazanovitch, 1989, p. 116).

Species assigned. - *Ungula convexa* Pander, 1830; *Obolus ingricus* Eichwald, 1829; *Obolus triangularis* Mickwitz, 1896; ?*Lingulella selwyni* Matthew, 1903.

Discussion. - The thick-shelled obolid genera *Dicellomus* Hall, 1871 and *Pseudodicellomus* Bell, 1962 from the Middle and Upper Cambrian of North America are somewhat similar to *Ungula* in the musculature and elevated visceral area. *Ungula* differs from both of these genera by having a heart-shaped depression in ventral visceral area and wider dorsal median groove. *Pseudodicellomus* also differs from *Ungula* in having a minutely pitted ornamentation.

The close resemblance of *Lingulella selwyni* Matthew, 1895 to *Ungula ingrica* (Eichwald, 1829) (referred to as *Obolus apollinis* Eichwald, 1829) was pointed out by Walcott (1912). He also synonymized *Obolus aequiputeis* Matthew, 1902 with *L. selwyni* and assigned the latter species to the genus *Obolus*. As the specimens illustrated by Walcott (1912, Pl. 36: 1,2; Pl. 37:1) as *Obolus selwyni* are closely similar to the species of the genus *Ungula*, *L. selwyni* is here provisionally assigned to this genus. *Ungula? selwyni* is reported from the sandy limestone of Division E2a at Young's Point, near Cape Breton, Nova Scotia (locality 307d of Mickwitz (1912)), corresponding to the MacMullin Formation (Hutchinson 1952), which represents a late Middle Cambrian - early Late Cambrian coarse siliciclastic pulse across all of Avalon (Landing 1996). According to E. Landing (pers. comm., 1996), the obolid locality is probably from the lower part of the MacMullin Formation of tentative late Middle Cambrian age. Thus, *Ungula? selwyni* could be the oldest species of the genus *Ungula*, so far known only from the Upper Cambrian of Baltoscandia.

Occurrence. - Middle? - Upper Cambrian; Estonia; Ingria, Russia; Sweden; Latvia; Lithuania; Poland; ?Nova Scotia, Canada.

Ungula convexa Pander, 1830

Fig. 53

Synonymy. - []1830 *Ungula convexa* sp. nov. - Pander, p. 59, Pl. 28: 1,2 []1830 *Ungula plana* sp. nov - Pander, p. 59, Pl. 28: 3, 5? []1830 *Ungula triangularis* sp. nov. - Pander, p. 59, Pl. 3: 23, Pl. 28: 9. []?1848 *Aulonotreta polita* Eichwald - Kutorga, 1848, p. 279 [in part]; Pl. 7:10a, 10b, 10e, 10f; not Pl. 7: 10c. []?1853 *Obolus apollinis* Eichwald - Davidson, p. 135 [in part], ?Pl. 9: 280, 281, 282, 284, 285; not Pl. 9: 283. []1989 *Ungula convexa* Pander - Popov & Khazanovitch, p. 177, Pl. 6: 5-13, 15-17; Pl. 7: 1-11. []cf. 1993 *Ungula convexa* Pander - Lashkov *et al.*, p. 101.

Neotype. - Selected by Popov & Khazanovitch (1989, p. 117). Specimen No. 122/12348 (CNIGR Museum, St. Petersburg); Izhora river, Upper Cambrian, Ladoga Formation, outcrop L-47 (Popov *et al.*, 1989).

Material. - Figured. Ventral valves: CNIGR 127/12348; GT Br 3530; GT Br 3531; GT Br 3534; GT Br 3535. Dorsal valves: CNIGR 124/12348; CNIGR 126/12348; GT Br 3532; GT Br 3533. Total of over 200 ventral and over 200 dorsal valves.

Diagnosis. - Shell dorsi-biconvex, subcircular in outline, smooth. Ventral valve gently and evenly convex. Ventral pseudointerarea high, with narrow, deep pedicle groove. Propareas high, flat, with well-expressed flexure lines. Ventral visceral area elevated, forming a platform with a heart-shaped depression. Umbonal muscle scars small, divided by a short median septum. Dorsal valve strongly and unevenly convex. Dorsal pseudointerarea with wide, high, slightly concave median groove, with well- defined flexure lines. Propareas high, reduced, lacking flexure lines. Dorsal visceral area slightly thickened.

Description. - Shell dorsi-biconvex, subcircular in outline. Shell surface smooth, with widely and unevenly spaced growth lamellae, up to 4 in an adult shell, often with abraded margins. Ventral valve gently and evenly convex. Ventral pseudointerarea with narrow, deep pedicle groove. Propareas high, flat, with well-defined flexure lines. Ventral visceral area elevated, forming a platform. Posterolateral and transmedian muscles forming composite, oval muscle scars close to propareas. Umbonal muscle scars small, separated by a short median ridge. *Vascula lateralia* arcuate, submarginal.

Dorsal valve strongly and unevenly convex, with maximum convexity at about one-third of the maximum shell length from the posterior margin. Dorsal pseudointerarea high, flat, with wide, slightly concave median groove. Propareas high, flat, lacking flexure lines. Dorsal visceral area slightly thickened, with small central muscle scars.

Discussion. - *Ungula convexa* Pander (1830) has been confused and synonymized either with *Obolus apollinis* Eichwald, 1829 or *Obolus ingricus* Eichwald, 1829. Popov & Khazanovitch (1989) showed that *U. convexa* is a valid species, occurring in older Upper Cambrian strata than the two species above.

As compared to the other species of the genus, the shell of *Ungula convexa* is more convex; the presence of growth lamellae with abraded margins is also a distinctive external feature. *Ungula convexa* differs from *Ungula ingrica* (Eichwald, 1829) by having a smaller and shallower, more posteriorly placed heart-shaped depression in the ventral visceral area, as well as higher and wider pseudointerareas, narrower pedicle groove and wider median groove. As compared to *Ungula convexa*, *Ungula inornata* (Mickwitz, 1896) has a flatter, subtriangular shell, ornamented with rugae, narrower pseudointerareas, wider, subtriangular, pedicle groove and narrower median groove.

Some specimens reported from the Cambrian-Ordovician boundary beds in the deep cores from Lithuania referred to *Ungula convexa* (Lashkov et al., 1993), were kindly presented for the study by Dr. L. Popov. In view of the similarities in general outline and some internal features, these specimens can be provisionally assigned to *Ungula* cf. *convexa*, but their state of preservation does not allow more precise identification.

Occurrence. - Upper Cambrian, upper subformation of the Ladoga Formation in Ingria, Russia. The valves have also been redeposited to the basal Tosna Formation. Localities: Tosna River, Izhora River, Naziya River, Lava River, Putilovo Quarry, Volkhov River, Sarya River, Syas River. Upper Cambrian, Tsitre Formation in Estonia. Locality: Saka outcrop.

Ungula ingrica (Eichwald, 1829)

Fig. 54

Synonymy. - []1829 *Obolus ingricus* n. sp. - Eichwald, p. 274. []1860 *Obolus ingricus* Eichwald - Eichwald, p. 926. []1861 *Obolus ingricus* Eichwald - Eichwald, p. 264. []1892 *Obolus Quenstedti* n. sp. - Mickwitz, p. 74 [in part], Fig. 1. []1896 *Obolus Apollinis* Eichwald - Mickwitz, p. 133 [in part], Pl. 1:1-14. []1896 *Obolus Apollinis* Eichwald var. *ingricus* n. var. - Mickwitz, p. 137, Pl. 1:15-28. []1896 *Obolus Apollinis* Eichwald var. *maximus* n. var. - Mickwitz, p. 140, Pl. 1:29-38. []1896 *Obolus Apollinis* Eichwald var. *Quenstedti* Mickwitz - Mickwitz p. 143, Pl. 1-6. []1898 *Obolus apollinis* Eichwald - Walcott, p. 385, Pl. 26:3-6. []1902 *Obolus apollinis* Eichwald var. Quenstedti - Matthew, 1902, p. 73; Pl. 1:10. []1905 *Obolus apollinis* Eichwald - Wiman, p. 62, Pl. 3:1-11. []1906 *Obolus apollinis* Eichwald - Moberg & Segerberg, p. 65, Pl. 3:1-3. []1912 *Obolus apollinis* Eichwald - Walcott, p. 381, Figs 4, 15, Pl. 7:1-8, 10-17; 14:6, 6a. []1912 *Obolus apollinis ingricus* (Eichwald) - Walcott, p. 384. []1912 *Obolus apollinis maximus* Mickwitz - Walcott, p. 384, Pl. 7:9; 14:7, 7a. []1912 *Obolus apollinis quenstedti* (Mickwitz) - Walcott, p. 384, Fig. 34a, b. [] ?1964 *Obolus apollinis* Eichwald - Biernat, p. 73, Figs. 1-7.[]1965 *Obolus apollinis* Eichwald - Rowell, p. H263, Fig. 159: 2a-d. [] 1969 *Obolus* (*Obolus*) *ingricus* Eichwald - Goryanskij, p. 22, Pl. 1:12-20. [] 1969 *Obolus* (*Obolus*) *apollinis* (Eichwald) - Goryanskij, Pl. 1:10-11. [] 1989 *Ungula ingrica* (Eichwald) - Popov & Khazanovitz (*in* Popov et al.), p. 119, Pl. 7:12, 16, 20, 21. []1993 *Ungula ingrica* (Eichwald) - Puura & Holmer, p. 217, Figs. 2A-F, 5I-K.

Lectotype. - Selected by Popov & Khazanovitch (1989, p. 119); Specimen No. 1/778 (Department of Historical Geology, St. Petersburg State University. The specimen was redeposited in the Tosna Formation, Luga river near Kingissepp (Yamburg), Ingria.

Figured material. - Ventral valves: GT Br 3577; GT Br 3578; GT Br 3579; GT Br 3580; GT Br 3581; GT Br 3582; GT Br 3583; GT Br 3585. Dorsal valves: GT Br 1702; GT Br 3584; GT Br 3586.

Additional material. - Sveral hundred ventral and dorsal valves from coquinas (not counted).

Diagnosis. - See Puura & Holmer (1993, p. 217).

Description. - Shell thick, moderately equibiconvex. Shell surface smooth, with fine indistinct growth lines and widely spaced growth lamellae. Ventral valve transversely subtriangular. Ventral pseudointerarea narrow, with narrow triangular pedicle groove. Propareas with well-defined flexure lines. Ventral visceral area elevated anteriorly, forming a platform with a deep heart-shaped depression at about mid-valve. Central, middle and outside lateral muscles forming two slightly elevated composite scars anterolateral of depression. Transmedian and anterior lateral muscles forming two composite scars posterolateral of the depression. *Vascula lateralia* arcuate, submarginal.

Dorsal valve transversely suboval. Dorsal pseudointerarea with wide, slightly concave median groove. Posterior part of dorsal valve slightly or strongly thickened. Anterior margin of thickening concave anteriorly, forming a median depression, with marginally placed, suboval central muscle scars. Transmedian muscle scars separate from combined middle and outside lateral muscle scars.

Discussion. - Both valves of *Ungula ingrica* are strongly variable in outline, convexity and thickness. The position and size of the muscle scars in both valves and the dimensions of the ventral heart-shaped depression are correlated to the extent of posterior thickening of the shell. The resulting apparent large variation of the internal characters, as observed in two-dimensional projections, was recognized by Mickwitz (1896), who described a number of morphological variants of *Ungula ingrica* as varieties of *Obolus apollinis*. As discussed by Goryanskij (1969) and Popov & Khazanovitch (1989) this morphological variability has a continuous character, and all the varieties of *Obolus apollinis* of Mickwitz can be synonymized with *Ungula ingrica* (see the synonymy).

Occurrence. - In Estonia, *Ungula ingrica* occurs in the Tsitre Formation and is particularly abundant in the Maardu Member of the Kallavere Formation. Localities in Estonia: Tõnismägi, Mäekalda, Hundikuristik, Suhkrumägi, Iru, Ülgase, Maardu quarries, Jägala River, Turjekelder, Toolse River, Vihula, Saka, Valkla River, subsurface south of Maardu, core M-77, depth 23.4-28.3 m. In Ingria, Russia, *U. ingrica* occurs in the Lomashka Formation and is reposited to the Tosna Formation. Localities in Ingria: Narva River, Luga River, Lomashka River, Suma River. In Sweden, *Ungula ingrica* occurs in the *'Obolus'* conglomerate at Sjurberg, Siljan District and Horns Udde, as well as in erratic boulders from Uppland (Puura & Holmer, 1993).

Ungula inornata (Mickwitz, 1896)

Fig. 55

Synonymy. - []1896 *Obolus triangularis* n. sp. - Mickwitz, p. 145, Pl. 2: 7-9. []1896 *Obolus triangularis* n.sp. var. *inornatus* n. var. - Mickwitz, p. 148, Pl. 2: 10-12. []1896 *Obolus panderi* n. sp. - Mickwitz, p. 149, Pl. 2: 13. []1906 *Obolus triangularis* Mickwitz - Moberg & Segerberg, p. 65. []1912 *Obolus triangularis* Mickwitz - Walcott, p. 419. []1969 *Obolus (Obolus) triangularis* Mickwitz - Goryanskij, p. 24, Pl. 1: 21, 22. []1989 *Ungula inornata* (Mickwitz) - Popov & Khazanovitch, p. 121: Pl. 6:1-4,14; Pl. 7:19,22-24. []1993 *Ungula inornata* (Mickwitz) - Puura & Holmer, p. 219; Fig. 2G-J.

Lectotype. - Selected by Popov & Khazanovitch (*in* Popov et al. 1989, p. 121). Specimen no. 10843 (CNIGR Museum, St. Petersburg). The specimen was redeposited into the Upper Cambrian Maardu Member, Jägala river, near Jägala-Joa, Estonia.

Material. - Ventral valves: GT Br 3536; GT Br 3537; GT Br 3538. Dorsal valve: GT Br 3539. Total of 116 ventral and 85 dorsal valves.

Diagnosis. - See Puura & Holmer (1993, p. 219).

Description. - Shell slightly dorsibiconvex, with well- developed concentric rugae. Ventral valve transversely subtriangular. Ventral pseudointerarea narrow, triangular, with triangular pedicle groove. Propareas high, narrow, with well defined flexure lines. Ventral visceral area slightly elevated anteriorly forming low platform with large shallow heart-shaped depression. Central, middle and outside lateral muscles forming two composite scars anterolateral of the depression. Transmedian and anterior lateral muscles forming two composite scars posterolateral of the depression. *Vascula lateralia* arcuate, submarginal.

Dorsal valve transversely subtriangular to transversely suboval, with shallow indistinct sulcus placed posteriorly. Dorsal pseudointerarea narrow, with wide median groove. Propareas reduced. Dorsal visceral area slightly elevated, with large, suboval central muscle scars. Transmedian muscle scars and combined middle and outside lateral muscle scars large, elongate oval.

Discussion. - *Ungula inornata* is the replacement name for *Obolus triangularis* Mickwitz, 1896 proposed by Popov & Khazanovich (1989) in recognition of the synonymy of *Obolus triangularis* Mickwitz, 1896 and *Obolus triangularis* var. *inornatus* Mickwitz, 1896. The introduction of the replacement name was necessary, because with the assignment of *Obolus triangularis* to the genus *Ungula*, *Ungula triangularis* would have been a junior secondary homonym of *Ungula triangularis* Pander, 1830.

Ungula inornata can be distinguished from other species of the genus mainly by the presence of well-developed concentric rugae on both valves and by the subtriangular outline of the ventral valve. The shell is considerably thinner posteriorly than that of *Ungula ingrica* and thus the pseudointerareas of both valves are also less thickened, and the heart-shaped depression in ventral visceral area is shallower. The dorsal valve of *U. inornata* has a posteriorly placed shallow indistinct sulcus that is not present in other species of the genus.

Occurrence. - Upper Cambrian, Ülgase Formation, northern Estonia. Redeposited specimens occur in the basal coquinas of the Maardu Member of the Kallavere Formation. Localities: Tõnismägi, Kadriorg, Mäekalda, Suhkrumägi, Hundikuristik, Iru, Ülgase, Jägala River, Valkla River. In Sweden, *U. inornata* occurs in the 'Obolus' beds at Sjurberg as well as in the erratic boulders at Gärdsjö; some questionable fragments occur in the 'Obolus' beds (interval 62.68-62.82 m) in the Finngrundet core (Puura & Holmer, 1993).

Genus *Schmidtites* Schuchert & Levene, 1929

Synonymy. - []1869 *Schmidtia* gen. nov. - Volborth, p. 208. []1892 *Schmidtia* Volborth - Hall & Clarke, p. 83. []1896 *Obolus (Schmidtia) Volborth* - Mickwitz, p. 158. []1908 *Obolus* (Schmidtia) Volborth - Walcott, p. 142. []1912 *Obolus (Schnmidtia)* Volborth - Walcott, p. 441. []1929 *Schmidtites* nom. subst. - Schuchert & Levene, p. 111. []1965 *Schmidtites* - Rowell, p. H266. []1969 *Obolus (Schmidtites)* Schuchert - Goryanskij, p. 24. []1989 Schmidtites Schuchert - Popov & Khazanovitch, p. 114. []1993 *Schmidtites* Schuchert & Levene - Puura & Holmer, p. 219.

Type and only species. - Original designation by Volborth, 1869, p. 209; *Schmidtia celata* Volborth, 1869; Kallavere Formation; environs of Aseri, Estonia.

Diagnosis. - Shell elongate oval or subtriangular, ventri- biconvex, thick-shelled. Ventral pseudointerarea with deep narrow pedicle groove. Ventral propareas elevated, slightly concave, with flexure lines. Dorsal pseudointerareas with concave median groove and reduced, elevated propareas. Visceral areas of both valves thickened. Shallow heart-shaped depression in ventral valve. Dorsal visceral area with long median projection bisected by low median ridge. *Vascula lateralia* of both valves subparallel, marginally placed. Dorsal *vascula media* short, widely divergent (modified after Popov & Khazanovitch, p. 114).

Discussion. - The genus *Schmidtia* established by Volborth (1869) was later considered by Mickwitz (1896) as a subgenus of *Obolus*. Schuchert & Levene (1929) pointed out that *Schmidtia* Volborth was a junior homonym of a sponge genus *Schmidtia* Balsamo-Crivelli, 1863 and introduced the substitution name *Schmidtites* for the subgenus. Rowell (1965) restored the generic rank of *Schmidtites*. The subgenus *Schmidtia* of Mickwitz (1896) included four species with a number of varieties. Further, Popov & Khazanovitch (1989) considered *Schmidtites* as a monotypic genus with one variable species *Schmidtites celatus* (Volborth), corresponding to *Obolus (Schmidtia) celatus, O (S.) acuminatus* and *O. (S.) crassus* of Mickwitz; *Obolus (Schmidtia) obtusus* of Mickwitz has been assigned to the genus *Oepikites* (Khazanovitch & Popov, 1984).

Schmidtites? simplex Williams, 1974 is a junior synonym of *Siphonotreta micula* M'Coy, 1851 (Lockley & Williams 1981); this species has been reassigned to the genus *Apatobolus* by Nazarov & Popov (1980). It is difficult to comment on the affinities of some microscopic juvenile obolids assigned by Biernat (1973) to *Schmidtites*; the morphological features observable are not sufficient to make a generic assignation.

Occurrence. - Upper Cambrian; Estonia; Ingria, Russia; Sweden.

Schmidtites celatus (Volborth, 1869)

Fig. 56

Synonymy. - []1869 *Schmidtia celata* n. sp. - Volborth, p. 209-212, Pl. 27:1-6. []1892 *Schmidtia celata* Volborth - Hall & Clarke, p. 83; Figs. 37, 38. []1896 *Obolus celatus* (Volborth) - Mickwitz, p. 159, Pl. 2:19-20. []1896 *Obolus celatus* var. *orbiculatus* n. var. - Mickwitz, p. 163, Pl. 2:21-22. []1896 *Obolus celatus* var. *praecisus* n. var. - Mickwitz, p. 166, Pl. 2: 37-38. []1896 *Obolus acuminatus* n. sp. - Mickwitz, p. 179, Pl. 2: 39, 40. []1896 *Obolus acuminatus* var. *alatus* n. var. - Mickwitz, p. 183, Pl. 2: 41, 42. []1896 *Obolus acuminatus* var. *humeratus* n. var. - Mickwitz, p. 184, Pl. 2: 43, 44. []1896 *Obolus acuminatus* var. *subtriangularis* n. var. - Mickwitz, p. 186, Pl. 2: 45, 46. []1896 *Obolus crassus* n. sp. - Mickwitz, p. 187, Pl. 2: 47-49, 52-55. []1896 *Obolus crassus* var. *angulatus* n. var. - Mickwitz, p. 193, Pl. 2: 50, 51. []1898 *Obolus* (*Lingulella*) *celatus* - Walcott, Pl. 26:1, 2. []1912 *Obolus* (*Schmidtia*) *celatus* (Volborth) - Walcott, p. 444, Pl. 14:1, 1a-c. []1965 *Schmidtites celatus* (Volborth) - Rowell, p. H266, Fig. 159:7a,b.[]1969 *Obolus* (*Schmidtites*) *celatus* (Volborth) - Goryanskij, p. 26, Pl. 2:4, 8, 9; not Pl. 2:5-7, 10). []1977 *Schmidtites celatus* (Volborth) - Rowell, Figs 2,3. [] 1989 *Schmidtites celatus* (Volborth) - Popov & Khazanovitch, p. 115, Pl. 3:12- 14; 4:5-14; 8:1. []1993 *Schmidtites celatus* (Volborth) - Puura & Holmer, p. 219, Figs. 2K, 3A-D.

Neotype. - Selected by Popov & Khazanovitch (*in* Popov et al 1989, p. 115). Specimen no. 97/12348 (CNIGR Museum, St. Petersburg); Toolse river; Upper Cambrian, Maardu Member.

Figured material. - Ventral valves: GT Br 1709; GT Br 3540; GT Br 3541; GT Br 3546; CNIGR 97/12348; CNIGR 104/12348; CNIGR 105/12348. Dorsal valves: GT Br 1710; GT Br 3542; GT Br 3543; GT Br 3544; GT Br 3545; CNIGR 102/12348.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - As for genus.

Description. - Shell slightly ventribiconvex. Shell surface smooth, with fine concentric growth-lines. Ventral valve subtriangular to subcircular or elongate oval. Ventral pseudointerarea with deep, narrow pedicle groove. Propareas elevated, slightly concave, with well-expressed flexure lines. Ventral visceral area thickened, with shallow, but well-developed heart-shaped depression. Composite muscle scars formed by central, middle and outside lateral muscles placed anterolateral of the depression, poorly defined in some specimens. *Vascula lateralia* subparallel, submarginal.

Dorsal valve subcircular to elongate oval. Dorsal pseudointerarea with concave median groove. Propareas high, reduced. Dorsal visceral thickened, bisected by a low median ridge. Central muscle scars elongate suboval, divergent. Anterior lateral muscle scars suboval, shallow, usually poorly defined.

Discussion. - This species was described as *Schmidtia celata* by Volborth (1869). Mickwitz (1896) described several new species of the subgenus *Obolus (Schmidtia)* Volborth. Goryanskij (1969) re-evaluated the infraspecific variation of *Schmidtites celatus* and synonymized most of Mickwitz's species with it.

Obolus obtusus Mickwitz, 1896, somewhat resembling *S. celatus* and considered by Goryanskij (1969) to be congeneric, has been assigned to the genus *Oepikites* by *Popov & Khazanovitch* (1989). *Oepikites obtusus* differs from *S. celatus* in having an elongate oval shell and by the morphology of the pseudointerareas of both valves, which are characteristic of the genus *Oepikites*.

Juvenile specimens of *Ungula ingrica* and *Ungula convexa* resemble *Schmidtites celatus*, but the juvenile *Ungula* shells are broader and circular.

Occurrence. - Upper Cambrian - Lower Ordovician, Tsitre and Kallavere Formations in Estonia. Localities in Estonia: Iru, Ülgase, Maardu quarries, Jägala River, Turjekelder, Valkla River, Vihula, Toolse River, Saka, subsurface south of Maardu, subsurface of Rakvere Phosphorite Deposit, subsurface in southern Estonia, Värska-6 core. Lomashka and Tosna formations in Ingria, Russia. Localities in Ingria: Luga River, subsurface of Kingisepp Phospohorite Deposit, Lomashka River, Solka River, Sarya River, Suma River, Tosna River, Putilovo Quarry, Volkhov River, Syas River. In Sweden, *S. celatus* occurs in the '*Obolus*' beds in the Finngrundet core (intervals 62.97-63.18 m and 62.68-62.82 m) as well as in erratic boulders from Uppland (Puura & Holmer, 1993).

Genus *Oepikites* Khazanovitch & Popov, 1984

Synonymy. - []1984 *Oepikites* gen. nov. - Khazanovitch & Popov (in Khazanovitch et al., p. 40). []1989 *Oepikites* Khazanovitch & Popov - Popov & Khazanovitch, p. 103.

Type species. - By original designation; *Oepikites macilentus* Khazanovitch & Popov (*in* Khazanovitch et al. 1984, p. 40); Middle Cambrian Sablinka Formation, Sarya river, Ingria, Russia.

Diagnosis. - Shell subacuminate, inequivalved, elongate oval to subtriangular. Propareas of both valves high, with well- defined flexure lines. Visceral areas of both valves slightly thickened. Dorsal visceral area with long anterior median projection, bisected by short median ridge. *Vascula lateralia* of both valves submarginal, arcuate; *vascula media* short, divergent.

Species assigned. - *Obolus* (*Schmidtia*) *obtusus* Mickwitz, 1896; *Lingulella acuta* Pelman, 1978; *Lingulella kitatiensis* Aksarina, 1978; *Oepikites macilentus* Popov & Khazanovitch, 1984; *Oepikites triquetrus* Popov & Khazanovitch, 1984; *Oepikites fragilis* Popov & Khazanovitch, 1984.

Discussion. - In shell outline and the morphology of visceral areas, *Oepikites* resembles *Schmidtites*. *Oepikites* differs by having a long and well-expressed dorsal anterior median septum, a wider median groove, a smaller and shallower depression in ventral visceral area and by the presence of pedicle nerve impression in adult specimens.

Except the species listed above, the specimens at Texas University, UT-32200b and UT-32200a, illustrated by Palmer (1954, Pl. 90:4,5, not Pl. 90:2) as "linguloid type B" from the Upper Cambrian Riley Formation (*Aphelaspis* Biozone), Texas, USA, possess generic characters of *Oepikites* and are here assigned to *Oepikites* sp.

Occurrence. - Middle - Upper Cambrian; Estonia; Ingria, Moscow Basin, Altai, Russia; Texas, USA; Sweden.

Oepikites macilentus Khazanovitch & Popov, 1984

Fig. 57A-C

Synonymy. - []1984 *Oepikites macilentus* sp. nov. - Khazanovitch & Popov (*in* Khazanovitch *et al.*), p. 40, Fig. 5, Pl. 3: 1-8. []1989 *Oepikites macilentus* Khazanovitch & Popov - Popov & Khazanovitch, p. 109, Pl. 3:1-5,7.

Holotype. - Ventral valve, specimen No 29/11916, CNIGR Museum; Sarya River, 800 m downstream of the Vojbokalo village, Middle Cambrian, Sablika Formation, Gertovo Member.

Figured material. - Ventral valves: CNIGR 61/12348; CNIGR 59/12348; Dorsal valve: CNIGR 62/12348.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - Shell gently equibiconvex, elongate suboval. Ventral pseudointerarea high, flat, with narrow, deep, triangular pedicle groove. Propareas narrow, with well-defined flexure lines, not reaching the shell margin. Ventral visceral area slightly elevated, with poorly defined heart-shaped depression. Dorsal pseudointerarea high, with well-defined flexure lines. Median groove wide, with narrow, shallow secondary groove. Dorsal visceral area with short median ridge.

Description. - Shell gently equibiconvex, elongate suboval. Shell surface smooth, with fine concentric growth lines. Ventral pseudointerarea high, flat, with narrow, deep, triangular pedicle groove. Propareas narrow, with well-defined flexure lines not reaching the shell margin. Ventral visceral area slightly elevated, with a poorly defined heart-shaped depression. Ventral muscle scars weakly impressed. *Vascula lateralia* arcuate, submarginal.

Dorsal pseudointerarea elevated above the valve floor, with well-defined flexure lines. Median groove wide, with a narrow, shallow secondary groove in the middle. Central muscle scars elongate oval, widely divergent, strongly impressed. Anterior lateral muscle scars elongate oval, subparallel, bisected by short median ridge. *Vascula lateralia* submarginal, arcuate. *Vascula media* short, divergent.

Discussion. - This species differs from all the other species of the genus by having a wide median groove with a secondary groove and dorsal propareas, laterally not reaching the valve margins.

Occurrence. - Middle Cambrian, the Gertovo Member of the Sablinka Formation, Ingria, Russia. Localities: Tosna River, Sarya River and Volkhov River.

Oepikites koltchanovi Khazanovitch & Popov, 1984

Fig. 57D-G

Synonymy. - []1984 *Oepikites koltchanovi* sp. nov. - Khazanovitch & Popov (in Khazanovitch et al.), p. 45, Fig. 6, Pl. 3: 9-13. []1989 *Oepikites koltchanovi* Khazanovitch & Popov - Popov & Khazanovitch, p. 109, Pl. 2: 8-11,17.

Holotype. - Dorsal valve, specimen No. 30/11916, CNIGR Museum, Syas river, right bank near the southern margin of the Rebrovo village, Middle Cambrian, Sablinka Formation, Rebrovo Member.

Figured material. - Ventral valves: GT Br 3547; GT Br 3548. Dorsal valves: CNIGR 53/12348; CNIGR 52/12348.

Additional material. - Several hundred of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - Shell gently equibiconvex, rounded subtriangular, with maximum width anterior to mid-shell. Ventral with narrow pedicle groove. Propareas with well-defined flexure lines. Ventral visceral area slightly elevated, with a heart- shaped depression. Dorsal pseudointerarea slightly concave, with wide median groove. Propareas reduced. Dorsal visceral area bisected by a long median ridge, extending to about two-thirds of the maximum valve length.

Description. - Shell gently equibiconvex, rounded subtriangular, with maximum width anterior to mid-shell. Ventral pseudointerarea wide, with narrow pedicle groove. Propareas with well-defined flexure lines. Ventral visceral area slightly elevated, with a heart-shaped depression. *Vascula lateralia* arcuate, marginal.

Dorsal pseudointerarea slightly concave, with wide median groove. Propareas reduced. Dorsal visceral area bisected by a long median ridge, extending to about two-thirds of the maximum valve length. Central muscle scars narrow, elongate, divergent. Anterior lateral muscle scars elongate oval, subparallel. *Vascula lateralia* submarginal, arcuate. *Vascula media* short, divergent.

Discussion. - This species is closely similar to *Oepikites fragilis*; it differs by having a longer dorsal median ridge and more elongate shell outline. Both species have suboval to rounded subtriangular shells, but the position of the maximum width in *O. fragilis* is slightly more anterior than that in *O. koltchanovi*.
Occurrence. - Middle Cambrian, the Rebrovo Member of the Sablinka Formation, Ingria, Russia. Localities: Syas and Volkhov rivers.

Oepikites obtusus (Mickwitz, 1896)

Fig. 57H-K

Synonymy. - []1896 ***Obolus (Schmidtia) obtusus*** sp. nov. - Mickwitz, p. 167, Pl. 2:23,24,33,34. []1912 ***Obolus (Schmidtia) obtusus*** Mickwitz - Walcott, p. 448, Pl. 14:3-3c. []1969 ***Obolus (Schmidtites) obtusus*** (Mickwitz) - Goryanskij, p. 27, Pl. 2:11-16, not Pl. 2:17-20. []1989 ***Oepikites obtusus*** (Mickwitz) - Popov & Khazanovitch, p. 109, Pl. 2:18,20-23.

Lectotype. - Selected by Popov & Khazanovitch (*in* Popov et al 1989, p. 109). Specimen no. 63/10843 (CNIGR Museum, St. Petersburg); Jägala river, environs of Jägala-Joa village, Upper Cambrian, Maardu Member.

Material. - Figured. Ventral valves: CNIGR 79/12348; CNIGR 81/12348. Dorsal valves: CNIGR 77/12348; CNIGR 78/12348; x11. Total of 24 ventral and 35 dorsal valves.

Diagnosis. - Shell gently biconvex, elongate oval. Ventral pseudointerarea with narrow triangular pedicle groove. Propareas with well-defined flexure lines, flat and low near the pedicle groove and high laterally. Ventral visceral area with wide and shallow suboval depression. Dorsal pseudointerarea with well-defined flexure lines and wide, slightly concave median groove and high, reduced propeareas. Dorsal visceral area bisected by long median ridge.

Description. - Shell gently biconvex, elongate oval. Shell surface smooth, with fine growth lines and irregularly spaced growth lamellae. Ventral pseudointerarea with narrow triangular pedicle groove. Propareas with well-defined flexure lines, flat and low near the pedicle groove, emerging laterally above the valve floor. Ventral visceral area with wide and shallow suboval depression. Narrow, median, pedicle furrow and pedicle nerve impressions forming two submedian furrows posterior of depression observable in some specimens. *Vascula lateralia* arcuate, submarginal.

Dorsal pseudointerarea with well-defined flexure lines and wide, slightly concave median

groove. Propeareas high, reduced.
Visceral area bisected by long median ridge. Central muscle scars elongate oval, slightly divergent. Anterior lateral muscle scars weakly impressed.

Discussion. - Popov & Khazanovitch (1989) reassigned *Obolus (Schmidtites) obtusus* Mickwitz, 1896 to the genus *Oepikites* Khazanovitch & Popov, 1984; a comparative discussion of *Oepikites* and *Schmidtites* was given above. As noted by Popov & Khazanovitch (1989) some specimens illustrated by Goryanskij (1969, Pl. 2: 17-20) as *Schmidtites obtusus* should be reassigned to *Oepikites koltchanovi.*

O. obtusus differs from other species of the genus by the distinct elongate oval outline of the shell.

Occurrence. - Upper Cambrian, Maardu Member, Kallavere Formation, Estonia. Localities in Estonia: Iru, Ülgase, Valkla.

Lomashka Formation, Ingria, Russia. Localities in Ingria: Lomashka River, Kingisepp Phosphorite Deposit, core 190, depth 36.9-37.3 m.

Oepikites triquetrus Popov & Khazanovitch, 1989

Fig. 58

Synonymy. - []1989 *Oepikites triquetrus* sp. nov. - Popov & Khazanovitch, p. 110, Pl. 2:1-7, Pl. 3:6,8-11.

Holotype. - CNIGR 73/12349; dorsal valve; Upper Cambrian, upper subformation of the Ladoga Formation, right bank of the Syas River, upstream of Rebrovo village.

Material. - Figured. Ventral valves: CNIGR 64/12348; CNIGR 66/12348; CNIGR 67/12348; CNIGR 68/12348; CNIGR 69/12348. Dorsal valves: CNIGR 71/12348; CNIGR 72/12348. Total of 111 ventral and 96 dorsal valves.

Diagnosis. - Shell equibiconvex, inequivalved. Ventral valve suboval. Ventral pseudointerarea with deep, narrow pedicle groove. Ventral propareas with well-defined flexure lines, in gerontic specimens accentuated by deep narrow grooves. Ventral visceral area slightly elevated, forming an oval depression. Dorsal pseudointerarea high, with shallow, wide median groove. Dorsal propareas with well-defined flexure lines, accentuated by narrow grooves. Dorsal visceral area elevated, with long and wide median tongue, bisected by a short median ridge.

Description. -- Shell equibiconvex, inequivalved. Shell surface smooth, with fine concentric growth lines and unevenly placed growth lamellae, narrower near the anterior margin. Ventral valve suboval. Ventral pseudointerarea with deep, narrow pedicle groove. Ventral propareas with well-defined flexure lines, in gerontic specimens accentuated by deep narrow grooves. Ventral visceral area slightly elevated, forming an oval depression. Outside lateral, middle lateral and central muscles forming closely placed paired muscle scars anterolateral of depression. *Vascula lateralia* arcuate, submarginal.

Dorsal pseudointerarea high, with shallow, wide median groove. Propareas with well-defined flexure lines, accentuated by narrow grooves. Dorsal visceral area elevated, with long and wide median tongue, bisected by a short median ridge. Central muscle scars suboval, slightly divergent, well impressed. Shallow paired impressions of gastroparietal glands occurring posterior of central muscle scars. Anterior lateral muscle scars small, elongate suboval. Transmedian muscles forming narrow elongate suboval scars anterior of pseudointerarea, separately from more anteriorly placed large suboval composite scars of outside lateral and middle lateral muscles. *Vascula lateralia* marginal, subparallel. *Vascula media* short, slightly divergent.

Discussion. - This species resembles *Oepikites koltchanovi* and *O. fragilis*. Adult shells of *O. triquetrus* are larger and thicker than in both above named species. As compared to *O. koltchanovi*, *O. triquetrus* has less elongate shell, with maximum width in slightly more anterior position. *O. triquetrus* differs from *O. fragilis* in possessing more elevated visceral areas.

Occurrence. - Upper Cambrian, upper subformation of the Ladoga Formation, Ingria, Russia. Redeposited valves occur in the Tosna Formation. Locality: Subsurface south of Maardu, core M-77, depth 29.0 m.

Oepikites fragilis Popov & Khazanovich, 1989

Fig. 59

Synonymy. - []1989 *Oepikites fragilis* sp. nov. - Popov & Khazanovitch (*in* Popov et al 1989), p. 106, Pl. 2: 13-16, 19; Pl. 3: 16-17; Pl. 5: 2-5.

Holotype. - Selected by Popov & Khazanovitch (*in* Popov et al 1989, p. 106). Specimen no. 43/12348 (CNIGR Museum, St. Petersburg); drill core M-77 south of Maardu, depth 37.0-38.0 m, Upper Cambrian, Ülgase Formation.

Figured material. - Ventral valves: GT Br 3551; GT Br 3552; GT Br 3553; CNIGR 37/12348; CNIGR 38/12348; CNIGR 41/12348; CNIGR 43/12348; CNIGR 45/12348. Dorsal valves: CNIGR 35/12348; CNIGR 36/12348; CNIGR 39/12348; 40/12348.

Additional material. - Over 300 ventral and over 300 dorsal valves.

Diagnosis. - Shell gently equibiconvex. Ventral valve suboval. Ventral pseudointerarea with narrow pedicle groove. Propareas high, with well-defined flexure lines, accentuated by narrow grooves. Ventral visceral area slightly elevated, with shallow heart-shape depression. Dorsal valve rounded subtriangular, with maximum width at about one-third of maximum shell length from the anterior margin. Dorsal pseudointerarea with wide, concave median groove and high, reduced, propareas. Dorsal visceral area slightly elevated, with a long median tongue, bisected by a short median ridge anterior of mid-valve.

Description. - Shell gently equibiconvex. Shell surface smooth, with fine, concentric growth lines. Ventral valve suboval. Ventral pseudointerarea with narrow pedicle groove. Propareas high, with well-expressed flexure lines, accentuated by narrow grooves. Ventral visceral area slightly elevated, with shallow heart-shape depression. Pedicle nerve impression extending from the median groove to the visceral area observable in some specimens. Composite muscle scars formed by central, middle and outside lateral muscles placed anterolateral of the depression weakly or moderately impressed. Elongate suboval to hexagonal depressions, up to 15 μm across, occurring posterolateral of the depression in some specimens may represent epithelial moulds. *Vascula lateralia* arcuate, submarginal.

Dorsal valve rounded subtriangular, with maximum width at about one-third of maximum shell length from the anterior margin. Dorsal pseudointerarea with wide concave median groove. Propareas high, reduced. Dorsal visceral area slightly elevated, with a long median tongue, bisected by a short median ridge anterior of mid-valve. Anterior lateral muscle scars narrow, elongate oval, subparallel, bisected by the median ridge. Central muscle scars elongate oval, divergent. *Vascula lateralia* submarginal, arcuate. *Vascula media* short, slightly divergent.

Occurrence. - Upper Cambrian, Ülgase Formation in Estonia. Localities in Estonia: Hundikuristik, Iru, subsurface south of Maardu, Ülgase, Turjekelder, Valkla River.

Lower subformation of the Ladoga Formation, Ingria, Russia. Localities: Volkhov River, Syas River.

Genus *Euobolus* (Mickwitz, 1896)

Synonymy. - []1896 *Obolus (Euobolus)* subgen. nov. - Mickwitz, p. 129, 133 [in part]. []1989 *Euobolus* Mickwitz - Popov & Khazanovitch, p. 102.

Type and only species. - Subsequent designation by Popov & Khazanovitch, 1989, p. 103; *Obolus elegans* Mickwitz, 1896, from Upper Cambrian Maardu Member at Jägala-Joa.

Diagnosis. - Shell subcircular, with parvicostellate radial ornamentation. Ventral pseudointerarea with well defined, narrow pedicle groove. Dorsal valve unknown (modified after Popov & Khazanovitch 1989, p. 102).

Discussion. - The genus *Euobolus* (Mickwitz), as revised by Popov & Khazanovitch (1989) is monotypic. The type species, distinguishable from other obolids by distinct parvicostellate ornamentation, remains poorly known.

Euobolus elegans (Mickwitz, 1896)

Fig. 60

Synonymy. - []1896 *Obolus elegans* sp. n. - Mickwitz, p. 157, Pl. 2:18. []1912 *Obolus elegans* Mickwitz - Walcott, p. 390, Pl. 15:3. []1989 *Euobolus elegans* Mickwitz - Popov & Khazanovitch, p. 103, Pl. 5:1.

Holotype. - Selected by Mickwitz (1896, p. 157); specimen no. 50/10892 (CNIGR Museum, St. Petersburg); the specimen was found redeposited in the Maardu Member, Jägala river, environs of Jägala-Joa village.

Material. - Figured. Ventral valves: CNIGR 37/12348; GT Br 3554. Total of 5 ventral valves.

Diagnosis. - As for genus.

Description. - Shell subcircular, with parvicostellate radial ornamentation. Ventral pseudointerarea with well defined, narrow pedicle groove (figured by Popov & Khazanovitch, Pl. 5:1a). Propareas high. Ventral visceral area with shallow heart-shaped depression. Transmedian and anterolateral muscles forming two arcuate, elongate composite muscle scars posterolateral of the depression. Dorsal valve unknown.

Occurrence. - Upper Cambrian - Lower Ordovician. Kallavere Formation, Estonia: Jägala River; subsurface of the Toolse and Rakvere phosphorite deposits, core T-129, depth 114.7-115.2 m, core 2162, depth 107.6-108.2 m. Tosna Formation, Ingria Russia: subsurface of the Kingisepp Phosphorite Deposit, core 190, depth 35.1-36.25 m.

Genus *Leptembolon* Mickwitz, 1896

Synonymy. - []1896 *Obolus (Leptembolon)* subgen. nov - Mickwitz, p. 130. []1908 *Obolus (Leptembolon)* - Walcott, p. 144. []1912 *Lingulella (Leptembolon)* (Mickwitz) - Walcott, p. 541. []1965 *Lingulella* Salter - Rowell, p. H266 [in part]. []1969 *Lingulella (Leptembolon)* (Mickwitz) - Goryanskij, p. 37. []1982 *Leptembolon* Mickwitz - Havlicek, p. 38. []1994 *Leptembolon* Mickwitz - Popov & Holmer, p. 47.

Type species. - Original designation by Mickwitz (1896, p. 130); *Obolus (Leptembolon) lingulaeformis*; Leetse Formation, Lepiku village in Leetse estate, Pakri Peninsula, northwestern Estonia.

Diagnosis. - See Popov & Holmer (1994, p. 47).

Species included. - *Obolus (Leptembolon) lingulaeformis* Mickwitz, 1896; *Lingula insons* Barrande, 1879; *Lingula testis* Barrande, 1879.

Discussion. - Mickwitz (1896) established *Leptembolon* as a subgenus of *Obolus*.

Leptembolon has been also regarded as a subgenus of *Lingulella* (Walcott 1908, 1912; Goryanskij 1969) and junior synonym of *Lingulella* (Rowell 1965). Following Havlicek (1982, p. 38) and Popov & Holmer (1994) *Leptembolon* is considered here at the rank of genus.

Occurrence. - Lower Ordovician; Estonia; South Urals, Russia; Bohemia; ?Poland.

Leptembolon lingulaeformis (Mickwitz, 1896)

Fig. 61

Synonymy. - []1896 *Obolus (Leptembolon) lingulaeformis* sp. nov. - Mickwitz, p. 200, Pl. 3:10-17. []1896 *Obolus (Leptembolon) lingulaeformis* var. *solidus* var. nov. - Mickwitz, p. 204, Pl. 3:17, 18. []1912 *Lingulella (Leptembolon) lingulaeformis* (Mickwitz) - Walcott, 1912, p. 542, Pl. 14:5, 5a. []1969 *Lingulella (Leptembolon) lingulaeformis* (Mickwitz) - Goryanskij, p. 38, Pl. 5:5-10. []1969 *Lingulella (Leptembolon) recta*, sp. nov. - Goryanskij, p. 39, Pl. 5:11-17. []1994 *Leptembolon lingulaeformis* (Mickwitz) - Popov & Holmer, p. 48, Fig. 48A-M, 49A-D [synonymy].

Lectotype. - Selected by Goryanskij (1969, p. 38); CNIGR 105/10892; ventral valve (Mickwitz 1896, Pl. 3:10); Leetse beds; coastal section at Leetse, Pakri Peninsula, northern Estonia.

Material. - Figured. Ventral valves: GT Br 3505; GT Br 3564; GT Br 3566; GT Br 3567; GT Br 3568; GT Br 3569. Dorsal valves: GT Br 3506; GT Br 3565; GT Br 3570. Total of 34 ventral and 26 dorsal valves.

Diagnosis. - See Popov & Holmer (1994, p. 47).

Description. - Shell subequally biconvex. Shell surface smooth, with fine concentric growth lines and narrowly and unevenly spaced growth lamellae, more than 10 in some specimens. Ventral valve elongate subtriangular, with maximum width at about one-third of maximum shell length from anterior margin. Ventral pseudointerarea triangular, about half as wide as valve, with narrowly triangular concave pedicle groove. Propareas high, with widely divergent flexure lines. Ventral visceral platform rhomboidal, extending to about mid-valve. *Vascula lateralia* marginal, arcuate, with proximal parts slightly divergent anteriorly.

Dorsal valve elongate suboval to subtriangular, with maximum width anterior to mid-valve. Dorsal pseudointerarea low, with wide wide median groove. Propareas reduced. Dorsal visceral area with wide and long median ridge extending almost to the anterior margin of the valve. Central muscle scars elongate oval, placed posterior of mid-valve. Anterior lateral muscle scars weakly impressed.

Discussion. - The material of *Leptembolon lingulaeformis* from Estonia shows a wide range of variation in shell outline. Considering the Estonian material and the specimens illustrated from the South Urals (Popov & Holmer 1989, p. 48, Fig. 48), adult and gerontic specimens appear to be more broadly triangular than juveniles. As noted by Popov & Holmer (1994), *Leptembolon recta* (Goryanskij, 1969) appears to fall within the variation range of *L. lingulaeformis* and is therefore considered to be a junior synonym of *L. lingulaeformis*.

Leptembolon insons insons (Barrande, 1879) from the Milina Formation and *L. insons testis* (Barrande, 1879) from the Klabava Formation of the Lower Ordovician of Bohemia are closely similar to *L. lingulaeformis*. The specimens of both above subspecies of *L. insons* illustrated by Havlicek (1982, Pl. 6), are elongate and narrow, with their maximum width at about the centre of the shell, as opposed to the subtriangular *L. lingulaeformis* which has the maximum width placed more anteriorly. The specimens of *L. insons* illustrated by Barrande (1879), Koliha (1924) and Havlicek (1982) appear to be outside of the variation range of *L. lingulaeformis*, but examination of larger collections would be required for a conclusive decision.

Specimens from the Lower Ordovician of Poland, illustrated by Bednarczyk (1964, Pls 3-8) as *Lingulella insons* (Barrande), *Lingulella insons lata* (Koliha), *Lingulella santa-crucensis* sp. nov. and *Lingulella zeiszneri* sp. nov. appear to be congeneric with *Leptembolon lingulaeformis*; in view of the poor illustrations, the comparison on specific level is difficult.

Occurrence. - Lower Ordovician, Leetse Formation, Estonia. Localities: Paldiski, Leetse, Osmussaar, Keila-Joa, Maardu Quarry. In South Urals, in the radius of 100 km west and south- west of Orsk, *L. lingulaeformis* occurs in the Akbulaksai and Kidryas Formations tentatively correlated with Hunneberg and Billingen Stages in Baltoscandia (Popov & Holmer 1994).

Genus *Lingulella* Salter, 1866

Type species. - Subsequent designation by Dall (1870, p. 159); *Lingula davisii* M'Coy, 1851; Upper Cambrian (Merioneth Series) Festiniog Beds; south of Penmorfa, Gwynedd, Wales.

Diagnosis. - see Popov & Holmer (1994, p. 41).

Discussion. - As noted by Krause & Rowell (1975, p. 14), a variety of smooth-shelled elongate obolids from Lower Palaeozoic have been included within this genus. As the interior characters of most of these taxa are unknown, their taxonomic relationships cannot be evaluated.

Lingulella antiquissima (Jeremejew, 1856)

Fig. 62D-G.

Synonymy. - []1856 *Lingulella antiquissima* sp. nov. - Jeremejew, p. 80, Fig. 6. []?1866 *Lingulella lepis sp. nov.* - *Salter on Ramsay, p. 334, Fig. 11. []1877 Lingulella nicholsoni* sp. nov. - Callaway, p. 668, Pl. 24:11. []1912 *Lingulella lepis* Salter - Walcott, p. 514, Pl. 31:4,4a-f [synonymy]. []?1982 *Lingulella lepis* Salter - Rushton & Bassett in Owens et al., o. 23, Pl.5p-u. []1982 *Lingulella nicholsoni* Callaway - Rushton & Bassett in Owens ei al., p. 21, Pl. 5j-o. []1989 *Lingulella antiquissima* - Popov & Khazanovitch, p. 124, Pls.4:1,2,4; Pl. 8: 6-10. []1994 *Lingulella antiquissima* - Popov & Holmer, p. 42, Figs 45A-M, 46, 47A-M [synonymy].

Neotype. - Selected by Popov & Khazanovitch (1989, p. 124); CNIGR 180/12348; ventral valve; Tosna Formation; Syas River near Rebrovo village, Ingria, Russia.

Material. - Figured. Ventral valve: CNIGR 180/12348. Dorsal valves: GT Br 3549; CNIGR 181/12348. Total of 20 ventral and 18 dorsal valves.

Diagnosis. - See Popov & Holmer (1994, p. 42).

Description. - Shell flattened to gently biconvex. Shell surface with fine concentric growth lines and micro-ornamentation of oval pits with maximum length reaching 15 μm, surrounded by clusters of smaller subcircular pits, each about 500 nm across. Ventral valve elongate subtriangular, with maximum width at about one-fourth of maximum shell length from the anterior margin. Dorsal valve suboval to subtriangular, with maximum width anterior of mid-shell. Valve interiors not examined.

Remarks. - The affinities of *Lingulella antiquissima* with *L. nicholsoni* Callaway, 1877 and *L. lepis* Salter, 1866 and other related species were discussed in detail by Popov and Holmer (1994, p. 42). The observed micro-ornamentation in *L. antiquissima* may provide some new clues for further taxonomical comparisons.

Occurrence. - Tosna Formation, Ingria, Russia. Localities: Lava River, Suma River, Syas River (for detailed occurrences, see Popov & Khazanovitch, 1989, p. 125). As discussed by Popov & Holmer (1994), *L. antiquissima* also occurs in Great Britain (Wales, Shropshire), Canada (Nova Scotia, Newfoundland), and possibly in Mauritania.

"*Lingulella*" *nitida* (Goryanskij, 1969)

Fig. 63

Synonymy. [] 1969 *Lingulella (Lingulella) (?) nitida* sp. nov. - Goryanskij, p. 36, Pl. 5:4.

Holotype. - Original designation; CNIGR 70/9960; figured by Goryanskij (1969, Pl. 5:4); Leetse Formation, Maardu Quarry, Estonia.

Material. - Figured. Complete shells: GT Br 3558; GT Br 3559; GT Br 3560; GT Br 3561; GT Br 3562; GT Br 3563. Total of 9 complete shells.

Description. - Shell thin, slightly convex, elongate oval. Shell surface smooth, with fine growth lines and with a very low and wide median fold extending for entire length of the shell. Growth lamellae expressed as cuspate incisions on the median fold, indistinct laterally.

Discussion. - Goryanskij (1969) provisionally referred this species to *Lingulella* Salter. "*L.*" *nitida* differs from other Lower Ordovician obolids known from Baltoscandia by having a distinct median fold. As internal characters of this species remain unknown, any further comparison is difficult at this stage.

Occurrence. - Lower Ordovician, Leetse Formation, northern Estonia. Localities: Paldiski and Maardu Quarry.

Genus *Expellobolus* Havlicek, 1982

Synonymy. - *Expellobolus* gen. nov. - Havlicek, 1982, p. 25.

Type species. - *Lingula expulsa* Barrande, 1879; Lower Ordovician, Trenice Formation, Krushna hora near Novy Jachymov, Bohemia.

Diagnosis. - See Havlicek, 1982, p. 25.

Species assigned. - *Lingula expulsa* Barrande, 1879; *Lingulella tetragona* Goryanskij, 1969; ?*Expellobolus?* sp. a. (Holmer, 1989); ?*Palaeobolus quadratus* Bulman, 1927.

Occurrence. - Lower - Middle? Ordovician; Estonia; Bohemia; ?South Wales; ?England; ?Sweden.

Expellobolus tetragonus (Goryanskij, 1969)

Fig. 62A-B

Synonymy. - []1969 *Lingulella (Lingulella) tetragona* sp. nov. - Goryanskij, p. 35, Pl. 5:1-3.

Holotype. - Original designation by Goryanskij (1969, p. 35); CNIGR 68/9960; ventral valve; Leetse Formation, Maardu Quarry, Estonia.

Material. - Figured. Ventral valve: holotype, CNIGR 68/9960. Dorsal valve: CNIGR 69/9960. Total of two dorsal and one ventral valve.

Diagnosis. - Shell flattened, subquadratic to elongate rectangular. Ventral pseudointerarea wide, triangular, with narrow deep pedicle groove. *Vascula lateralia* of both valves submedian, arcuate. Dorsal visceral area bisected by very fine dorsal median ridge, extending to about mid-valve. Dorsal central muscle scars tiny, suboval.

Description. - Shell flattened, subquadratic to elongate rectangular. Ventral pseudointerarea wide, triangular, with narrow deep pedicle groove. Propareas high, flat, with well- expressed flexure lines. Muscle scars weakly impressed. *Vascula lateralia* submedian, arcuate. Dorsal pseudointerarea with wide concave median groove. Propareas high, flat, reduced. Dorsal visceral area bisected by very fine dorsal median ridge, extending to about mid-valve. Central muscle scars tiny, suboval, at about one-third of the maximum valve length from the posterior margin.

Discussion. - This species, described by Goryanskij (1969) as *Lingulella (Lingulella) tetragona* is here assigned to the genus *Expellobolus* Havlicek, 1982. *E. tetragonus* closely resembles the type species, *E. expulsus* (Barrande, 1879) by having a subrectangular outline, as well as the presence of dorsal median septum and the morphology of the pseudointerareas. Another closely similar species, *Palaeobolus quadratus* Bulman, 1927, more recently illustrated by Rushton & Bassett (*in* Owens *et al.*, 1982, Pl. 6a-l.) is here provisionally assigned to the genus *Expellobolus*. *E. tetragonus* differs from both the species named above by having longer dorsal median ridge and smaller, tiny dorsal central muscle scars.

Occurrence. - This very rare species has been found only from the Joa Member of the Leetse Formation in the Maardu Quarry, northern Estonia.

Expellobolus? sp.

Fig. 62C

Synonymy. - []?1989 *Lingulella* aff. *tetragona* Goryanskij - Popov & Khazanovitch, p. 126, Pl. 9: 16-18, Pl. 10:1-3.

Material. - A single specimen, figured from Mäeküla, Estonia. Deformed ventral valve: GT Br 3550.

Description. - Shell flattened, elongate subrectangular, with fine concentric growth lines and growth lamellae.

Remarks. - On the basis of its subrectangular outline, the single specimen described is comparable with the type species of the genus *Expellobolus* (Havlicek, 1982) and related species discussed above, and it is here provisionally assigned to this genus. The specimen resembles, and is probably conspecific with, *Lingulella* aff. *tetragona* illustrated by Popov & Khazanovitch (1989) from the Varangu Formation in northeastern Estonia.

Occurrence. - The described specimen originates from the Lower Ordovician Türisalu Formation at Mäeküla, Tallinn. Possibly conspecific specimens have been illustrated by Popov & Khazanovitch (1989) as *Lingulella* aff. *tetragona* from the Varangu Formation at Aseri, northeastern Estonia.

Genus *Ralfia* Popov & Khazanovitch, 1989

Synonymy. - []1989 *Ralfia* gen. nov. - Popov & Khazanovitch, p. 126. []1994 *Ralfia* Popov & Khazanovitch - Popov & Holmer, 1994, p. 54.

Type species. - *Ungula ovata* Pander, 1830; Upper Cambrian, Ladogo Formation, St. Petersburg region, Russia.

Species assigned. - Type species and ?*Lingula? bryogaptorum* (Moberg and Segerberg, 1906).

Diagnosis. - See Popov & Holmer (1994, p. 54).

Occurrence. - Upper Cambrian - ?Lower Ordovician; Ingria, Russia; Estonia; ?Sweden.

Ralfia ovata (Pander, 1830)

Fig. 64

Synonymy. - []1830 *Ungula ovata* sp. nov. - Pander, 1830, p. 59, Pl. 3:23, Pl. 28:6. [] 1989 *Ralfia ovata* (Pander) - Popov & Khazanovitch, p. 127, Pl. 9: 4-15.

Neotype. - Selected by Popov & Khazanovitch (1989, p. 127); ventral valve, specimen No 203/12348, CNIGR Museum; Upper Cambrian, Ladoga Formation, Izhora river.

Material. - Figured. Ventral valves: CNIGR 203/12348; CNIGR 205/12348; CNIGR 208/12348; GT Br 3249. Dorsal valves: CNIGR 199/12348; CNIGR 202/12348; CNIGR 209/12348; GT Br 3250. Total of 33 ventral and 47 dorsal valves.

Diagnosis. - Shell subequally biconvex, subtriangular, rounded, subequivalved. Ventral pseudointerarea small, rhomboidal, with narrow, deep pedicle groove and subparallel flexure lines. Ventral *vascula lateralia* subparallel, submarginal. Dorsal pesudointerarea reduced, rhomboidal. Dorsal visceral area with long median projection, extending anterior to mid-valve.

Description. - Shell subequally biconvex. Shell surface smooth, with narrow growth lines and widely and unevenly spaced growth lamellae. Ventral valve rounded elongate subtriangular, with maximum width anterior of mid-valve. Ventral pseudointerarea small, rhomboidal, with narrow, deep pedicle groove and subparallel flexure lines. Ventral visceral area slightly thickened, extending to about mid- valve. Central, middle and outside lateral muscles forming two strongly impressed suboval and convergent scars posterior to mid- valve. Combined transmedian and anterior lateral muscle scars lanceolate, slightly divergent, strongly impressed. Ventral *vascula lateralia* subparallel, submarginal.

Dorsal valve elongate subtriangular to suboval.

Dorsal pseudointerarea reduced, rhomboidal. Dorsal visceral area with long median projection, extending anterior to mid-valve. Cental muscle scars large, elongate suboval, slightly divergent. Anterior lateral muscle scars small, suboval, weakly impressed. *Vascula lateralia* subparallel, submarginal. *Vascula media* short, divergent.

Discussion. - This species, described by Pander (1830) as *Ungula ovata* was assigned to a new genus *Ralfia* by Popov & Khazanovitch (1989) as it differs from the related obolids by its vestigial rhomboidal pseudointerareas.

Lingula? bryograptorum Moberg & Segerberg (1906), provisionally assigned to the genus *Ralfia* by Popov & Holmer (1994, p. 54) resembles *R. ovata* in having rhomboidal, reduced pseudointerareas. However, the rarity and poor preservation of *R.? bryograptorum* does not permit a closer comparison.

Occurrence. - Upper Cambrian, upper subformation of Ladoga Formation, Ingria, Russia. Redeposited specimens occur in the Tosna Formation. Localities: Tosna River, Naziya River, Izhora River and Sarya River.

Genus *Rebrovia* Popov & Khazanovitch, 1989

Synonymy. - []1989 *Rebrovia* gen. nov. - Popov & Khazanovitch, p. 112.

Type and only species. - Original designation by Popov & Khazanovitch (1989, p. 112); *Rebrovia chernetskae* Popov & Khazanovitch, 1989; Upper Cambrian, Ladoga Formation, right bank of the Syas River upstream of the southern margin of Rebrovo village.

Diagnosis. - Shell acuminate, elongate oval to subtriangular, subequibiconvex, inequivalved. Shell surface ornamented by fine undulating rugae. Ventral pseudointerarea with narrow pedicle groove. Dorsal pseudointerarea undivided, lacking flexure lines. Dorsal visceral area with narrow anterior projection extending anterior to mid-valve. *Vascula lateralia* of both valves marginal, slightly divergent in posterior half. Dorsal *vascula media* short, slightly divergent to subparallel.

Discussion. - The ornamentation of undulating rugae in *Rebrovia* is comparable to that of *Westonia* Walcott, 1901 and *Glyptoglossella* (Cooper, 1956). *Rebrovia* differs from these genera by having a very high ventral pseudointerarea with narrower pedicle groove and and high, undivided dorsal pseudointerarea.

Occurrence - Upper Cambrian; Estonia; Ingria and White Sea coast near Arkhangelsk, Russia.

Rebrovia chernetskae Popov & Khazanovitch, 1989

Fig. 65

Synonymy. - []1989 *Rebrovia chernetskae* sp. nov. - Popov & Khazanovitch, p. 112, Fig. 20, Pl. 5:6-17. []cf. 1994 *Rebrovia* cf. *chernetskae* - Popov & Goryanskij, p. 34, Fig. 2F-G.

Diagnosis. - As for genus.

Material. - Figured. Ventral valves: GT Br 3891; GT Br 3893; GT Br 3895; CNIGR 86/12348; CNIGR 88/12348; RM Br 136361. Dorsal valves: GT Br 3892; GT Br 3894; GT Br 3896; CNIGR 84/12348; CNIGR 85/12348. Total of 37 ventral and 28 dorsal valves.

Description. - Shell slightly convex, elongate oval, inequivalved. Shell surface ornamented by fine undulating rugae. Ventral valve with maximum width anterior of mid-valve. Ventral pseudointerarea high, with long narrow pedicle groove. Propareas low, concave, with very fine, subparallel flexure lines. Ventral *vascula lateralia* marginal, slightly divergent in posterior half. Transmedian and anterior lateral muscles forming two strongly impressed, lanceolate, subparallel scars anterolateral to pseudointerarea. Other ventral muscle scars weakly impressed. Dorsal pseudointerarea high, gently concave, undivided, lacking flexure lines. Dorsal visceral area with narrow anterior projection extending anterior to mid-valve. Central muscle scars elongate oval, slightly divergent. Dorsal *vascula lateralia* marginal, slightly divergent in posterior half. Dorsal *vascula media* short, slightly divergent to subparallel.

Discussion. - *Rebrovia* cf. *chernetskae* described by Popov & Goryanskij (1994) from the Upper Cambrian at the White Sea Coast, from the cores drilled in a radius of 100 km from Arkhangelsk is closely similar to and probably conspecific with *R. chernetskae*.
Occurrence. - Upper Cambrian; Ladoga and Lomashka formations, Ingria, Russia. Localities: Lomashka, Izhora and Syas rivers. Ülgase Formation, Estonia. Locality: Ülgase.

Genus *Paldiskia* Goryanskij, 1969

Synonymy. - []1969 *Paldiskia* gen. nov. - Goryanskij, p. 28.

Type species. - Original designation; *Paldiskia obscuricostata* Goryanskij, 1969, p. 28; Leetse Formation, Paldiski, northern Estonia.

Diagnosis. - Shell subequibiconvex, subtriangular, with radial ribs in apical region of both valves. Larval and postlarval shells with pitted micro-ornamentation. Pedicle groove broadly triangular. Propareas narrow and high, with poorly defined flexure lines. Ventral visceral area weakly impressed.

Species assigned. - *Paldiskia obscuricostata* Goryanskij, 1969; *Paldiskia orbiculata* Goryanskij, 1969; ?*Paldiskia?* sp. (Popov & Goryanskij 1994).

Occurrence. - ?Upper Cambrian - Lower Ordovician, Estonia; White Sea coast in the environs of Arkhangelsk, Russia.

Discussion. - In the general shell outline, finely pitted external surface and ventral interior characters, *Paldiskia* is similar to *Thysanotos*. *Paldiskia* differs in having a radial ornamentation and in lacking marginal spines.

Paldiskia obscuricostata Goryanskij, 1969

Fig. 66A

Synonymy. - []1969 *Paldiskia obscuricostata* sp. nov. - Goryanskij, 1969, p. 29, Pl. 3: 1-4.

Holotype. - Original designation; CNIGR 43/9960; ventral valve; Lower Ordovician, Leetse Formation; Paldiski, Estonia. Refigured here Fig. P18A.

Material. - Figured: holotype, ventral valve, CNIGR 43/9960. Total of 4 ventral valves.

Diagnosis. - Shell gently biconvex, with fine, indistinct radial ribs. Ventral valve rounded subtriangular, with sharpened apical part and with maximum width anterior of mid-valve.

Description. - Shell gently biconvex. Shell surface smooth, with fine, indistinct radial ribs, fine concentric growth lines and growth lamellae, tightly spaced near the anterior margin of the shell and widely and unevenly spaced in the posterior 3/4 of the shell. Ventral valve rounded subtriangular, with sharpened apical part and with maximum width anterior of mid-valve. Ventral valve interior poorly known . Ventral pseudointerarea triangular, with concave triangular pedicle groove (Goryanskij, 1969, Pl. 3:4). Propareas high, reduced, with poorly defined flexure lines. Dorsal valves unknown.

Discussion. - This and related species of *Paldiskia* are rare and rather poorly known and can be compared only on the basis of external characters. *P. obscuricostata* differs from *P. orbiculata* in lacking concentric rugae and well-defined radial costellae in the apical part of the shell.

The specimens from the Upper Cambrian of White Sea Coast, environs of Arkhangelsk, Russia illustrated by Popov & Goryanskij (1994, Fig. 2A-E) as *Paldiskia*? sp. were provisionally assigned to this genus on the basis of general outline and radial costellae in the apical part of the shell. As compared to *P. obscuricostata*, the illustrated ventral valve of *Paldiskia* sp. is more broadly triangular, with better defined radial costellae in the apical part.

Occurrence. - Lower Ordovician, Leetse Formation, environs of Paldiski and Maardu Quarry, Estonia.

Paldiskia orbiculata Goryanskij, 1969

Fig. 66B.

Synonymy. - []1969 *Paldiskia orbiculata* sp. nov. - Goryanskij, 1969, p. 29, Pl. 3: 1-4.

Holotype. - Original designation; CNIGR 47/9960; ventral valve, figured by Goryanskij (1969, Pl. 3:5); Leetse Formation, Maardu Quarry, Estonia.

Material. - Figured. Ventral valve: GT Br 3576. Total of 4 ventral and 2 dorsal valves.

Diagnosis. - Shell subcircular, ornamented by concentric rugellae and radial ribs of variable length, well expressed in the posterior part. Margins of growth lamellae observable in marginal parts. Internal characters weakly impressed.

Discussion. - This species differs from *Paldiskia obscuricostata* by the subcircular outline of the shell and ornamentation.

Occurrence. - Lower Ordovician, Leetse Formation, Maardu Quarry, Estonia.

Genus *Thysanotos* Mickwitz, 1896

Synonymy. - []1896 *Obolus (Thysanotos)* subgen. nov. Mickwitz, p. 130. []1908 *Obolus (Mickwitzella)* subgen. nov. Walcott, p. 70. []1912 *Obolus (Mickwitzella)* - Walcott, p. 434. []1965 *Thysanotos* Mickwitz - Rowell, p. H266. []1969 *Thysanotos* Mickwitz - Goryanskij, p. 33. []1982 *Thysanotos* Mickwitz - Havlicek, 1982. []1994 *Thysanotos* Mickwitz - Popov & Holmer, p. 38.

Type and only species. - Original designation by Mickwitz (1896, p. 130); *Obolus siluricus* Eichwald, 1840; Leetse Formation; northern Estonia.

Diagnosis. - See Popov & Holmer (1994, p. 38).

Remarks. - Mickwitz (1896) introduced *Thysanotos* as a subgenus of *Obolus*. Walcott (1908) considered *Thysanotos* as a junior homonym of a gastropod *Thysanota* Albers, 1860 and proposed new name *Mickwitzella* for the subgenus to resolve this homonymy. Rowell (1965) noted the lack of homonymy because of the different gender of the names *Thysanotos* and

Thysanota, and elevated *Thysanotos* in rank to genus.

The genus *Thysanobolus* Havlicek (1982), described from the Trenice and Milina formations of Bohemia was assigned three species: *Thysanobolus lingulides* Havlicek, 1982, *T. pirolus* Havlicek, 1982 and *Obolus giganteus* Koliha, 1937. As discussed by Popov & Holmer (1994, p. 38), all illustrated specimens of these three species (Havlicek, 1982), some of which may have been affected by *post mortem* deformations, are within the variation range of *T. siluricus* and are considered to be subjective junior synonyms of the type species.

Hyperobolus Havlicek, 1982 closely resembles *Thysanotos* in shell outline and in the configuration of visceral areas. *Thysanotos* can be distinguished by more transverse suboval shell and ornament of elevated rugellae, superposed by concentric lamellae with marginal spines. *Hyperobolus* is ornamented by evenly spaced fine concentric growth lines superposed by growth lamellae lacking marginal spines.

Occurrence. - Lower Ordovician, Arenig, Estonia, South Urals, Bohemia, ?Poland, ?Germany.

Thysanotos siluricus (Eichwald, 1840)

Fig. 67

Synonymy. - []1840b *Obolus siluricus* sp. nov. Eichwald, p. 195. []1843 *Obolus siluricus* - Eichwald, p. 7, Pl. 1:15a-c. []1845 *Obolus siluricus* Eichwald - de Verneuil (*in* Murchison *et al.*), p. 291 [in part]. [] 1848 *Aulonotreta polita* sp. nov. Kutorga, p. 279 [in part]. []1859 *Obolus siluricus* Eichwald - Eichwald, Pl. 37:6, 7a- b. [] 1860 *Obolus siluricus* Eichwald - Eichwald, p. 297. []1896 *Obolus (Thysanotos) siluricus* Eichwald - Mickwitz, p. 195, Pl. 3: 1-9. []1912 *Obolus (Mickwitziella) siluricus* Eichwald - Walcott, p. 434, Pl. 30:1-4 [synonymy]. []1924 *Obolus (Lingulobolus) Feistmanteli* (Barrande) var. *Barrandei* (Kloucek) - Koliha, p. 19, Pl. 1:6. []1924 *Obolus (Lingulobolus) Feistmanteli* (Barrande) var. *Barrandei prima* var. nov. - Koliha, p. 19, Pl. 1:6. []1937 *Obolus giganteus* sp. nov. - Koliha, p. 481. []?1955 *Obolus (Thysanotos) siluricus* Eichwald - Sdzuy, p. 7, Pl. 1:1-4. []?1956 *Obolus siluricus* Eichwald - Müller, p. 52, Figs 1-5. []1962 *Obolus (Thysanotos) siluricus* Eichwald - Bednarczyk, p. 157, Pl. 30:3,4. []1964 *Obolus (Thysanotos) siluricus* Eichwald - Bednarczyk, p. 157, Pl. 1:1-14, Pl. 9:8-12. []1965 *Thysanotos siluricus* (Eichwald) - Rowell, p. H266; Fig. 159:8. []1969 *Thysanotos siluricus* (Eichwald) - Goryanskij, p. 32, Pl. 4:1-10 [synonymy]. []1982 *Thysanotos siluricus* (Eichwald) - Havlicek, p. 24, Pl. 2:1-6. []1982 *Thysanotos primus* (Koliha) - Havlicek, p. 22, Pl. 2:7-8. []1982 *Thysanobolus linguides* sp. nov. - Havlicek, p. 21, Pl. 2:10-13. []1982 *Thysanobolus giganteus* (Koliha) - Havlicek, p. 22, Pl. 2:9, Pl. 4-13. []1982 *Thysanobolus pirolus* sp. nov. - Havlicek, p. 23, Pl. 10:10-11. []1994 *Thysanotos siluricus* (Eichwald) - Popov & Holmer, p. 39, Figs. 43-44.

Lectotype. - Selected by Goryanskij (1969, p. 33); ventral valve illustrated by Eichwald (1843, Pl. 1:15a, b); specimen in the University of St. Petersburg, Department of Geology; lower part of the Leetse Fm.; environs of Paldiski, Pakri Peninsula, NW Estonia.

Material. - Figured. Complete shell: GT Br 3501. Ventral valves: GT Br 3503; GT Br 3504; GT Br 3556; GT Br 3557; GT Br 3571. Dorsal valves: GT Br 3502; GT Br 3555; GT Br 3510. Total of 46 ventral and 39 dorsal valves.

Diagnosis. - As for genus.

Description. - Shell dorsi-biconvex, subcircular to transversely suboval in outline. Shell surface covered by high, widely spaced rugellae, superposed by concentric lamellae with marginal spines. Larval and postlarval shell finely pitted. Ventral pseudointerarea orthocline, with narrow, deep, triangular pedicle groove. Propareas high, with well-defined flexure lines. Ventral visceral area slightly elevated, subtriangular, not extending to mid-length. Ventral *vascula lateralia* submarginal, arcuate slightly divergent in the proximal parts.

Dorsal psudointerarea low, anacline, with wide concave median groove. Propareas high, with well-defined flexure lines, reduced in larger specimens. Dorsal visceral area with median tongue, extending to about mid-length, laterally bounded by two low arcuate ridges. Dorsal *vascula lateralia* submarginal, widely divergent in proximal parts.

Discussion. - A description and illustration of *Obolus siluricus* by Eichwald (1843, Pl. 1:15a-c) was previously considered as the first description of this species. However, as pointed out by Goryanskij (1969, p. 32), the first description of *Obolus siluricus* was published in a Russian edition of an earlier study by Eichwald (1840b). The Russian edition appears to be a slightly emended version of a better known German edition (Eichwald, 1840a), where the material of *T. siluricus* is apparently mentioned under the description of *Obolus apollinis*, but not assigned to a separate species.

As well as its occurrence in the type area in Estonia, *Thysanotos siluricus* has been reported from the Lower Ordovician in the South Urals, Bohemia, Poland and Germany. Of these reports, only the well-documented occurrences of *T. siluricus* in the South Urals (Popov & Holmer, 1994) and the Prague Basin in central Bohemia (Havlicek, 1982) can be confirmed with confidence. Havlicek (1982) assigned a variety described by Koliha (1924) as *Obolus (Lingulobolus) Feistmanteli* (Barrande) var. *Barrandei prima* from the Trenice Formation in Bohemia to a separate species *Thysanotos primus*, distinguished from *T. siluricus* by smaller size and coarser rugellae. However, these differences appear to be within the variation range of *T. siluricus* from the type area in NW Estonia; thus *T. primus* is a junior subjective synonym of *T. siluricus*. As discussed above, *Thysanobolus lingulides* Havlicek, 1982, *T. pirolus* Havlicek, 1982 and *T. giganteus* (Koliha, 1937), illustrated by Havlicek (1982) from the Trenice and Milina formations in Bohemia, are also considered to be junior subjective synonyms of *T. siluricus*.

Bednarczyk (1962, 1964) has reported *Thysanotos siluricus* from the Zbilutka and Koziel beds, correlating to the Hunneberg and Billingen stages, in the Holy Cross Mountains, Poland. In view of the poor illustrations, the identification of the specimens illustrated by Bednarczyk (1964, Pl. 1) cannot be confirmed with confidence; however, at least two specimens (Pl. 1:3,5) appear to be ornamented by concentric rugellae superposed by growth lamellae with marginal spines, characteristic of *T. siluricus*. The triangular platform-like ventral visceral area with widely divergent *vascula lateralia* (Bednarczyk 1964, Pl. 1:2) is also closely similar to *T. siluricus*. Thus, with some reservations, these Polish specimens can be considered as conspecific with *Thysanotos siluricus*.

The occurrence of *Thysanotos siluricus* in the Tremadocian Leimitz Shale in Bavaria, Germany, cannot be confirmed with confidence. The growth lamellae with marginal spines, characteristic of *T. siluricus*, could not be observed in the latex casts of the poorly preserved internal moulds illustrated by Sdzuy (1955, pl. 1:1-4). By shell outline and ornamentation, these moulds, illustrated as *Thysanotos siluricus*, somewhat resemble *Hyperobolus feistmanteli* (Barrande, 1879). The illustrations by Barrande (1868) and Walcott (1912) show that all of the Bavarian obolids included by Sdzuy (1955) to the synonymy of his *T. siluricus*, e.g. *Obolus? palliatus* Barrande, 1868, *Obolus? minor* Barrande, 1868, *Lingula bavarica* Barrande, 1868 and *Lingula cedens* Barrande, 1868 also lack the spines on the growth lamellae.

Another German occurrence of *Thysanotos siluricus* has been reported by Müller (1956) from the Tremadocian of the Frauenbach quartzites at Siegmundsburg, near Steinheid, Thüringia. The specimens are poorly preserved and appear to be deformed *post mortem*. In the configuration of the dorsal visceral area, the specimens illustrated by Müller (1956, Figs 1- 5) resemble both *T. siluricus* and *Hyperobolus feistmanteli* (Barrande, 1879). The preserved features of these specimens are not sufficient for confirming their identification as *T. siluricus*.

Occurrence. - Lower Ordovician, *Paroistodus proteus* conodont Biozone, Klooga and Joa members, Leetse Formation, Estonia. Localities: Osmussaar, Väike-Pakri island, Paldiski, Leetse, Keila-Joa, Türisalu, Harku trench, Hundikuristik, Mäekalda, Iru, Mäeküla, Maardu, Jägala-Joa; subsurface of Hiiumaa island, Kiideva core No. 362, depth 231.1 m, and Kassari islet near Hiiumaa, core F-371, depth 168.3 m; subsurface of NW Estonia, core D-32, depth 207.3 m.

In South Urals, this species occurs in the Lower Ordovician Akbulaksai and Alimbet formations, correlative to the Hunneberg and Billingen stages in Baltoscandia (Popov & Holmer, 1994). In the Prague Basin, central Bohemia, *Thysanotos siluricus* occurs in the Lower Ordovician Trenice and Milina formations. These formations have been referred to the Tremadoc by Havlicek (1982a, b). However, as Havlicek *et al.* (1991, p. 30) refer the Estonian *Thysanotos* fauna to the Tremadoc, the age of the Trenice and Milina formations remains disputable. As yet, there is no solid evidence from microfossils to support an age of the Trenice and Milina formations any older than *Paroistodus proteus* conodont Biozone; therefore, it is possible that the levels with *Thysanotos siluricus* in these formations are no older than the Hunneberg Stage in Baltoscandia.

Possible occurrences in the Holy Cross Mountains, Poland, are associated with the Zbilutka and Koziel beds (Bednarczyk 1964, p. 74, Table 2) and have been broadly correlated to the Hunneberg and Billingen stages in Baltoscandia. As discussed above, the reported occurrences in Bavaria and Thüringia, Germany, cannot be confirmed with confidence.

Consequently, the range of *Thysanotos siluricus* is best documented in Baltoscandia, where it corresponds to the *Paroistodus proteus* conodont Biozone; there is no solid evidence for earlier occurrences of *Thysanotos siluricus* in other regions.

Genus *Estoniobolus* gen. nov.

Name. - After Estonia.

Type and only species. - *Obolus eichwaldi* Mickwitz, 1896; Maardu Member, Kallavere Formation; Jägala River, Estonia.

Diagnosis. - Shell gently convex, transversely suboval, with weak concentric growth lines, finely and weakly radially striated. Larval and sublarval shell with very fine subcircular pits. Ventral pseudointerarea with wide, slightly concave pedicle groove. Propareas wide, with well-expressed flexure lines. Ventral visceral area elevated, with large, deep, heart-shaped depression and high, narrow, median ridge posterior of depression. Dorsal pseudointerarea undivided, with subparallel flexure lines. Dorsal visceral area slightly concave, bounded by two divergent ridges.

Discussion. - *Estoniobolus* gen. nov. somewhat resembles *Ungula* (Pander, 1830) and differs from most other lingulids in having a large, deep heart-shaped depression in the ventral visceral area. The wide concave pedicle groove in the dorsal valve is also similar to that of the type species of *Ungula*. *Estoniobolus* differs from *Ungula* by having a narrow median ridge posterior to the ventral heart- shaped depression, wider pedicle groove, concave dorsal visceral area and an ornament of very fine pits on larval and postlarval shell. Pitted larval and postlarval shell has been considered as diagnostic of the family Zhanatellidae (Popov et al., 1994, p. 70), but also occurs among the obolid genera, e.g., in *Hyperobolus* Havlicek, 1982, *Rosobolus* Havlicek, 1982, *Thysanotos* and *Paldiskia*. In view of similarities to *Ungula* in the morphology of interior characters, *Estoniobolus* gen. nov. is here assigned to the family *Obolidae* King.

Occurrence. - Upper Cambrian - Lower Ordovician; Maardu Member, Kallavere Formation, Estonia.

Estoniobolus eichwaldi (Mickwitz, 1896)

Fig. 68

Synonymy. - []1896 *Obolus eichwaldi* sp. nov. - Mickwitz, p. 154, Pl. 2:15a-15d. []1912 *Obolus eichwaldi* Mickwitz - Walcott, p. 390.

Holotype. - By monotypy; dorsal valve, CNIGR 55/10892, figured by Mickwitz (1896, Pl. 2:15a-d); Cambrian-Ordovician boundary beds; Maardu Member, Kallavere Formation, Jägala River, Estonia.

Material. - Figured. Ventral valves: GT Br 3897; GT Br 3899; GT Br 3900. Dorsal valve: GT Br 3898. Total of 26 ventral and 18 dorsal valves.

Diagnosis. - As for genus.

Description. - Shell gently convex, transversely suboval. Shell surface with weak concentric growth lines, finely and weakly radially striated. Larval and sublarval shell with very fine subcircular pits, up to 5 μm across.

Ventral pseudointerarea low, with wide, slightly concave pedicle groove. Propareas wide, with well-expressed flexure lines. Ventral visceral area elevated, with large, deep, heart-shaped depression and high, narrow, median ridge posterior of depression. Central, middle and outside lateral muscles forming two arcuate composite scars anterolateral of depression. Composite scars of transmedian and anterior lateral muscles large, suboval, strongly impressed, slightly divergent.

Dorsal pseudointerarea undivided, with subparallel flexure lines. Dorsal visceral area bounded by two wide, high, divergent ridges, slightly concave, with low median ridge.

Discussion. - This species was known by a single dorsal valve illustrated by Mickwitz (1896, Pl. 2:15) as *Obolus eichwaldi*. Based on the studies of ventral and dorsal valve interiors and shell micro-ornamentation of new well-preserved material, this species is assigned here to a new genus, *Estoniobolus*.

Occurrence. - Upper Cambrian - Lower Ordovician, Kallavere Formation, northern Estonia. Localities: Keila-Joa, Ülgase.

Genus *Foveola* Goryanskij, 1969

Synonymy. - []1969 *Foveola* gen. nov. - Goryanskij, p. 30. []1980 *Faveolla* Goryanskij - Nazarov & Popov, 1980, p. 81.

Type species. - Original designation by Goryanskij (1969, p. 30); *Foveola maarduensis*; Lower Ordovician, Leetse Formation, northern Estonia.

Diagnosis. - Shell subcircular, gently biconvex. Postlarval shell coarsely pitted; larval shell smooth. Ventral pseudointerarea with deep, narrow pedicle groove. Ventral propareas high, lacking flexure lines. Dorsal pseudointerarea high, undivided.

Species included. - *Foveola maarduensis* Goryanskij, 1969; *Obolus?* sp. 4 (Cooper 1956, p. 193); *Foveola* sp. (Nazarov & Popov, 1980, p. 81).

Discussion. - *Foveola* can be distinguished from other Early Palaeozoic obolids by smooth larval and coarsely pitted postlarval shell. As well as those of the type species, these features have been documented in *Foveola* sp. from the Middle Ordovician Karakan Formation of the Central Kazakhstan (Nazarov & Popov 1980, p. 81, Pl. 28:1,2) and in an unnamed species from the Middle Ordovician Pratt Ferry limestone in Alabama, USA (Cooper, 1956, p. 193;

Pl. 9:20-21; Pl. 11:6-8), referred to the genus *Foveola* by Goryanskij (1969, p. 30).

Occurrence. - Lower - Middle Ordovician; Estonia; Central Kazakhstan; Alabama, USA.

Foveola maarduensis Goryanskij, 1969

Fig. 69

Synonymy. - []1969 *Foveola maarduensis* sp. nov. - Goryanskij, p. 31, Pl. 3: 10-14.

Holotype. - CNIGR 52/9960; dorsal valve; Leetse Formation, Maardu Quarry, northern Estonia; figured by Goryanskij (1969, Pl. 3:10); refigured here Fig. Pl.19A.

Material. - Figured. Ventral valves: RM Br 136352; RM Br 136353; GT Br 3573. Dorsal valves: CNIGR 52/9960; GT Br 3572; GT Br 3574. Total of 11 ventral and 6 dorsal valves.

Diagnosis. - As for genus.

Description. - Shell gently biconvex, subcircular. Larval shell smooth. Postlarval shell surface coarsely pitted, with unevenly spaced concentric growth lamellae. Ventral pseudointerarea with deep narrow pedicle groove and high propareas, lacking flexure lines (Goryanskij 1969, Pl. 3:14). Dorsal pseudointerarea wide, high, undivided. Internal characters in both valves weakly impressed.

Discussion. - The possibly congeneric Middle Ordovician species *Obolus?* sp. 4 from Alabama, USA (Cooper 1956) and *Foveola* sp. from Central Kazakhstan (Nazarov & Popov 1980) differ from *Foveola maarduensis* by coarser pitting of the postlarval shell.

Occurrence. - Lower Ordovician, Hunneberg Stage, Leetse Formation, northern Estonia. Localities: Keila-Joa and Maardu Quarry.

Genus *Vassilkovia* Popov & Khazanovitch, 1989

Synonymy. - []1989 *Vassilkovia* gen. nov. - Popov & Khazanovitch, p. 123.

Diagnosis. - Shell equibiconvex, inequivalved, with growth lines crossed by transverse lines and small, closely spaced granules. Ventral pseudointerarea orthocline, high, with deep, narrow, triangular pedicle groove. Propareas elevated, high, with well-expressed flexure lines, accentuated by narrow grooves. Dorsal pseudointerarea with wide concave median groove. Propareas narrow, high, with fine, weakly impressed flexure lines. Interior characters of both valves weakly impressed.

Type species. - *Vassilkovia granulata* Popov & Khazanovitch, 1989.

Species included. - Type species and *Vassilkovia* sp. (Khazanovitch & Popov 1989, p. 124).

Discussion. - *Vassilkovia* is distinguishable from other obolids by the pitted larval and finely granulate postlarval shell.

Vassilkovia granulata Popov et Khazanovitch, 1989

Fig. 70

Synonymy. - []1989 *Vassilkovia granulata* gen. et sp. nov. - Popov & Khazanovitch, p. 123, Pl. 8: 3-5.

Holotype. - CNIGR 176/12348; ventral valve; Upper Cambrian, Ladoga Formation, right bank of the Lava river near the Gorodishche village.

Material. - Figured. Ventral valve: CNIGR 176/12348. Dorsal valve: CNIGR 177/12348. Total of 5 ventral and 2 dorsal valves.

Diagnosis. - As for genus.

Description. - Shell gently biconvex. Ventral valve elongate subtriangular. Ventral pseudointerarea orthocline, high, with deep triangular pedicle groove. Propareas elevated, high, with well-expressed flexure lines, accentuated by narrow grooves. Dorsal valve suboval. Dorsal pseudointerarea with wide concave median groove. Propareas narrow, high, with fine, weakly impressed flexure lines. Interior characters of both valves weakly impressed.

Discussion. - The ornamentation of *Vassilkovia* sp. (Popov & Khazanovitch, 1989, p. 124) from the Tosna Formation at Lava River, Ingria, Russia is closely similar to *Vassilkovia granulata*; *Vassilkovia* sp. differs by having an elongate oval shell outline.

Occurrence. - Upper Cambrian, upper subformation of the Ladoga Formation, Ingria, Russia. Locality: Lava River.

Order *Siphonotretida* Kuhn, 1949
Superfamily *Siphonotretoidea* Kutorga, 1848
Family *Siphonotretidae* Kutorga, 1848

Genus *Eosiphonotreta* Havlicek, 1982

Type species. -- *Terebratula verrucosa* Eichwald, 1840; Kunda Stage, Popovka near Pulkovo, Ingria, Russia.

Diagnosis and species included - See Havlicek, 1982, p. 57.

Discussion. - In addition to the species included by Havlicek (1982), *Siphonotreta mamatensis* Popov (in Nazarov & Popov, 1980, p. 116, Pl. 19:11-14) may belong to this genus. *Siphonotreta uralensis* Lermontova, 1933, assigned by Havlicek (1982) to *Eosiphonotreta* has been reassigned by Popov and Holmer (1994) to the genus *Siphonobolus* Havlicek, 1982.

As noted by Havlicek (1982, p. 57), *Eosiphonotreta* differs from *Siphonotreta* Verneuil by having a thinner shell and low, conical ventral valve with apsacline to catacline pseudointerarea, and in lacking an elevated ventral visceral platform. *Eosiphonotreta* differs from *Siphonotretella* Popov & Holmer, 1994 by being about five times larger in size. Also, the pedicle foramen of *Eosiphonotreta* is enlarged by resorption, while that of *Siphonotretella* is small and subcircular.

Eosiphonotreta? acrotretomorpha (Goryanskij, 1969)

Fig. 71

Synonymy. - []1969 *Siphonotreta acrotretomorpha* sp. nov. - Goryanskij, p. 85, Pl. 14: 6-9. []not 1973 *Siphonotreta acrotretomorpha* Goryanskij - Biernat, p. 105, Text-Fig. 39; Pl. 27:4-10, Pl. 28:1-7, Pl. 29:1-5, Pl. 30:6-8.

Holotype. - Ventral valve in the University of St. Petersburg, Department of Geology, figured by Goryanskij, 1969, Pl. 14:6; Leetse Formation, environs of Paldiski, Estonia.

Material. - Figured. Ventral valves: CNIGR 195/12348; GT Br 3587. Dorsal valves: CNIGR 236/9960; GT Br 3242. Total of 7 ventral and 6 dorsal valves.

Description. - Shell subcircular in outline. Shell surface with indistinct concentric growth lines and growth lamellae. Shell ornamented by densely spaced spines of two sizes, with smaller density in apical regions. Smaller spines aligned along growth lamellae; larger spines irregularly spaced. Ventral valve moderately high, subconical. Pedicle foramen posterior to apex, enlarged by resorption, lacking pedicle track. Internal pedicle tube large, narrowing towards the foramen. Dorsal valve slightly convex, flattened, with maximum convexity in the apical part.

Discussion. - This species was assigned to the genus *Eosiphonotreta* by Havlicek (1982). This assignement is followed here, as the interior characters are unknown. Goryanskij (1969, p. 86) pointed out the close resemblance of *E.? acrotretomorpha* to *Siphonotreta uralensis* Lermontova, 1933 from the Koagash Formation in South Urals. The latter species has been recently illustrated by Popov & Holmer (1994, p. 82, Fig. 73), who assigned it to the genus

Siphonobolus Havlicek, 1982. *Siphonobolus uralensis* differs from *S. acrotretomorpha* by having a longer and narrower pedicle tube and flatter ventral valve.

Popov & Holmer (1994, p. 84-86) pointed out that the specimens from the Tremadocian chalcedonites from Holy Cross Mountains in Poland illustrated by Biernat (1973) as *Siphonotreta acrotretomorpha* are closely similar to *Siphonotretella* sp. from the Koagash Formation in South Urals and assigned them to the genus *Siphonotretella* Holmer & Popov, 1994.

Mergl (1995) described *Siphonotretella* sp. from the Milina and Klabava formations in Central Bohemia and pointed out that it resembles *Eosiphonotreta acrotretomorpha*, but is about one third of the size. The specimens illustrated by Mergl (1995, p. 107, Pl. 4:7-11) differ also by having a subcircular pedicle foramen, not enlarged by resorption.

Eosiphonotreta? mamatensis (Popov in Nazarov & Popov, p. 116, Pl. 29: 5-7) has a wide internal pedicle tube, closely similar to that of *E.? acrotretomorpha*; it differs by having an ornamentation of deep rugae.

Occurrence. - Lower Ordovician, Leetse Formation, Estonia. Localities: Paldiski, Keila-Joa and Maardu Quarry.

Genus *Helmersenia* Pander, 1860

Synonymy. - []1860 *Discina* - Eichwald (in part), p. 910. []1860 *Helmersenia* gen. nov. - Pander, p. 48. [] 1912 *Helmersenia* Pander - Walcott, p. 367. []1965 *Helmersenia* Pander - Rowell, p. H288. []1969 *Helmersenia* Pander - Goryanskij, p. 98 (synonymy). []not 1973 Helmersenia Pander - Biernat, p. 110. []1989 *Helmersenia* Pander - Popov & Khazanovitch, p. 134.

Type and only species. - Original designation by Pander (1860), *Siphonotreta ladogensis* Jeremejew, 1856; Upper Cambrian - Lower Ordovician, Tosna Formation, Ingria, Russia.

Diagnosis. - Shell equibiconvex, with widely spaced uniform hollow spines. Foramen apical, circular, minute. Ventral pseudointerarea low, apsacline, undivided. Dorsal pseudointerarea wide, poorly divided, with anacline propareas. Internal pedicle tube short, flattened dorsoventrally, lying on the valve floor, closed in adults. Ventral visceral area thickened (modified after Popov & Khazanovitch, p. 134).

Discussion. - The morphological similarity of *Helmersenia* and *Acanthambonia* was noted by Goryanskij (1969, p. 99 and Popov & Nõlvak (1987, p. 17). *Acanthambonia* differs from *Helmersenia* by having a relatively high ventral pseudointerarea and a flat, long inner pedicle tube.

Helmersenia ladogensis (Jeremejew, 1856)

Fig. 72

Synonymy. - []1856 *Siphonotreta ladogensis* sp. nov. - Jeremejew, p. 73, 80; Figs 5a-c. []1860 *Discina buchii* Eichwald - p. 914 (in part). []1860 *Helmersenia ladogensis* (Jeremejew) - Pander, Pl. 2: 2a-g. []1877 *Helmersenia jeremejewi* Pander - Dall, p. 31. []1887 *Keyserlingia panderi* sp. n. - Karpinsky, p. 476. []1887 *Helmersenia jeremejewi* Pander - Oehlert, p. 1264. []?1892 *Helmersenia* sp. Pander. - Hall & Clarke, p. 119, Pl. 4: 4,5. []1912 *Helmersenia ladogensis* (Jeremejew) - Walcott, p. 368, Pl. 63: 7, 7a-f. []1965 *Helmersenia ladogensis* (Zheremezhev) - Rowell, p. H288, Fig. 180: 2a-e. []1969 *Helmersenia ladogensis* (Jeremejew) - Goryanskij, p. 99, Pl. 19: 1-12, 14-21; not Pl. 19:13. []not 1973 *Helmersenia cf. ladogensis* (Jeremejev) - Biernat, p. 110, Fig. 40, Pl. 23: 1-7. []1986 *Helmersenia ladogensis* (Yeremejew) - Kaljo et al., Pl. 1:8,9. [] 1989 *Helmersenia ladogensis* (Jeremejew) - Popov & Khazanovitch, p. 135, Pl. 12: 10-15.

Neotype. - Selected by Popov & Khazanovitch (1989, p. 135); CNIGR 254/12348; ventral valve; Tosna Formation; left bank of Volkhov River, outcrop L-42 of Popov et al. (1989), Ingria, Russia.

Figured material. - Ventral valves: GT Br 3198; GT Br 3203; GT Br 3200; GT Br 3201; GT Br 3205; GT Br 3206; GT Br 3208. Dorsal valves: GT Br 3197; GT Br 3199; GT Br 3202; GT Br 3204; GT Br 3207.

Additional material. - Hundreds of ventral and dorsal valves from coquinas (not counted).

Diagnosis. - As for genus.

Description. - Shell equibiconvex, with widely and regularly spaced uniform hollow spines forming a reticular pattern, and indistinct fine concentric growth lines. Pedicle foramen apical, circular, minute. Ventral pseudointerarea low, apsacline, undivided. Internal pedicle tube short, flattened dorsoventrally, lying on the valve floor, closed in adults. Dorsal pseudointerarea wide, poorly divided, with anacline propareas. Ventral visceral area thickened. Internal characters of both valves poorly expressed.

Discussion. - As noted by Goryanskij (1969, p. 99), juvenile dorsal valves of *Eosiphonotreta? acrotretomorpha* somewhat resemble and have been sometimes confused with *H. ladogensis*. For example, specimens from the Leetse Formation figured by Goryanskij (1969, Pl. 19: 13) from the Maardu Quarry and reported by Mägi (in Mägi & Viira 1976) from Keila-Joa as *H. ladogensis*, actually represent *Eosiphonotreta? acrotretomorpha* Goryanskij. The valves of *H. ladogensis* differ by having regularly spaced spines, forming a reticular pattern.

Occurrence. - Upper Cambrian - Lower Ordovician. Tosna Formation in Ingria, Russia. Localities: Narva, Luga, Lomashka, Izhora, Tosna, Naziya, Lava rivers, in abundance at Volkhov and Syas rivers. Kallavere Formation in subsurface of Hiiumaa Island, NW Estonia. Locality: environs of Kärdla, core K-11, depth 78.8- 80.4 m.

Genus *Schizambon* Walcott, 1884

Type species. - Subsequent designation by Oehlert (in Fischer 1887, p. 1266); *Schizambon typicalis* Walcott, 1884; Lower Ordovician Pogonip Limestone, Hamburg Ridge, Eureka district, Nevada.

Diagnosis. - see Popov & Holmer (1994, p. 87).

Occurrence. - Upper Cambrian - Middle Ordovician; North America, Europe, Asia.

Schizambon? esthonia Walcott, 1912

Fig. 73B-F

Synonymy. - [] 1912 *Schizambon? esthonia* sp. nov. - Walcott, p. 622, Pl. 84:4. [] 1969 *Schizambon esthonia* Walcott - Goryanskij, p. 92, Pl. 18: 2,3.

Holotype. - By monotypy, specimen in United States National Museum, USNM 52222a; ventral valve; described and figured by Walcott (p. 622, 1912, Pl. 84:4); Leetse Formation; environs of Paldiski, Estonia.

As Walcott (1912, p. 622) clearly stated that this species was based on a single specimen, it is the holotype by monotypy. The specimen was reported from the Ungulite Grit (Obolus Sandstone) at Baltischport (Paldiski), Estonia. This level, corresponding to the Kallavere Formation is apparenly in error, as all the further studies have confirmed that in this and other localities *Schizambon? esthonia* occurs in the upper part of the Glauconite Sandstone of the present Leetse Formation.

Material. - Figured. Ventral valves: GT Br 3242; GT Br 3244; GT Br 3245. Dorsal valves: Br 3243; GT Br 3246. Total of 21 ventral and 16 dorsal valves.

Description. - Shell dorsibiconvex, subcircular. Shell surface ornamented by fine, tightly and irregularly spaced spines of about equal size and growth lamellae, tightening marginally. Ventral valve low, subconical. Pedicle foramen anterior to apex, shallow, extending to elongate triangular pedicle track. Ventral valve interior with a short internal pedicle tube.

Dorsal valve subcircular, strongly convex. Dorsal pseudointerarea a flat plate overhanging interior of valve. Interior characters of both valves poorly defined.

Discussion. - Mickwitz (1912) provisionally assigned this species to *Schizambon*. Goryanskij (1969), pointing out its resemblance to the type species, *S. typicalis* Walcott, 1884 in surface ornamentation, considered its assignment to *Schizambon* definite. However, the examination of the interiors of both valves, not available for the previous authors, suggests the need to return to the provisional assignment of Mickwitz.

Schizambon? esthonia is similar to the type species in having fine, evenly spaced spines and the flat plate-like dorsal pseudointerarea overhanging the interior of valve. However, it has a short internal pedicle tube not characteristic of *Schizambon*, but comparable to that in *Multispinula*. It differs from *Multispinula* by having uniform spines. *S.? esthonia* may represent a new genus, but with the restricted material available at this stage, its provisional assignment to *Schizambon* is maintained.

Schizambon ovalis Goryanskij, 1969

Fig. 73A

Synonymy. - []1969 *Schizambon ovalis* sp. nov - Goryanskij, p. 93, Pl. 18:1.

Holotype. - CNIGR 216/9960; ventral valve; Leetse Formation, Paldiski, Estonia; figured by Goryanskij (1969, Pl. 18:1); refigured here Fig. 73A.

Material. - Holotype and some shell fragments.

Description. - Shell moderately and equally biconvex, elongate oval. Shell surface with growth lamellae of about equal width, ornamented by numerous thin curved spines, increasing in number anteriorly. Pedicle foramen short, about 1 mm, enlarging to a wide pedicle track. Dorsal valve and valve interiors unknown.

Remarks. - Goryanskij (1969) assigned this poorly known species to *Schizambon*, and this assignment is followed here. From other species of *Schizambon*, *S. ovalis* differs by having an elongate suboval shell.

Genus *Gorchakovia* Popov & Khazanovitch, 1989

Synonymy. - []1989 Gorchakovia gen. nov. - Popov & Khazanovitch, p. 135.

Diagnosis. - Shell ventribiconvex, with fine, evenly spaced spines of uniform size. Pedicle track large, widely triangular, with small posterior plate. Ventral pseudointerarea procline to catacline, undivided. Dorsal pseudointerarea vestigial, internal pedicle tube lacking. Interior characters poorly defined.

Type and only species. - *Gorchakovia granulata* Popov et Khazanovitch, 1989.

Discussion. - *Gorchakovia* is one of the oldest known siphonotretids. By size, outline and evenly spaced spines, it is comparable to *Helmersenia*. *Gorchakovia* differs by having large, widely triangular pedicle track and lacking pedicle tube.

Occurrence. - Upper Cambrian, Ingria, Russia.

Gorchakovia granulata Popov & Khazanovitch, 1989

Fig. 74

Synonymy. - []1989 *Gorchakovia granulata* sp. nov. - Popov & Khazanovitch, p. 136, Pl. 11:11-15.

Holotype. - CNIGR 259/12348; Upper Cambrian, lower subformation of the Ladoga Formation, near Gorchakovchina village, right bank of the Volkhov River.

Material. - Figured. Ventral valves: GT Br 3209; GT Br 3210; GT Br 3211. Dorsal valves: GT Br 3212; GT Br 3213. Total of 5 ventral and 12 dorsal valves.

Diagnosis. - As for genus.

Description. - Shell ventribiconvex. Shell surface with concentric growth lines and fine, evenly spaced spines of uniform size, forming a reticular pattern. Ventral valve low subconical, transversely suboval. Pedicle track large, widely triangular, with small posterior plate. Ventral pseudointerarea procline to catacline, undivided. Dorsal valve gently convex, subcircular, with finely pitted larval shell. Dorsal pseudointerarea vestigial. Internal pedicle tube lacking. Interior characters poorly defined.

Occurrence. - Upper Cambrian, Lower subformation of the Ladoga Formation, Volkhov River, Ingria, Russia.

Order Acrotretida Kuhn, 1949
Superfamily Acrotretoidea Schuchert, 1893
Family Acrotretidae Schuchert, 1893

Genus *Acrotreta* Kutorga, 1848

Type species. - Subsequent designation by Davidson (1853, p. 133); *Acrotreta subconica* Kutorga, 1848; Lower Ordovician; Päite Member, Billingen Stage, Tosna River, Ingria, Russia.

Diagnosis. - See Holmer & Popov (1994).

Occurrence. - Lower-Middle Ordovician (Upper Tremadoc - Llandeilo); Estonia; Ingria, Russia; Holy Cross Mountains, Poland; South Ural Mountains, Kazakhstan; Siljan District, Sweden; Bohemia; Alabama, USA.

Acrotreta sp.

Fig. 75

Material. - Figured. Ventral valves: GT Br 3214; GT Br 3215.
Total of 3 ventral valves.

Description. - Ventral valve high, conical, with the maximum height in the umbonal area anterior to the pedicle foramen. Ventral pseudointerarea procline to slightly catacline, divided by shallow intertrough. Pedicle foramen relatively large, subcircular, not enclosed within the larval shell. Dorsal valve unknown.

Discussion. - By their general morphology, the few incomplete valves are assigned to the genus *Acrotreta*. Specific assignment of these specimens is difficult without knowledge of complete ventral valves and morphology of the dorsal valves. The specimens somewhat resemble the type species, *Acrotreta subconica* Kutorga, 1848, abundant in the Mäeküla Member (uppermost Leetse Formation, Billingen Stage) in Estonia (Holmer & Popov 1994). Another similar species is *Acrotreta korynevskii* Popov & Holmer, 1994 known form the Tremadoc Akbulak-Sai formation and lower Arenig Koagash Formation, South Ural Mountains, Kazakhstan.

Occurrence. - Lower Ordovician. Joa Member, Leetse Formation; Maardu Quarry, northern Estonia.

Genus *Angulotreta* Palmer, 1954

Type species. - Original designation; *Angulotreta triangularis* Palmer, 1954, p. 769, Pl. 91:1-6.

Diagnosis. - See Palmer (1954, p. 769).

Species included. - *Angulotreta triangularis* Palmer, 1954; *A. postapicalis* Palmer, 1954 and *A. missourensis* Kurtz, 1971 (see Popov & Khazanovitch, 1989, p. 129).

Occurrence. - Upper Cambrian; Estonia; Ingria and Novaya Zemlya, Russia; Texas and Missouri, USA.

Angulotreta postapicalis Palmer, 1954

Fig. 76

Synonymy. - []1954 *Angulotreta postapicalis* sp. nov. - Palmer, p. 769, Pl. 91: 8-10. []1985 *Angulotreta postapicalis* Palmer - Popov, p. 21, Pl. 2: 5- 14, Fig. 8. []1989 *Angulotreta postapicalis* Palmer - Popov & Khazanovitch, p. 128, Pl. 10: 17, Pl. 12: 7-9.

Holotype. - ?UT-32207a, dorsal valve; at Texas University, Austin, Texas, USA; Bureau of Economic Geology locality 16T-6-10A (LL); *Cedarina-Cedaria* Zone, Cap Mountain limestone member, Blanco County, Texas, USA; illustrated by Palmer (1954, Pl. 91:8).

The dorsal valve UT-32207a is referred to as the holotype in the original description by Palmer (1954, p. 769), but in the same paper, a ventral valve UT-32207b is illustrated as the holotype on Fig. 91:8, p. 773.

Material. - Ventral valve: GT Br 3216. Dorsal valves: 3217; GT Br 3218. Total of 56 ventral and 62 dorsal valves.

Diagnosis. - See Palmer (1954, p. 769).

Description. - Shell subcircular to transversely suboval, ventribiconvex. Postlarval shell surface with narrow growth lines. Larval shell with regularly spaced pits of about equal size, up to 700 nm across. Ventral valve low subconical. Pedicle foramen circular, apical. Dorsal valve transversely suboval, flattened. Dorsal pseudointerarea with wide, concave median groove. Propareas flat, reduced. Dorsal median septum narrow, high, buttressing the pseudointerarea, extending anteriorly to about two-thirds of maximum valve length. Cardinal muscle scars slightly elevated, diverging anteriorly.

Discussion. - As pointed out by Palmer (1954, p. 769), the dorsal valve of the type species, *Angulotreta triangularis* Palmer, 1954, differs from *A. postapicalis* by the slightly more anteriorly placed apical pits and by lacking a distinct marker for the position of the internal pedicle opening. As noted by Kurtz (1971, p. 474), *A. missouriensis* Kurtz, 1971 differs from *A. postapicalis* by having a moderately high, curved apsaconical profile and ovate to subovate internal pedicle opening. The ventral valves of these three species are closely similar and have mostly been regarded as indistinguishable (Palmer, 1954; Kurtz, 1971).

Occurrence. - Upper Cambrian; Ülgase Formation in Estonia and lower subformation of the Ladoga Formation in Ingria, Russia. Localities: Hundikuristik, Turjekelder and Valkla River in Estonia; Volkhov and Syas rivers in Ingria.

Cedarina/Cedaria Zone, Cap Mountain limestone member, Riley Formation, Central Texas, USA (Palmer 1954). Upper Cambrian sandstone and shale beds, southern beach of the Gribovaya Bay, Southern Island of Novaya Zemlya, Arctic Russia (Popov 1985).

Genus *Semitreta* Biernat, 1973

Type species. - Original designation by Biernat (1973, p. 75); *Semitreta maior* Biernat, 1973; Tremadoc chalcedonites, Holy Cross Mountains, Poland.

Diagnosis. - See Popov & Holmer (1994, p. 122).

Species included. - *Semitreta maior* Biernat, 1973; ?*Torynelasma? magnum* Goryanskij, 1969.

Semitreta? magna (Goryanskij, 1969)

Fig. 77

Synonymy. - []1969 *Torynelasma? magnum* sp. nov. - Goryanskij, p. 72, Pl. 12: 12-14. []aff. 1994 *Semitreta?* aff. *magna* (Goryanskij, 1969) - Popov and Holmer - p. 123, Fig. 99A-D.

Holotype. - Ventral valve figured by Goryanskij (1969, Pl. 12:12); Tosna Formation, Lava River near Vassilkovo village, St. Petersburg region, Russia.

Material. - Figured. Ventral valves: GT Br 3223; GT Br 3224; GT Br 3225; GT Br 3226. Total of 14 ventral valves.

Description. - Ventral valve high conical, about as high as long. Ventral pseudointerarea apsacline, slightly flattened. Postlarval shell covered by closely spaced filae. Ventral interior and dorsal valve unknown.

Discussion. - Only ventral valve exteriors of this species are known. High apsaconical ventral valve is characteristic of *Semitreta*, *Hansotreta* Krause & Rowell (1975), *Biernatia* Holmer (1989) and *Opsiconidion* Ludvigsen (1974). Still, the assignation of these shells to *Biernatia* and *Opsiconidion* is rather unlikely in view of their larger size and thicker shell. Here, a study by Popov & Holmer (1994) is followed, where similar acrotretid shells, provisionally assigned to the same species were classified as *Semitreta?*.

Genus *Eurytreta* Rowell, 1966

Eurytreta? sp.

Fig. 78

Material. - Figured. Composite mould of ventral valve: GT Br 3220. Composite moulds of dorsal valves: GT Br 3219; GT Br 3221; GT Br 3222. Total of more than 50 moulds of different preservation.

Description. - Shell transversely suboval. Dorsal valve gently convex, subcircular, with indistinct sulcus and low median ridge, strongly impressed in composite moulds. Ventral valve strongly convex, with slightly apsacline pseudointerarea, poorly defined laterally. Pedicle foramen small and subcircular, situated within the larval shell. Anterior slope of the valve convex in the cross-section. Shell microstructure typical of acrotretoids; tertiary layer composed of columnar laminae (see also Williams & Holmer 1992).

Remarks. - This species can be referred either to *Eurytreta* or *Ottenbyella*. Median ridge, strongly impressed on the composite moulds suggests the affinity with *Eurytreta*. Without knowledge of the ventral valve interior, exact generic assignment is difficult.

Occurrence. - Lower Ordovician, Varangu Stage, uppermost Türisalu Formation, northeastern Estonia. Locality: subsurface in NE Estonia, environs of Kohtla-Järve, south of Püssi, core No. 80, depth 78.7-78.8 m.

Family Ceratretidae Rowell, 1965
Genus *Ceratreta* Bell, 1941

Type species. - Original designation; *Ceratreta hebes* Bell, 1941, p. 233; Upper Cambrian (*Conaspis* Biozone) Dry Creek Shale; Montana, USA.

Diagnosis. - Shell transversely oval in outline with moderately wide posterior margin. Ornament of evenly spaced rugellae. Ventral valve highly conical, generally more than half as high as wide. Ventral pseudointerarea procline to apsacline, divided by wide intertrough. Pedicle foramen lenticular in outline. Apical process, ridge-like or forming high septum, supported by pedicle tube along posterior slope. Dorsal valve with wide pseudointerarea occupying more than half of valve width. Median buttress present. Median septum variably developed, usually long, triangular.

Species assigned. - *Ceratreta hebes* Bell, 1941 and *Acrotreta tanneri* Metzger, 1922.

Remarks. - As noted by Holmer and Popov (1990), *Ceratreta dilatata* Williams and Curry (1985), from the Lower Ordovician (upper Arenig) of Ireland, is not considered to belong to the ceratretids, but appears to be an early representative of the subfamily Torynelasmatinae.

Ceratreta tanneri (Metzger, 1922)

Fig. 79

Synonymy. - []1922 *Acrotreta tanneri* sp. nov. - Metzger, p. 4, Fig 1A-I. []1968 *Ceratreta tanneri* (Metzger) - Martinsson, p. 139, Figs. 2-7. []1982 *Ceratreta tanneri* (Metzger) - Tynni, p. 49, Pl. 1:1-2. []1989 *Ceratreta tanneri* (Metzger) - Popov & Khazanovitch, p. 130, Pl. 10:4-16. []1990 *Ceratreta tanneri* (Metzger) - Holmer & Popov, p. 251, Figs. 4-6. [] 1993 *Ceratreta tanneri* (Metzger) - Puura & Holmer, p. 227.

Lectotype. - Selected by Martinsson (1968); dorsal valve (coll. V. Korvenkontio); figured by Metzger (1922, Fig. 1C), from fissure filling at Långbergsöda-Öjen, parish of Saltvik, Åland. Specimen missing from the collections in Helsinki (Holmer and Popov 1990).

Material. - Figured. Ventral valve: GT Br 3226. Dorsal valves: GT Br 3223; GT Br 3224;

GT Br 3225; GT Br 3227; GT Br 3228. Total of 23 ventral and 45 dorsal valves.

Diagnosis. - See Holmer & Popov (1990).

Remarks. - A detailed description of this species has recently been given by Holmer & Popov (1990), based on a large material from Sweden and East Baltic.

Occurrence. - Upper Cambrian; Ülgase and Tsitre Formations, Estonia. Localities: Hundikuristik, Ülgase, Iru, Turjekelder, Valkla, subsurface south of Maardu, core M-77, depth 36.0-37.0 m; subsurface of Rakvere Phosphorite Deposit, core P- 1653, depth 88.4-88.75 m. Lower subformation of the Ladoga Formation, Syas River, Ingria, Russia. Upper Cambrian clastic dykes in the Island of Åland, Finland (Martinsson 1968), Upper Cambrian sandstones in Östergötland and Siljan District, Sweden (Holmer & Popov 1990).

Genus *Keyserlingia* Pander, 1861

Synonymy. - []1861 *Keyserlingia* gen. nov. - Pander (*in* Helmersen), p. 46. []1912 *Keyserlingia* Pander - Walcott, 1912, p. 628 (synonymy). []1963 *Clistotrema* gen. nov. - Rowell, p. 35. []1965 *Clistotrema* Rowell - Rowell, p. H278. []1969 *Keyserlingia* Pander - Goryanskij, p. 76. []1989 *Keyserlingia* Pander - Popov & Khazanovitch, p. 130.

Type species. - Subsequent designation by Dall (1871, p. 75); *Orbicula reversa* de Verneuil, 1845, from the Upper Cambrian Ladoga Formation, Ingria (St. Petersburg district), Russia.

Diagnosis. -- Shell subcircular to transversely suboval. Ventral valve low conical with thickened rim of lamellose shell along posterior margin. Ventral pseudointerarea procline to catacline, divided by broad intertrough. Pedicle foramen elongate lenticular placed in listrium-like furrow. Ventral apical process forming high thickened septum, usually with distinctive muscle platform. Apical process perforated posteriorly by internal pedicle tube. Cardinal muscle fields of both valves forming strongly elevated, sometimes undercut platforms. Dorsal median septum low triangular (modified after Popov & Khazanovitch, 1989, p. 131).

Species assigned. - *Orbicula reversa* de Verneuil, 1845 and *Orbicula buchii* de Verneuil, 1845.

Occurrence. - Upper Cambrian; northern Estonia; Ingria, Russia; Sweden.

Discussion. - The genus has been referred to the siphonotretids (Walcott 1912, p. 628; Goryanskij 1960, p. 181) as well as to the discinids (Goryanskij 1969, p. 76). However, as discussed by Holmer & Ushatinskaya (1994), the ceratretids are acrotretoids.

The nomenclatorial difficulties surrounding *Keyserlingia* were discussed in detail by Rowell (1963, p. 35). Some of these difficulties were due to the fact that Pander (1861) did not select a type species, and later authors (e.g. Walcott 1912) assumed that it was the rather well known *K. buchii* de Verneuil. However, as pointed out by Rowell (1963), the comparatively less well known *K. reversa* de Verneuil was selected as a type species by Dall (1871). This species was described by de Verneuil (*in* Murchison *et al.* 1845) based on a single ventral valve collected from the Upper Cambrian sandstones close to Krasnye Selo outside St. Petersburg, Ingria. The type material of all the species described by de Verneuil (1845) seems to be lost (C. Emig, personal communication to Leonid Popov, 1986). This caused Rowell (1965, p. H279) to declare *Keyserlingia* as a "virtually unknown" genus, and Rowell (1963) named the genus *Clistotrema*, with the type species, *Orbicula buchii* de Verneuil.

Popov and Khazanovitch (1989) redescribed *Keyserlingia reversa* and selected a neotype from the Upper Cambrian Ladoga Formation at Dudergoff hills, near Krasnoye Selo; they also demonstrated that *K. reversa* and *K. buchii* are independent, but closely related species. Thus, *Clistotrema* Rowell is a junior synonym of *Keyserlingia*.

Keyserlingia reversa de Verneuil, 1845

Fig. 80

Synonymy. - []1845 ***Orbicula reversa*** **sp. nov., p. 289, Pl. 19:2a, b** []1912 *Orbicula reversa* de Verneuil - Walcott, p. 630. [] *Discina reversa* (de Verneuil) - Eichwald, p. 914. []?1969 *Keyserlingia buchii* (de Verneuil). Goryanskij, Pl. 13: 1-3, 5. []1989 *Keyserlingia reversa* (de Verneuil). - Popov & Khazanovitch, 1989, p. 132, Pl. 4:3, Pl. 10:18, Pl.12:1- 6.

Neotype. -- Selected by Popov and Khazanovitch (1989, p. 132); CNIGR 234/12348, ventral valve; Upper Cambrian Ladoga Formation (sample L-48/1 in Popov et al. 1989, p. 38), Kirchoff hill to the north from the Karvala village, Dudergoff, Ingria, Russia. The specimen figured by de Verneuil (*in Murchison et al.* 1845) is lost, but was collected from an unnamed locality close to Krasnoye Selo. The only known exposures with the Upper Cambrian sandstones in this region are the old quarries on the Kirkhof Hill near Karvala village and on the Kavelachta Hill, but the latter locality is no longer accessible.

Material. -- Figured. Ventral valves: GT Br 3231; GT Br 3232; GT Br 3233; GT Br 3234; GT Br 3247. Dorsal valves: GT Br 3229; GT Br 3230. Total of 68 ventral and 31 dorsal valves.

Diagnosis. -- Ventral valve with maximum height placed about one-fifth to one-third of maximum valve length from posterior margin. Ventral pseudointerarea strongly procline. Apical process forming long median septum. Cardinal muscle scars of both valves strongly thickened, but not forming undercut platforms.

Description. -- Shell subcircular to transversely suboval in outline. Shell surface ornamented by fine growth lines and a few, widely spaced growth lamellae. Ventral valve low conical with maximum height placed about one-fifth to one-third of the maximum valve length from the posterior margin. Ventral pseudointerarea strongly procline with well developed, deep intertrough. Pedicle foramen elongate lenticular, placed in short listrium-like furrow. Posterior margin with thickened rim of lamellose shell. Ventral apical process forming high, narrow septum, extending for most of the valve length, with a distinctive thickened muscle platform at about mid-valve. Apical process perforated posteriorly by internal pedicle tube. Ventral cardinal muscle fields situated posterolaterally, raised above the valve floor, but usually damaged and hollow.

Dorsal valve gently and unevenly convex, with maximum height about one-fourth of the maximum valve length from the posterior margin. Dorsal pseudointerarea narrow, with wide concave median groove and anacline propareas. Dorsal median septum low. Median buttress elongate, somewhat widening posteriorly. Dorsal cardinal muscle scars large, strongly thickened and elevated, extending anterior to mid-valve.

Discussion. -- *K. reversa* differs from *K. buchii* in having a more rounded outline with a subcentrally placed ventral apex, a procline ventral pseudointerarea, a less elongated pedicle opening placed in a shorter listrium-like groove, a more narrow apical process forming a long septum, and cardinal muscle fields that do not form undercut platforms.

Occurrence. -- Upper Cambrian; Ladoga Formation of Ingria, Russia. Finngrundet core, South Bothnian submarine district, Sweden (Puura & Holmer 1993).

Keyserlingia buchii de Verneuil, 1845

Fig. 81

Synonymy. - []1845 *Orbicula buchii* de Verneuil, p. 288, Pl. 19: 1a-c. []1850 *Orbicella buchii* de Verneuil - d'Orbigny, 1850, p. 20 [in part]. [] *Discina buchii* (de Verneuil) - Eichwald, 1860, p. 914. [] 1861 *Keyserlingia buchii* (de Verneuil); Pander, p. 46, Pl. 2:1a,c,h. []1892 *Keyserlingia buchii* (de Verneuil) - Hall & Clarke, p. 118, Pl. 4:1-3. [] 1912 *Keyserlingia buchii* (de Verneuil) - Walcott, p. 628, Pl. 81:4a-e. []1960 *Keyserlingia buchii* (de Verneuil) - Goryanskij, p. 181, Pl. 5: 3-7 (copied from Walcott 1912). []1965 *Keyserlingia buchii* (de Verneuil) - Rowell, 1965, p. H278, Fig. 171, Figs 4a-e. [] 1969 *Keyserlingia buchii* (de Verneuil) - Goryanskij, p. 78, Pl. 13:4,6,7 (?not Pl. 13:1-3, 5). [] 1989 *Keyserlingia buchii* (de Vernuil) - Popov & Khazanovitch, p. 133, Pl. 11:1-10.

Neotype. - Selected by Popov and Khazanovitch (1989, p. 133); CNIGR 244/12348, ventral valve; Ladoga Formation, Upper Cambrian, river Izhora, Ingria, Russia. The specimen figured by de Verneuil's (1845) is lost, but it is clear from the description that it came from this locality.

Figured material. - Ventral valves: GT Br 3238; GT Br 3239. Dorsal valves: GT Br 3235; GT Br 3236; GT Br 3237; GT Br 3248.

Additional material. - Several hundred dorsal and ventral valves from coquinas (not counted).

Diagnosis. -- Ventral valve with maximum height close to posterior margin. Ventral pseudointerarea catacline to procline. Pedicle foramen placed in long listrium-like grove. Apical process exceptionally thickened and forming high muscular platform, extending somewhat anterior to mid-valve. Cardinal muscle fields of both valves strongly thickened and forming undercut platforms, extending to centre of valve.

Description. -- Shell transversely oval in outline. Shell surface ornamented with fine growth lines and a few, widely spaced growth lamellae. Ventral valve strongly convex in lateral profile, with maximum height placed close to the posterior margin. Ventral pseudointerarea catacline to slightly procline with deep intertrough. Pedicle foramen lenticular, placed in long listrium-like groove. Apical process strongly thickened, forming high spoon-like muscular platform, extending somewhat anterior to mid- valve. Ventral umbonal muscles ('apical pits') placed on cylindrical platforms, placed directly lateral to the apical process.

Dorsal valve gently and unevenly convex, with maximum height placed about one-fourth of the maximum valve length from the posterior margin. Dorsal pseudointerarea wide, with deep median groove and anacline to orthocline propareas. Dorsal interior with low, triangular median septum and strongly elongate median buttress, slightly raised posteriorly. Cardinal muscle fields of both valves strongly thickened, forming undercut platforms extending to mid-valve.

Discussion. -- *Keyserlingia buchii* is a highly variable species, in particular in the convexity and lateral profile of the ventral valve. Goryanskij (1969) considered *Discina sinuata* Leuchtenberg, 1857 to be a junior synonym to *K. buchii*. However, examination of the specimen illustrated by Eichwald (1861b, p. 911, Pl. 23:30a, b) indicates that it is some kind of deformed craniid species.

Occurrence. -- Upper Cambrian of Estonia (Tsitre Formation and the lower part of Maardu Member) and Ingria (Ladoga and Lomashka Formations).

Superfamily Acrotheloidea Schindewolf, 1955
Family Acrothelidae Walcott & Schuchert, 1908
Subfamily Acrothelinae Walcott & Schuchert, 1908

Genus *Orbithele* Sdzuy, 1955

Type species. - Original designation by Sdzuy (1955, p. 9); *Discina contraria* Barrande, 1868; Leimitz Shale, Tremadoc, Bavaria.

Diagnosis and species included. - See Holmer & Popov (1994, p. 144).

Orbithele sp.

Fig. 82

Synonymy. - []1969 *Orbithele* sp. - Goryanskij, p. 79, Pl. 13:8,9.

Material. - Two ventral valves; figured: GT Br 3240; GT Br 3241.

Description. - Larval shell well defined, transversely oval, with larval spines. Outside the larval shell, juvenile shell ornamented by fine costellae and rugellae. Postlarval shell with irregularly spaced knob-shaped pustules, forming high, irregular, wavy rows.

Remarks. - By the characters of larval, juvenile and postlarval shell, these fragmentarily preserved specimens resemble *Orbithele ceratopygarum* Brøgger, 1882 (see Popov & Holmer 1994, p. 146). The studied specimens of *Orbithele* sp. appear to have a thicker shell. The state of preservation of the Estonian specimens does not allow a judgement to be made on whether they are conspecific with *O. ceratopygarum* or if they represent a separate species.

Occurrence. - Lower Ordovician, Leetse Formation, Maardu Quarry, Estonia.

PALAEOECOLOGY, TAPHONOMY AND BIOSTRATIGRAPHY

Life habits

Most modern lingulate brachiopods, e.g. *Lingula* and *Glottidia* and some disciniids, e.g. genera *Discina* and *Discinisca* are known from shallow water habitats, less than 30 m deep, with some species restricted to tidal zone (Zezina 1976, p. 44). Their ability to survive extreme changes in salinity and oxygen regime in tidal zone has been attributed to a specific kind of metabolism (Emig 1976), characterized by low oxygen consumption rates and, in *Lingula anatina*, a haemerythrin-based respiratory cycle (James *et al.* 1992).

All known modern lingulid brachiopods have infaunal habits. The genera *Lingula* and *Glottidia* live in the burrows in soft sediment, with long pedicles attached to the bottom of a burrow. Representatives of both genera have been observed to burrow by entering the sediment with the anterior part of the shell (Thayer & Steele-Petrovic 1975; Savazzi 1991a).

Savazzi (1986, 1991b) pointed out the similarities of the terrace-like ornamentation in lingulaceans to burrowing sculptures in infaunal arthropods, bivalves and gastropods. He interpreted the divaricate terraces in a Cambrian obolid *Westonia*, which face away from the pedicle, as indicating pedicle-first burrowing. The ornamentation of *Rebrovia chernetskae* (Fig. 65) somewhat resembles to that of *Westonia*, and by analogy, could possibly be interpreted as a burrowing sculpture. However, as pointed out by Savazzi

(1991b), terrace-like sculptures are not necessarily a pre- requisite for a burrowing life habit; moreover, Recent burrowing lingulids lack this kind of sculptures.

Popov *et al.* (1989) pointed out the reduction of the pedicle groove in *Ungula* during ontogeny and the asymmetry in the shape of the valves in *Schmidtites* and *Oepikites* as being suggestive of an epifaunal habit. As the lingulates from the Middle Cambrian - lowermost Ordovician *Obolus* Sandstone have never been recorded in life position, there is no conclusive evidence for their infaunal habits. However, infaunal habits can be suggested for some representatives of the *Thysanotos* fauna, in particular for *Leptembolon lingulaeformis* which was documented by Goryanskij (1969, Pl. 5:17) in life position and for "*Lingulella*" *nitida* (personal field observations).

Post mortem degradation and taphonomy

The composition and structure of a fossil shell depends largely on *post mortem* physico-chemical processes it has been subjected to. For instance, *post mortem* dehydration of subaerially exposed shells of *Lingula anatina* has been observed to cause a deformation resulting in reduced shell width and folded, compressed lateral margins (E. Savazzi, pers. comm., 1996). Emig (1986) has suggested that Recent lingulids can fossilize only in extreme conditions of rapid burial. He examined the *post mortem* alteration of Recent *Lingula anatina* and *Lingula reevei* and observed the successive stages of degradation of the organic matrix, shell softening and structural disaggregation. Shell margins of *Lingula* were decomposed rapidly, while the central highly mineralized portion persisted longer. Owing to rapid degradation of organic matrix and mechanical abrasion, the chitino-phosphatic shell decomposed totally during 2-3 weeks (Emig, 1990). However, as pointed out by Cusack & Williams (1996), Palaeozoic lingulids, having considerably thicker and stronger shells than thin-shelled modern lingulids, were probably more resistant to mechanical destruction.

Still, these observations are intriguing for interpreting the preservation of fossil lingulate shells reworked to the coquinas. For instance, not only most of the acrotretoids, but also posteriorly thickened valves of *Ungula* spp. invariably lack the anterior margin. These shells could possess fragile anterior margins with high organic content. In contrast, completely preserved valves of *Oepikites* spp. and *Schmidtites celatus* suggest stronger architecture of the shells of these species. *Post mortem* mineralization of organic-rich shell laminae discussed by Nemliher & Puura (in press) could also contribute to the mechanical resistance of the fossil lingulate shells.

As the lingulate shells are not particularly resistant to mechanical transport, their long-distance lateral transport appears to be unlikely. However, taphonomical bias is evident from the observations of the distribution of lingulate distribution in *Obolus* Sandstone (Popov et al. 1989; Popov & Khazanovitch 1992). Kidwell (1986) presented a theoretical model analysing the implications of taphonomical bias caused by various sedimentological factors, e.g., differential rates of sedimentation, hydrodynamical sorting, winnowing and reworking of fossils into younger sediments. Proceeding from Kidwell's model, Oja (1995) discussed sedimentological aspects of accumulation of the shelly phosphorite in Estonia, pointing out the rõle of winnowing and bottom currents in accumulation of the lingulate coquinas. Hiller (1993) reported coquinas of Recent lingulate *Discina* from the coast of Namibia, regarding them as a modern analogue of Estonian *Obolus* conglomerate.

Lingulate biostratigraphy

The biostratigraphical interpretations of the studied sections are based on studies of co-occurrences conodonts, acritarchs, graptolites and lingulate brachiopods (Heinsalu *et al.* 1987; Kaljo *et al.* 1986, 1988; Popov *et al.* 1989; Mens *et al.* 1989, 1993, 1996; Nemliher & Puura 1996; Mens & Puura 1996; Einasto *et al.* 1996). For the Upper Cambrian - Hunneberg strata of Estonia and Ingria, conodont biostratigraphy has provided the highest resolution (Kaljo *et al.* 1968; Popov *et al.* 1989; Mens *et al.* 1993). Detailed conodont biozonation and documentation of co-occurrences of lingulate brachiopods and conodonts has allowed the critical evaluation of lingulate brachiopod distribution, recognition of redeposited specimens and the establishment of lingulate biozones (Popov *et al.* 1989). Further studies have confirmed the applicability of these biozones for regional correlations within Baltoscandia (Holmer & Popov 1990; Puura & Holmer 1993; Mens *et al.* 1993).

Figure 83 shows the distribution of the studied brachiopods according to the lingulate brachiopod biozones. Most biozones are defined by first appearances of the biozonal species.

Obolus ruchini Biozone. - The base of this zone is defined by the first appearance of *Obolus ruchini* Khazanovitch & Popov. As well as the biozonal species, the lingulate assemblage characteristic of this biozone includes *Oepikites macilentus* Khazanovitch & Popov. Based on an acritarch assemblage (Borovko et al. 1984) and the occurrence of a bradoriid *Vojbokalina magnifica* Melnikova (*in* Khazanovitch et al. 1984), a Middle Cambrian age, roughly corresponding to some part of the *Paradoxides paradoxissimus* trilobite Biozone in Scandinavia has been suggested for this biozone (Popov et al. 1989). The fauna of this biozone is confined to the Gertovo Member of the Sablinka Formation in Ingria.

Obolus transversus Biozone. - The base of this biozone is defined by the first appearance of *Obolus transversus* Pander. As well as the biozonal species, the lingulate assemblage includes *Oepikites koltchanovi* Khazanovitch & Popov. This assemblage is restricted to the Rebrovo Member of the Sablinka Formation in Ingria. The lack of other groups of fauna makes precise age determination of this zone difficult. A tentative Middle Cambrian age has been suggested by Popov et al. (1989), based on the stratigraphic position of the Rebrovo Member, overlying the Gertovo Member, yielding a Middle Cambrian fauna, and underlying the Ladoga Formation of earliest Upper Cambrian age containing conodonts of the *Westergaardodina bicuspidata* Subzone in the basal part.

Ungula inornata Biozone. - The base of the biozone is defined by the first appearance of *Ungula inornata* (Mickwitz). The characteristic lingulate assemblage, including *U. inornata*, *Oepikites fragilis* Popov & Khazanovitch, 1989, and *Angulotreta postapicalis* Palmer, 1954 is confined to the Ülgase Formation in northern Estonia (Mens *et al.* 1993). In Ingria the characteristic assemblage, represented by the two latter species and *Gorchakovia granulata* Popov & Khazanovitch (Popov et al. 1989), is restricted to the lower subformation of the Ladoga Formation.

Tentative distant correlations of this biozone based on the occurrence of rare *Angulotreta postapicalis* suggest an early Late Cambrian age. In addition to its occurrence in Estonia and Ingria, this species has been recorded from the lowermost Upper Cambrian *Cedaria/Cedarina* Bioone in Texas, USA (Palmer 1954) and the Upper Cambrian of Novaya Zemlya, Russia (Popov 1985).

Ungula convexa Biozone. - The base of the biozone is defined by the first appearance of *Ungula convexa* (Pander). The characteristic lingulate assemblage of this biozone including *U. convexa*, *Keyserlingia reversa* (de Verneuil), *Ralfia ovata* (Pander) and *Oepikites triquetrus* Popov & Khazanovitch, is confined to the Tsitre Formation in Estonia (Mens et al. 1993) and to the upper subformation of the Ladoga Formation in Ingria (Popov et al. 1989). *Vassilkovia granulata* occurs in the upper part of this biozone in Ingria. The first appearances of *Schmidtites celatus* (Volborth) and *Keyserlingia buchii* (de Verneuil) are documented from within this biozone (Mens et al. 1993). An acritarch assemblage, co-occurring with *Ungula convexa*, suggests a tentative correlation of the base of the *U. convexa* Biozone with some level within the *Parabolina spinulosa* trilobite Biozone (Mens et al. 1993).

Ungula ingrica Biozone. - The base of this Biozone is defined by the first appearance of *Ungula ingrica* (Eichwald). Rare occurrences of *Oepikites obtusus*, *Euobolus elegans* and *Estoniobolus eichwaldi* are also confined to this interval. The associated lingulates mostly include species transitional from the *Ungula convexa* Biozone, such as *Schmidtites celatus*, *Keyserlingia buchii*, *Rebrovia chernetskae* and *Ralfia ovata*. The conodonts co-occurring with *Ungula ingrica* suggest a correlation with *Proconodontus* sub-Biozone and *Cordylodus andresi* and lowermost *C. proavus* biozones.

Obolus apollinis Biozone. - The base of the biozone is defined by the first appearance of *Obolus apollinis* Eichwald. The characteristic lingulate assemblage, including *O. apollinis*, *Helmersenia ladogensis* (Jeremejew) and rare *Lingulella antiquissima* (Jeremejew), occur in the Tosna and Koporye formations in Ingria and in the upper part of Kallavere Formation in Estonia. The co-occurring conodonts suggest that the base of the *O. apollinis* Biozone is within the *Cordylodus proavus* conodont Biozone (Mens *et al.* 1993). The upper limit of the *O. apollinis* Biozone is within the *Cordylodus angulatus* conodont Biozone (Popov *et al.* 1989). The conodont correlation suggests that the range of *Ungula ingrica*, *Keyserlingia buchii* and *Schmidtites celatus* extends to the lower part of the *Obolus apollinis* Biozone, although, owing to the different lithofacies association, they have not been recorded as co-occurring with *O. apollinis*, except when reworked to coquinas (e.g., in Luga River near Kingisepp).

Obolus apollinis has been traditionally referred to as an index species, especially in the context of the former definition of the Cambrian-Ordovician boundary in the East

European Platform, when it was attributed to the base of the *Cordylodus proavus* Biozone (Alichova 1960; Grigelis 1978; Männil 1987). It should be therefore emphasized, that in previous studies, with the exception of Kaljo et al. (1986), Popov et al. (1989) and Mens et al. (1993), *Obolus apollinis* has been invariably confused with *Ungula ingrica* or other obolid species (see systematic palaeontology). According to present knowledge, the true *Obolus apollinis* has been recorded only from Ingria and Estonia.

"*Eurytreta*" Biozone. - The interval between the upper limit of the *O. apollinis* Biozone and the base of the *Thysanotos siluricus* Biozone approximately corresponds to the *Drepanoistodus deltifer* conodont Biozone. This interval, represented by upper part of the black shales of the Türisalu and Koporye Formations and with the greenish-grey clays of Varangu and Naziya formations is very poor in benthic fauna. Rare acrotretoid brachiopods *Eurytreta?* sp., show some affinities to the species of *Eurytreta* and *Ottenbyella* recorded from the Bjørkasholmen Formation in Sweden and Norway (Popov & Holmer 1994). This biozone, outlined here because of its potential utility for correlation, remains poorly defined at present. Rare obolids, recorded from this level, include *Expellobolus* sp. and possibly conspecific specimens reported by Popov *et al.* (1989) as *Lingulella* aff. *tetragona*.

Thysanotos siluricus Biozone. - The base of this biozone is defined by the first appearance of *Thysanotos siluricus* (Eichwald). The characteristic assemblage includes *T. siluricus*, *Leptembolon lingulaeformis* (Mickwitz), *Eosiphonotreta acrotretomorpha* (Goryanskij), *Foveola maarduensis* (Goryanskij), and rare *Paldiskia obscuricostata* (Goryanskij), *P. orbiculata* (Goryanskij), *Expellobolus tetragonus* (Goryanskij), "*Lingulella*" *nitida* (Goryanskij), *Orbithele* sp. and *Schizambon ovalis* (Goryanskij). *Schizambon? esthonia* (Walcott) is recorded from the uppermost part of the *T. siluricus* Biozone.

The range of the *Thysanotos siluricus* Biozone approximately corresponds to that of the *Paroistodus proteus* conodont Biozone. The upper limit of the biozone is defined by the appearance of rich fauna of clitambonitacean and plectambonitacean brachiopods (Öpik, 1933, 1934; Rubel & Popov 1994), at the level, approximating to the base of the *Prioniodus elegans* conodont Biozone.

In the study area, the fauna of the *Thysanotos siluricus* Zone is known mostly from Estonia, where it is confined to the Klooga and Iru members of the Leetse Formation. An exception is the occurrence of *Eosiphonotreta acrotretomorpha* in the Lakity Member of the Lava River section in Ingria (Dronov *et al.* 1995, Fig. 2).

As noted by Popov & Holmer (1994, p. 32), the *Leptembolon* - *Thysanotos* assemblage has been recorded from a wide geographic area surrounding the East European Platform. However, as yet, only the occurrences of *Thysanotos siluricus* in Estonia, South Urals (Popov & Holmer 1994), Bohemia (Havlicek 1982), and most likely, in Poland (Bednarczyk 1964), can be confirmed with confidence (see Systematic Palaeontology herein). It should be also noted that, as yet, there is no solid evidence for the occurrence of *T. siluricus* below the base of the *Paroistodus proteus* conodont Biozone. Therefore, all the previously reported Tremadoc occurrences of *T. siluricus*, e.g., from Poland (Bednarczyk 1964) and Bohemia (Havlicek 1982), should be critically re-evaluated.

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Figure captions

Fig. 1. Locality maps. Outcrops indicated by squares, drill core sites by open circles. []A. Map of Estonia and Ingria (St. Petersburg district of Russia). []B. Detailed locality map of northwestern Estonia.

Fig. 2. Generalized bedrock map of Estonia, Ingria and adjacent areas (modified after Vaher *et al.* 1992). Legend: AR-PR$_1$ - Archean and Lower Proterozoic crystalline basement; Jn - Jotnian; V$_2$ - Upper Vendian; Є - Cambrian; O$_{1-2}$ - Lower and Middle Ordovician; O$_3$ - Upper Ordovician; S$_1$ - Lower Silurian; S$_2$ - Upper Silurian; D$_1$ - Lower Devonian; D$_2$ - Middle Devonian; D$_3$ - Upper Devonian.

Fig. 3. Distribution of Ordovician (post-Tremadoc) confacies belts in the Baltoscandian basin (from Jaanusson 1995).

Fig. 4. Major chrono- and lithostratigraphic units of Middle Cambrian - Hunneberg strata in Estonia and Ingria, and their correlation with traditional units.

Fig. 5. Legend to stratigraphical columns.

Fig. 6. Distribution of lingulates and selected conodonts in core F-353, near Kidaste, Hiiumaa island. Conodont data after V. Viira (*in* Mens *et al.* 1993).

Fig. 7. Lingulate distribution in core K-11, near Kärdla airport, Hiiumaa island.

Fig. 8. Lingulate occurrence in core D-32, southeast of Haapsalu, western Estonia.

Fig. 9. Section at the east coast of Osmussaar island, showing the upper part of the glauconite sandstone of the Leetse Formation overlain by limestones of the Pakri Formation (see also Fig. 10).

Fig. 10. Cambrian-Ordovician boundary beds in Osmussaar island. Description of core 410 after L. Põlma (*in* Puura & Tuuling 1988).

Fig. 11. Cambrian-Ordovician boundary beds at the northeastern coast of the Pakri Peninsula. A section showing the lower part of the Maardu Member, with the Upper Cambrian basal conglomerate, overlying the Lower Cambrian Tiskre Formation (see also Fig. 12).

Fig. 12. Distribution of lingulates, graptolites and selected conodonts in the Pakri Cape section. Conodont and graptolite data after V. Viira and D. Kaljo (both *in* Mens *et al.* 1996), respectively.

Fig. 13. Coastal section north of Paldiski, Pakri Peninsula, showing glauconite sandstone of

the Leetse Formation, overlain by the Lower Ordovician limestone succession (see also Fig. 14).

Fig. 14. Distribution of lingulates and selected conodonts in the Paldiski section. Conodont data after V. Viira (*in* Mens & Puura 1996).

Fig. 15. Distribution of lingulates and selected conodonts in the Kaila-Joa section. Conodont data after V. Viira (*in* Mägi & Viira 1976; Mägi *et al.* 1989).

Fig. 16. Section in the Harku trench south-west of the Harku Quarry, near former Mäeküla. The succession of clays of the Varangu Formation, glauconite sandstones of the Joa Member and carbonate-cemented glauconite sandstones of the Mäeküla Member, rests on the black shales of the Türisalu Formation. The Mäeküla Member is overlain by the succession of limestones of the Volkhov and Kunda Stages.

Fig 17. Lingulate distribution in the Harku trench section.

Fig 18. Distribution of lingulates and selected graptolites and conodonts in the Tônismägi section, Tallinn. Graptolite and conodont data after D. Kaljo and V. Viira (both *in* Kaljo *et al.* 1988), respectively. See also Paalits (1995) for acritarch distribution.

Fig. 19. Distribution of lingulates, graptolites and selected conodonts in the sections at Mäekalda, Tallinn. Conodont and graptolite data after V. Viira (*in* Mens *et al.* 1989; Einasto *et al.* 1996) and D. Kaljo (*in* Mens *et al.* 1989).

Fig. 20. Distribution of lingulates, graptolites and selected conodonts in the Suhkrumägi section, Tallinn. Conodont and graptolite data after Viira (1966), Kaljo & Kivimägi (1976) and Kaljo *et al.* (1986). See also Volkova & Mens (1988) for acritarch distribution.

Fig. 21. Distribution of lingulates and selected conodonts in the Hundikuristik section, Tallinn. Conodont data after V. Viira (*in* Mens *et al.* 1989).

Fig. 22. Section at Iru, Tallinn, showing distribution of lingulate brachiopods and selected conodont occurrences. Conodont data after V. Viira (pers. comm., 1996).

Fig. 23. Distribution of lingulates and selected conodonts in the sections at Ülgase. Conodont data after V. Viira (*in* Heinsalu *et al.* 1987).

Fig. 24. Lingulate distribution in core M-72, 30 km southeast of Tallinn. See also Paalits (1992b) for the acritarch distribution.

Fig. 25. Distribution of lingulates and selected conodonts in the sections along the Jägala River. Conodont data after Viira (1974).

Fig. 26. Distribution of lingulates and selected conodonts in a section on the Valkla River. Conodont data after V. Viira (pers. comm., 1996).

Fig. 27. Distribution of lingulates and selected conodonts in the Turjekelder section. Conodont data after V. Viira (*in* Kaljo *et al.* 1986).

Fig. 28. Distribution of lingulates and selected conodonts in the sections near Vihula, along the Suurjõgi River. Conodont data after Viira *et al.* (1987).

Fig. 29. Distribution of lingulates and selected conodonts in the section at the Toolse River (after Popov *et al.* 1989).

Fig. 30. Distribution of lingulates and selected conodonts in the Saka section. Conodont data after V. Viira (*in* Heinsalu *et al.* 1991a).

Fig. 31. Distribution of lingulates and selected conodonts in core R-2162, south-east of Rakvere. Conodont data after V. Viira (*in Heinsalu et al.* 1994).

Fig. 32. Lingulate distribution in core R-1555, east of Rakvere.

Fig. 33. Lingulate occurrence in core 80, south of Püssi, NE Estonia.

Fig. 34. Lingulate distribution in core Värska-6, SE Estonia.

Fig. 35. Lingulate occurrence in the Laanemetsa core, SE Estonia.

Fig. 36. Lingulate distribution in a section in a right bank of the Narva River, within the city limits of Ivangorod (after Popov *et al.* 1989).

Fig. 37. Distribution of lingulates and selected conodonts in a section on the Luga River (after Popov *et al.* 1989).

Fig. 38. Occurrences of lingulates and selected conodonts in a section on the Solka River (after Popov *et al.* 1989).

Fig. 39. Distribution of lingulates and selected conodonts in a section on the Suma River (after Popov *et al.* 1989).

Fig. 40. Distribution of lingulate and selected graptolites and conodonts in a section on the Lomashka River (after Kaljo *et al.* 1986; Popov *et al.* 1989).

Fig. 41. Lingulate distribution in a section at Kirchoff, at Duderoiff Heights, south-west of St. Petersburg (after Popov *et al.* 1989).

Fig. 42. Distribution of lingulate brachiopods and selected conodonts in the sections along the Izhora River (after Borovko *et al.* 1984; Popov *et al.* 1989).

Fig. 43. Section at the Tosna River, showing the the succession of sandstones of the Middle Cambrian Sablinka Formation, Upper Cambrian Ladoga Formation and Upper Cambrian-Lower Ordovician Tosna Formation (photo by L. Popov, 1987).

Fig. 44. Distribution of lingulate brachiopods and selected conodonts in the sections along the Tosna River (after Popov *et al.* 1989).

Fig. 45. Distribution of lingulate brachiopods and selected conodonts in a section on the Naziya River (after Borovko & Sergeyeva 1984; Popov *et al.* 1989).

Fig. 46. Distribution of lingulate brachiopods and selected conodonts in a section on the Lava River (after Popov *et al.* 1989 and Dronov *et al.* 1995).

Fig. 47. Distribution of lingulate brachiopods and selected conodonts in sections along the Sarya River (after Popov *et al.* 1989 and Dronov *et al.* 1995).

Fig. 48. Distribution of lingulate brachiopods and selected conodonts in sections along the Volkhov River (after Popov *et al.* 1989).

Fig. 49. Distribution of lingulate brachiopods and selected conodonts in sections along the Syas River (after Popov *et al.* 1989).

Fig. 50. *Obolus apollinis* Eichwald. []A-D. Upper Cambrian - Lower Ordovician, Tosna Formation; Lava River, Ingria, Russia. []A. Ventral valve interior; GT Br 1703; x6.5. []B. Dorsal valve interior; GT Br 1706; x6.5. []C. Dorsal valve exterior; GT Br 1704, x6.5. []D. Ventral valve exterior; GT Br 1705, x6.5. []E-I. Upper Cambrian - Lower Ordovician, Kallavere Formation; Rakvere Phosphorite Deposit, Estonia; core 1555, depth 103.7-104 m. []E. Ventral valve interior; GT Br 3512; x6. []F. Detail of E; ventral pseudointerarea; x10. []G. Oblique view of dorsal valve interior; GT Br 3513; x10. []H. Detail of G; ventral pseudointerarea; x15. []I. Ventral valve exterior, GT Br 3514; x7.

Fig. 51. *Obolus ruchini* Khazanovitch & Popov; Middle Cambrian, Sablinka Formation, Gertovo Member. []A. Ventral valve interior; left bank of the Sarya River, near Vojbokalo village; GT Br 3515; x8. []B.-I. Right bank of the Volkhov River, upstream of Gorchakovshchina village. []B. Ventral valve interior GT Br 3516; x8. []C. Ventral valve interior; GT Br 3517; x8. []D. Dorsal valve interior; GT Br 3518; x8. []E. Dorsal valve interior; GT Br 3519; x5. []F. Dorsal valve exterior; GT Br 3520; x8. []G. Ventral valve exterior; GT Br 3521; x8. []H. Oblique view of ventral valve exterior; GT Br 3522; x4. []I. Ventral valve exterior, GT Br 3523; x8.

Fig. 52. *Obolus transversus* (Pander); Middle Cambrian, Sablinka Formation, Rebrovo

Member; right bank of the Volkhov River, upstream of the Gorchakovshchina village. []A. Ventral valve interior; GT Br 3524; x8. []B. Ventral pseudointerarea; GT Br 3525; x10. []C. Oblique view of dorsal valve interior; GT Br 3526; x4. []D. Dorsal valve exterior; GT Br 3527; x6. []E. Ventral valve exterior; GT Br 3528; x5. []F. Ventral valve exterior; GT Br 3529; x5.

Fig. 53. *Ungula convexa* Pander. []A.-I. Upper Cambrian, Ladoga Formation; Ingria, Russia. []A. Ventral valve interior; left bank of the Izhora River; CNIGR 127/12348; x3.5. []B. Ventral valve interior; Lava River; GT Br 3530; x4. []C. Detail of B; oblique view of ventral pseudointerarea; x10. []D. Ventral valve interior; Lava River; GT Br 3531; x4. []E. Detail of D; ventral pseudointerarea; x10. []F. Dorsal valve interior; Lava River; CNIGR 124/12348; x3. []G. Dorsal valve interior; Naziya River; CNIGR 126/12348; x3.5. []H. Dorsal valve interior; Lava River; GT Br 3532; x4. []I. Oblique posterior view of H; x4. []J-K. Tsitre Formation, Saka, Estonia. []J. Dorsal valve exterior; GT Br 3533; x3. []K. Ventral valve exterior; GT Br 3534; x3. []L. Lava River; ventral valve exterior; GT Br 3535; x4.

Fig. 54. *Ungula ingrica* (Eichwald) []A.-H. Maardu Member, Kallavere Formation []A. Ventral valve interior; Iru; GT Br 3577; x3. []B. Ventral valve interior; Iru; GT Br 3578; x3. []C. Ventral valve interior; Ülgase; GT Br 3579; x4.5 []D. Ventral valve interior; Iru; GT Br 3580; x3.5 []E. Ventral valve interior; Iru; GT Br 3581; x3.5. []F. Ventral valve interior; Roosimägi at Maardu; GT Br 3582; x3.5 []G. Dorsal valve interior; GT Br 3583; Ülgase; x3.5 []H. Dorsal valve interior; Iru; GT Br 3584; x5. []I. Dorsal valve interior; Tsitre Formation; Turjekelder section; GT Br 1702; x6. []J. Ventral valve exterior; Maardu Member, Kallavere Formation; Iru; GT Br 3585, x5. []K. Dorsal valve exterior; Maardu Member, Kallavere Formation; Iru; GT Br 3586, x5.

Fig. 55. *Ungula inornata* (Mickwitz); reworked specimens from the Maardu Member, Kallavere Formation; Iru. []A. Ventral valve interior; GT Br 3536; x3. []B. Ventral valve interior; GT Br 3537; x3. []C. Ventral valve interior; GT Br 3538; x3. []D. Ventral valve exterior of C; GT Br 3538; x3. []E. Dorsal valve interior; GT Br 3539; x2.5 []F. Ventral valve exterior of B; GT Br 3537; x3.

Fig. 56. *Schmidtites celatus* (Volborth) []A-B. Tsitre Formation; Turjekelder section. []A. Ventral valve interior; GT Br 1709; x10. []B. Dorsal valve interior, GT Br 1710; x10. []C. Neotype; ventral valve interior; Maardu Member, Kallavere Formation; Toolse River; CNIGR 97/12348; x11. []D. Ventral valve interior; GT Br 3540; x9. []E. Detail of D, ventral pseudointerarea and visceral area; x15. []F. Ventral valve interior; GT Br 3541; x15. []G. Dorsal valve interior; GT Br 3542; x9. []H. Dorsal valve interior; GT Br 3543; x11. []I. Dorsal valve interior; Ladoga Formation; Syas River; CNIGR 102/12348; x10. []J. Dorsal valve interior; GT Br 3544; x20. []K- L. Lomashka Formation; Kingisepp Phosphorite Deposit, core 190, depth 36.9-37.3 m. []K. Ventral valve exterior; CNIGR 104/12348; x10. []L. Ventral valve exterior; CNIGR 105/12348; x10. []M. Dorsal valve exterior; GT Br 3545; x12. []N. Ventral valve exterior; GT Br 3546; x7.

Fig. 57. []A-C. *Oepikites macilentus* Khazanovitch & Popov; Middle Cambrian, Ingria, Russia. []A-B. Sablinka Formation, Gertovo Member; Sarya River []A. Ventral valve interior; CNIGR 61/12348; x14. []B. Dorsal valve interior; CNIGR 62/12348; x14. []C. Ventral valve exterior; Sablinka Formation, Gertovo Member; Tosna River; CNIGR 59/12348; x14. []D-G. *Oepikites koltchanovi* Khazanovitch & Popov. []D. Ventral valve interior; GT Br 3547; x10. []E. Oblique view of ventral valve exterior; GT Br 3548; x15. []F.-G. Sablinka Formation; Kingisepp Phosphorite Deposit; core 208; depth 41.2-41.7 m. []Dorsal valve interior; CNIGR 53/12348; x11. []G. Dorsal valve exterior; CNIGR 52/12348. []H-K. *Oepikites obtusus* (Mickwitz). []H-I. Maardu Member, Kallavere Formation; Valkla River. []H. Ventral valve interior; CNIGR 79/12348; x11. []I. Ventral valve interior; CNIGR 81/12348; x11. []J. Dorsal valve interior; Lomashka Formation; Kingisepp Phosphorite Deposit; core 190, depth 36.9-37.3 m.; CNIGR 77/12348; x10. []K. Dorsal valve exterior; Maardu Member, Kallavere Formation; Valkla River; CNIGR 78/12348; x11.

Fig. 58. *Oepikites triquetrus* Popov & Khazanovitch; Ladoga Formation, upper subformation; Syas River. []A. Ventral valve interior; CNIGR 67/12348; x10. []B. Ventral valve interior; CNIGR 68/12348; x11. []C. Ventral valve interior; CNIGR 69/12348; x10. []D. Ventral valve interior; CNIGR 64/12348; x12. []E. Holotype; dorsal valve interior; CNIGR 72/12348; x15. []F. Ventral valve exterior; CNIGR 66/12348; x12. []G. Dorsal valve exterior; CNIGR 71/12348; x11.

Fig. 59. *Oepikites fragilis* Popov & Khazanovitch. []A. Holotype; ventral valve interior; Ülgase Formation; subsurface south of Maardu; core M-77; depth 37-38 m; CNIGR 43/12348; x30. []B. Ventral valve interior; GT Br 3551; x8. []C. Dorsal valve interior; Ülgase Formation; Valkla River; CNIGR 35/12348; x11. []D-E. Ladoga Formation; upper subformation; Syas River. []D. Ventral valve interior; CNIGR 45/12348; x10. []E. Ventral valve interior; CNIGR 38/12348; x14. []F. Ventral valve interior; Ülgase Formation; Valkla River; CNIGR 41/12348; x10. []G. Ventral pseudointerarea and visceral area; Ülgase Formation; Turjekelder; GT Br 3552; x15 []H. Detail of D; impressions of epithelial cells; x500. []I. Dorsal valve exterior; Ülgase Formation; core M-77; depth 32.2-33.2; CNIGR 36/12348; x25. []J. Dorsal valve interior; Ülgase Formation; Valkla River; CNIGR 40/12348; x10 []K. Ventral valve exterior; Ülgase Formation, Turjekelder; GT Br 3553; x10. []L. Detail of Q; x60. []M. Ventral valve exterior; Ülgase Formation; Valkla River; CNIGR 37/12348; x10. []N. Dorsal valve exterior; Ülgase Formation; Valkla River; CNIGR 39/12348; x11.

Fig. 60. *Euobolus elegans* (Mickwitz). []A. Ventral valve exterior; Tosna Formation; Kingisepp Phosphorite Deposit; core 190, depth 35.1-36.1 m; CNIGR 37/12348; x12. []B. Ventral valve exterior; GT Br 3554; Rakvere Phosphorite Deposit; core 2162, depth 107.6-108.2 m; x15.

Fig. 61. *Leptembolon lingulaeformis* (Mickwitz); Leetse Formation; northern Estonia. []A. Ventral valve interior; Iru; GT Br 3505; x4.5 []B. Ventral valve interior; Mäeküla; GT Br 3564; x4 []C. Dorsal valve interior; GT Br 3565; Leetse; x4 []D. Dorsal valve interior; Leetse;

GT Br 3506; x3.5. []E. Ventral valve exterior; Leetse; x3.5; GT Br 3566. []F. Ventral valve exterior; GT Br 3567; Leetse; x4. []G. Ventral valve exterior; Leetse; GT Br 3568; x4 []H. Ventral valve exterior; Keila-Joa; GT Br 3569; x5 []I. Dorsal valve exterior; Leetse; GT Br 3570; x3.

Fig. 62. []A-B. *Expellobolus tetragonus* (Gorjansky). []A. Dorsal valve interior; CNIGR 69/9960; x7 []B. Holotype; ventral valve interior; CNIGR 68/9960; x5. []C. *Expellobolus?* sp.; Türisalu Formation; Mäeküla; deformed ventral valve; GT Br 3550; x3. []D.-G. *Lingulella? antiquissima* (Jeremejew); Tosna Formation; Syas River. []D. Dorsal valve exterior; GT Br 3549; x7. []E. Detail of D; x250 []F. Neotype; ventral valve exterior; CNIGR 180/12348; x5. []G. Dorsal valve exterior; CNIGR 181/12348; x5.

Fig. 63. "*Lingulella*" *nitida* Gorjansky; Leetse Formation; Paldiski. Complete shells. []A. GT Br 3558; x7. []B. GT Br 3559; x6 []C. GT Br 3560; x8 []D. GT Br 3561; x6 []E. GT Br 3562; x7 []F. GT Br 3563; x9.

Fig. 64. *Ralfia ovata* Popov & Khazanovitch. []A.-F. Tosna Formation; Tosna River. []A. Ventral valve interior; CNIGR 203/12348; x10. []B. Ventral valve interior; CNIGR 205/12348; x7. []C. Ventral valve interior; GT Br 3249; x8 []D. Dorsal valve interior; CNIGR 199/12348; x11. []E. Dorsal valve interior; GT Br 3250; x8. []F. Dorsal valve interior; Ladoga Formation; Izhora River; CNIGR 209/12348; x9. []G. Dorsal valve exterior; Tosna Formation; Tosna River; CNIGR 202/12348; x10. []H. Ventral valve exterior; Ladoga Formation; Izhora River; CNIGR 208/12348; x9.

Fig. 65. *Rebrovia chernetskae* Khazanovitch & Popov. Ladoga Formation; Syas River. []A. Ventral valve exterior; GT Br 3891; x20. []B. Ventral valve exterior; Ladoga Formation; CNIGR 86/12348; x21. []C. Dorsal valve exterior; GT Br 3892; x30. []D. Ventral valve exterior; GT Br 3893; x25.[]E. Holotype; dorsal valve exterior; CNIGR 85/12348; x20. []F. Dorsal valve exterior; GT Br 3894; x30. []G. Ventral valve interior; RM Br 136361; x35. []H. Ventral valve interior; CNIGR 88/12348; x20. []I. Ventral pseudointerarea; GT Br 3895; x50. []J. Dorsal valve interior; GT Br 3896; x25. []K. Dorsal valve interior; CNIGR 84/12348; x25.

Fig. 66. []A. *Paldiskia obscuricostata* Gorjansky; Leetse Formation; Paldiski; ventral valve exterior; CNIGR 43/9960; x3. []B. *Paldiskia orbiculata* Gorjansky; Leetse Formation; Keila-Joa; ventral valve exterior; GT Br 3576.

Fig. 67. *Thysanotos siluricus* (Eichwald). []A. Ventral valve interior; Leetse Formation; Väike-Pakri Island; GT Br 3504; x2.5 []B. Dorsal valve interior; Leetse Formation; Paldiski; GT Br 3502; x3. []C.-E. Leetse Formation; subsurface of NW Estonia; core D-32, depth 207.3 m. []C. Dorsal valve interior; GT Br 3555; x3.5 []D. Ventral valve exterior; GT Br 3556; x3.5 []E. Dorsal valve interior; GT Br 3557; x3. []F.-G. Complete shell; Leetse Formation; Hundikuristik; GT Br 3501. []F. Profile view, x4. []G. Dorsal view, x4. []H. Dorsal valve interior; Leetse Formation; GT Br 3510; x2. []I. Ventral valve interior; Leetse

Formation; Mäeküla; GT Br 3503; x3. []J. Ventral valve exterior; Leetse Formation; Paldiski; GT Br 3571; x5. []K. Detail of anterior part of J, showing ornament of postlarval shell; x150.

Fig. 68. *Estoniobolus eichwaldi* (Mickwitz); Upper Cambrian-Lower Ordovician, Kallavere Formation, Maardu Member; Ülgase. []A. Ventral valve interior; GT Br 3897; x6.[]B. Dorsal valve interior; GT Br 3898; x5. []C. Detail of B; dorsal psedointerarea; x15. []D. Ventral valve exterior; GT Br 3899; x5. []E. Ventral valve exterior; GT Br 3900; x8. []F. Detail of B; baculate shell structure; x5000. []G. Detail of E; pitted ornamentation of the shell; x120. []H. Detail of E; ornament of concentric growth lines and radial filae; x15. []I. Detail of G; close-up of the pitted ornamentation; x300.

Fig. 69. *Foveola maarduensis* Gorjansky; Leetse Formation; northern Estonia. []A. Holotype; dorsal valve valve exterior; Maardu quarry, CNIGR 52/9960; x5. []B. Dorsal valve exterior; Keila-Joa; GT Br 3572; x6. []C. Ventral valve valve exterior; Keila-Joa; RM Br 136352; x4.[]D. Ventral valve ornamentation; Keila-Joa; RM Br 136353; x15. []E. Incomplete ventral valve exterior; Leetse Formation; Maardu Quarry; GT Br 3573; x8. []F. Incomplete dorsal valve interior; Leetse Formation; Maardu Quarry; GT Br 3574; x7.5.

Fig. 70. *Vassilkovia granulata* Popov & Khazanovitch; Ladoga Formation; upper subformation; Lava River. []A. Holotype; ventral valve interior; CNIGR 176/12348; x5. []B.-C. Dorsal valve; CNIGR 177/12348. []B. Interior; x5. []C. Exterior; x5.

Fig. 71. *Eosiphonotreta? acrotretomorpha* Gorjansky; Leetse Formation, Estonia. []A. Holotype; Ventral valve exterior; Paldiski; CNIGR 195/12348; x9. []B. Dorsal valve exterior; Maardu quarry; CNIGR 236/9960; x8. []C. Dorsal valve exterior; GT Br 3242; x25. []D. Ventral valve exterior; GT Br 3587; Keila-Joa; x17. []E. Detail of D; x75. []F. Lateral view of D; x16.

Fig. 72. *Helmersenia ladogensis* Jeremejew. []A-F. Kallavere Formation; Hiiumaa Island; core K-11, depth 80.4 m. []A. Ventral valve exterior; GT Br 3198; x15. []B. Posterior oblique view of A; x15 []C. Dorsal exterior; GT Br 3199; x15. []D. Posterior oblique view of C; x15 []E. Detail of ventral valve interior; GT Br 3200; x300. []F. Detail of E; x1000. []G.- I. Tosna Formation; Volkhov River. []G. Ventral valve exterior; GT Br 3201; x20; []H. Dorsal valve exterior; GT Br 3202; x30. []I. Dorsal valve interior; GT Br 3197; x20. []J-M. Tosna Formation; Syas River. []J. Ventral valve exterior; GT Br 3203; x20. []K. Dorsal valve exterior; GT Br 3204; x20. []L. Ventral valve interior; GT Br 3205; x20. []M. Detail of ventral valve interior showing the pedicle tube; GT Br 3206; x50 []N-O. Tosna Formation; Lomashka River; valves with slightly eroded surface. []N. Dorsal valve exterior; GT Br 3207; x20 []O. Ventral valve exterior; GT Br 3208; x20.

Fig. 73. []A. *Schizambon ovalis* Gorjansky. Holotype; Leetse Formation; Paldiski; ventral valve exterior; CNIGR 216/12348; x5. []B-F. *Schizambon? esthonia* Walcott; Leetse Formation; Northern Estonia. []B.-D. Keila-Joa. []B. Ventral valve exterior; GT Br 3242;

x3. []C. Dorsal valve exterior; GT Br 3243; x6. []D.- F. Mäeküla []D. Ventral valve interior; GT Br 3244; x10. []E. Ventral valve interior; GT Br 3245; x6. []F. Dorsal valve interior; GT Br 3246; x5.

Fig. 74. *Gorchakovia granulata* Popov & Khazanovitch; Ladoga Formation, section near Gortchakovshchina village, right bank of the Volkhov River, Ingria, Russia. []A. Ventral valve exterior; GT Br 3209; x40. []B. Ventral valve exterior; GT Br 3210; x40. []C. Ventral valve interior; GT Br 3211; x40. []D. Dorsal valve exterior; GT Br 3212; x40. []E. Detail of D; pitted larval shell; x120. []F. Dorsal valve interior; GT Br 3213; x30.

Fig. 75. *Acrotreta* sp.; Leetse Formation; Maardu Quarry. []A. Ventral valve exterior; GT Br 3214; x60. []B. Oblique lateral view of ventral valve exterior; GT Br 3215; x60.

Fig. 76. *Angulotreta postapicalis* Palmer. []A-C. Ventral valve exterior; Ülgase Formation; Hundikuristik; Tallinn; Estonia; GT Br 3216. []A. Oblique lateral view; x50. []B. Detail of A; x200. []C. Detail of A; lateral view of pitted larval shell; x500. []D.-F. Ülgase Formation; Turjekelder; Estonia. []D. Dorsal valve exterior; GT Br 3217; x35. []E. Detail of E; pitted larval shell; x200. []F. Dorsal valve interior; GT Br 3218; x20.

Fig. 77. *Semitreta? magna* (Gorjansky); Leetse Formation, northern Estonia. []A.-C. Maardu quarry. []A. Ventral valve exterior; GT Br 3223; x50. []B. Ventral valve exterior; GT Br 3224; x40. []C. Oblique lateral view of ventral valve exterior; GT Br 3225; x30. []D. Oblique lateral view of ventral valve exterior; Joa Member; Leetse Formation; Harku trench; Estonia; GT Br 3226; x15.

Fig. 78. *Eurytreta?* sp. [] A. Composite mould of dorsal valve interior; GT Br 3219; x25. []Oblique view of A; x50. []C. Composite mould of ventral valve exterior; GT Br 3220; x150 []D. Composite mould of dorsal valve exterior; GT Br 3221; x25. []E. Fragmentary composite mould of dorsal valve exterior with partly preserved shell; GT Br 3222; x40. []F. Detail of E; shell structure; x2000.

Fig. 79. *Ceratreta tanneri* (Metzger); Ülgase Formation; Rakvere Phosphorite Deposit; core P-1653, depth 88.4-88.7 m; Estonia. []A. Dorsal valve exterior; GT Br 3223; x15. []B; Dorsal valve interior; GT Br 3224; x15. []C. Dorsal valve exterior; GT Br 3225; x30. []D. Ventral valve exterior; GT Br 3226; x18. []E. Oblique posterior view of dorsal valve exterior; GT Br 3227; x20. []F. Incomplete dorsal valve exterior; GT Br 3228; x20.

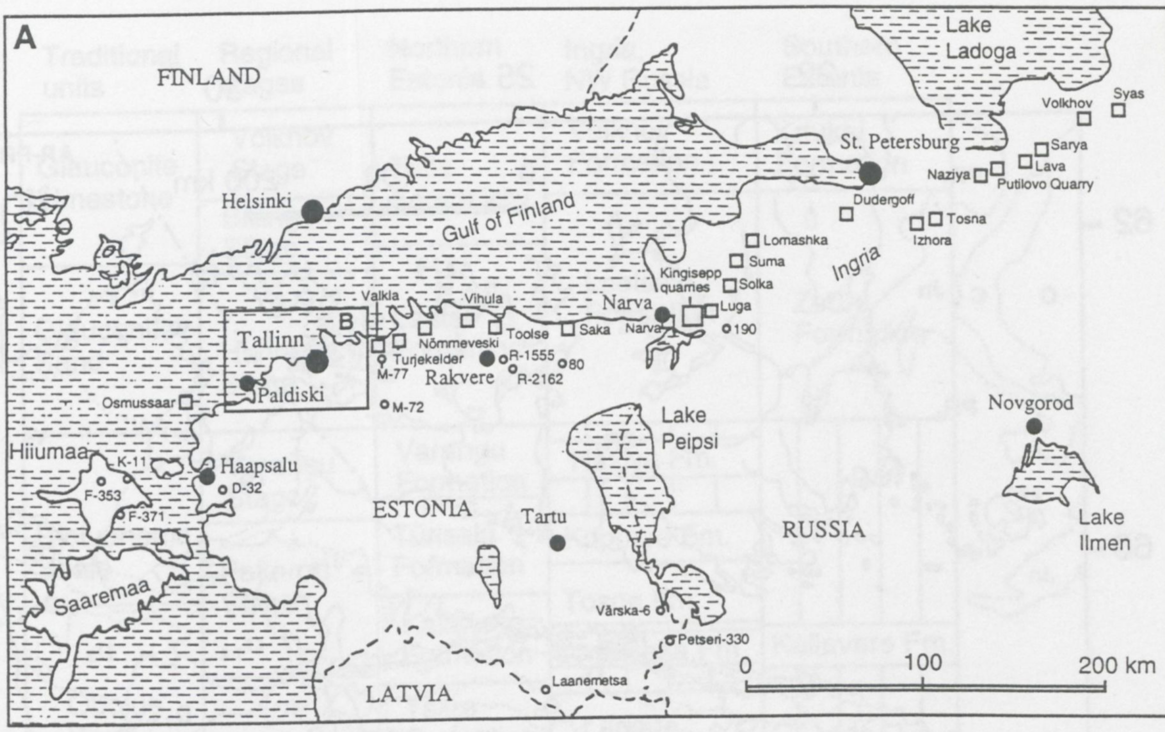
Fig. 80. *Keyserlingia reversa* (de Verneuil); Ladoga Formation; Kirchoff Hill, Dudergoff Heights, Ingria, Russia. []A. Dorsal valve exterior; GT Br 3229; x25. []B. Lateral view of A; x25. []C. Dorsal valve interior; GT Br 3230; x25. []D. Ventral valve exterior; GT Br 3231; x15. []E. Lateral view of D; x20 []F. Posterior view of D, showing pedicle furrow; x80. []G. Detail of D; x80. []H. Ventral valve interior; GT Br 3232; x25. []I. Oblique lateral view of H; x25 []J. Lateral view of ventral valve interior; GT Br 3233; x30. []K. Detail of ventral valve interior; GT Br 3234; x35. [] L. Detail of ventral valve interior, showing internal

pedicle tube; GT Br 3247; x85.

Fig. 81. *Keyserlingia buchii* (de Verneuil); Maardu Member, Kallavere Formation; northern Estonia. []A. Dorsal valve exterior; Ülgase; GT Br 3235; x12. []B. Dorsal valve interior; Maardu Quarry; GT Br 3236; x10. []C. Posterior view of B; x17. []D. Lateral view of B; x20. []E. Ventral valve exterior; GT Br 3237; x7. []F. Posterolateral view of E; x9. []G. Detail of posterior view of E, showing intertrough; x75. []H. Lateral view of ventral valve exterior; Jägala River; GT Br 3248; x12. []I. Detail of posterior view of H; x25. []J. Ventral valve interior; Ülgase; GT Br 3238; x8. []K. Posterolateral view of J; x10. []L. Detail of J, showing muscular platform; x20. []M. Ventral valve interior; GT Br 3239; x7.

Fig. 82. *Orbithele* sp.; Leetse Formation; Maardu Quarry; Estonia. []A. Posterior view of ventral valve exterior; GT Br 3240; x40. []B. Ventral valve exterior; GT Br 3241; x30.

Fig. 83. Lingulate distribution in Middle Cambrian - Hunneberg strata of Estonia and Ingria, with a tentative correlation of lingulate and conodont biozones.


A
FINLAND
Lake Ladoga
Helsinki
Gulf of Finland
St. Petersburg
Volkhov
Syas
Sarya
Naziya
Lava
Putilovo Quarry
Dudergoff
Tosna
Izhora
Lomashka
Suma
Solka
Ingria
Kingisepp quarries
Luga
Narva
190
Valkla
Vihula
Nõmmeveski
Toolse
Saka
Tallinn
B
Turjekelder
M-77
R-1555
80
Rakvere
R-2162
Paldiski
Osmussaar
M-72
Novgorod
Lake Peipsi
Hiiumaa
K-11
Haapsalu
D-32
F-353
F-371
ESTONIA
Tartu
RUSSIA
Lake Ilmen
Saaremaa
Värska-6
Petseri-330
0
100
200 km
Laanemetsa
LATVIA

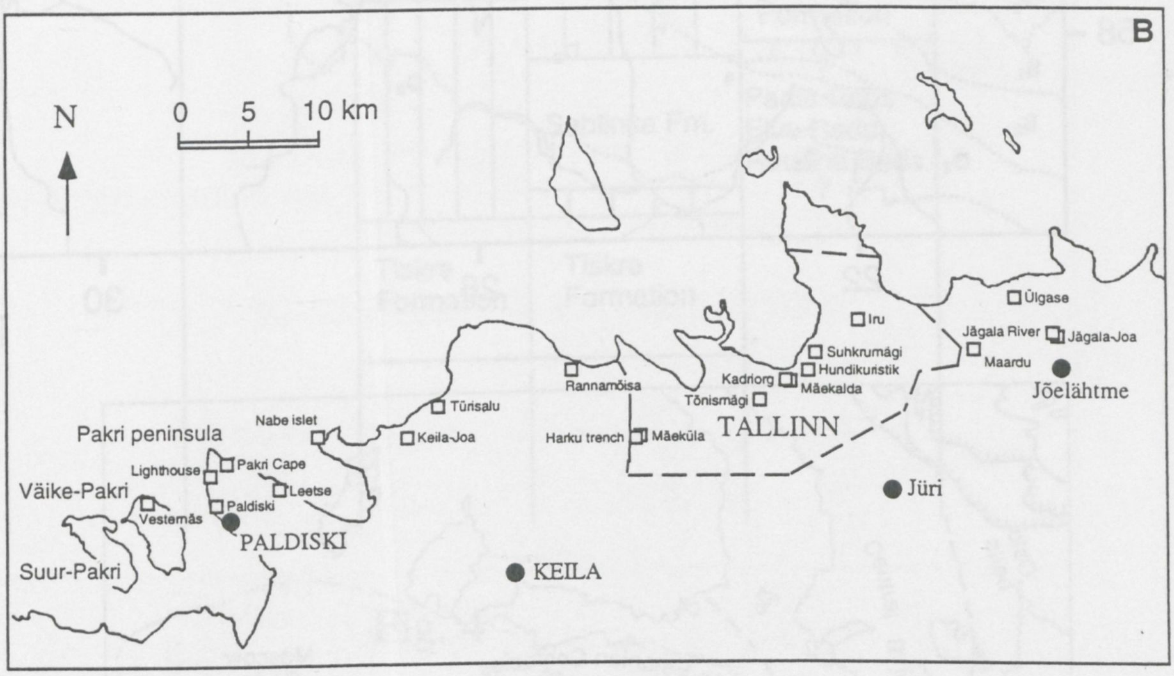
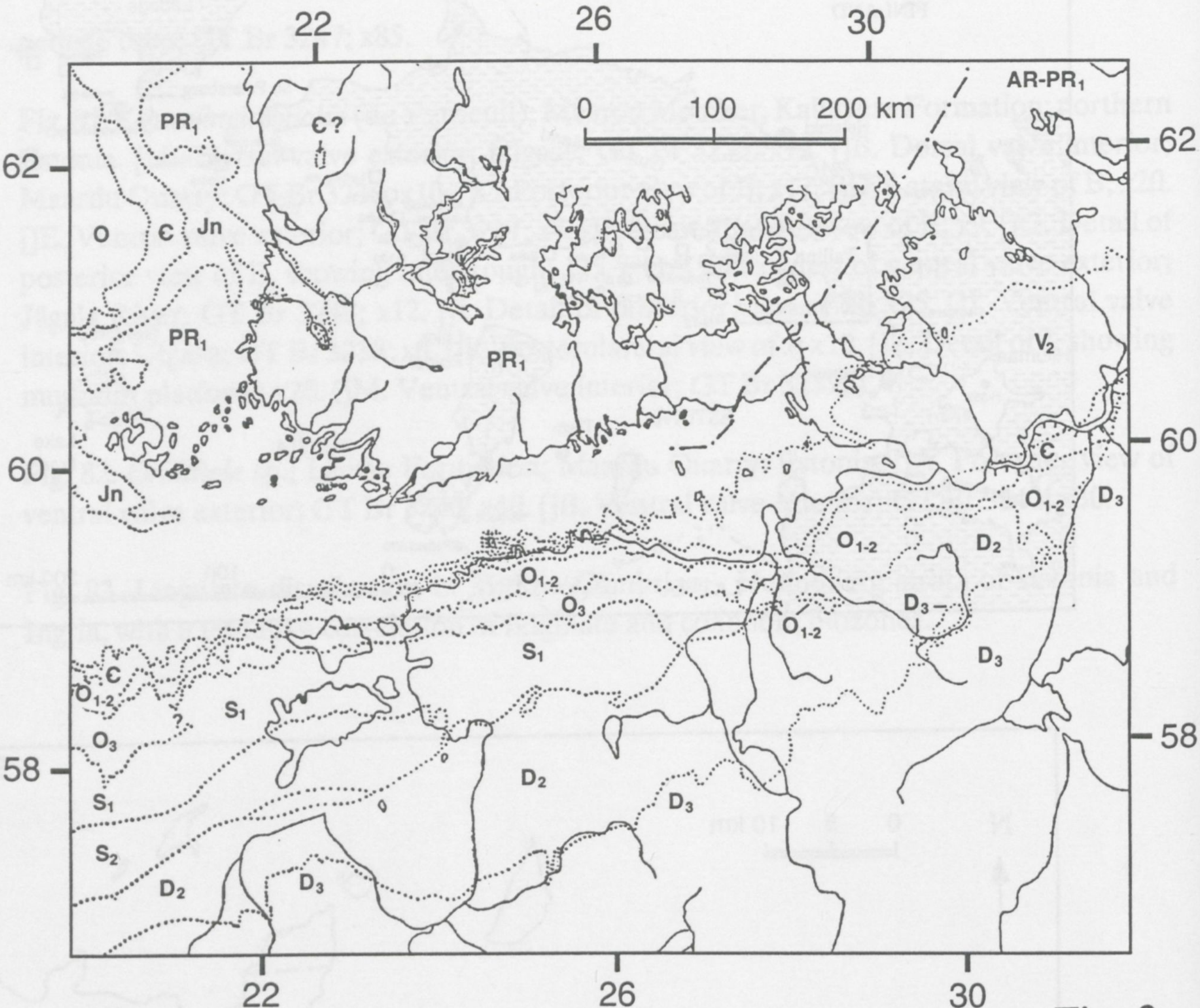
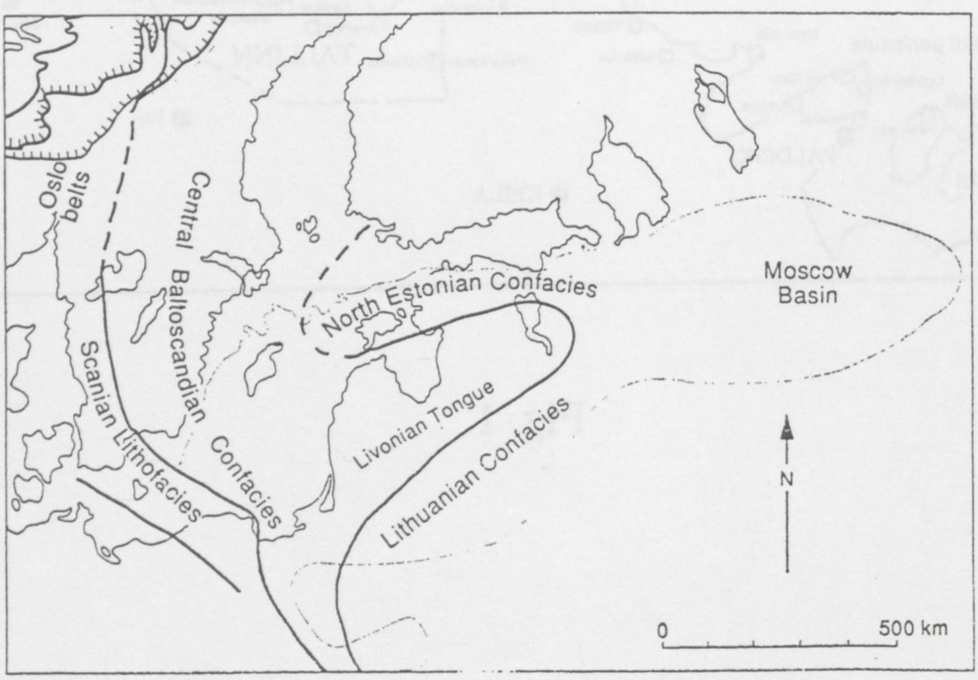

B
N
0
5
10 km
Ülgase
Iru
Jägala River
Jägala-Joa
Suhkrumägi
Maardu
Hundikuristik
Jõelähtme
Rannamõisa
Kadriorg
Mäekalda
Tõnismägi
Türisalu
Nabe islet
Keila-Joa
Harku trench
Mäeküla
TALLINN
Pakri peninsula
Lighthouse
Pakri Cape
Leetse
Väike-Pakri
Vesternäs
Paldiski
Jüri
PALDISKI
Suur-Pakri
KEILA

Fig. 1


22
26
30
0 100 200 km
AR-PR$_1$
62
60
58
PR$_1$
Є?
O
Є
Jn
PR$_1$
PR$_1$
V$_2$
Jn
C
O$_{1-2}$
D$_3$
O$_{1-2}$
D$_2$
O$_{1-2}$
O$_3$
D$_3$
O$_{1-2}$
S$_1$
D$_3$
C
O$_{1-2}$
S$_1$
O$_3$
D$_2$
S$_1$
D$_3$
S$_2$
D$_2$
D$_3$
Fig. 2


Oslo belts
Central Baltoscandian Confacies
Scanian Lithofacies
North Estonian Confacies
Moscow Basin
Livonian Tongue
Lithuanian Confacies
N
0
500 km
Fig. 3

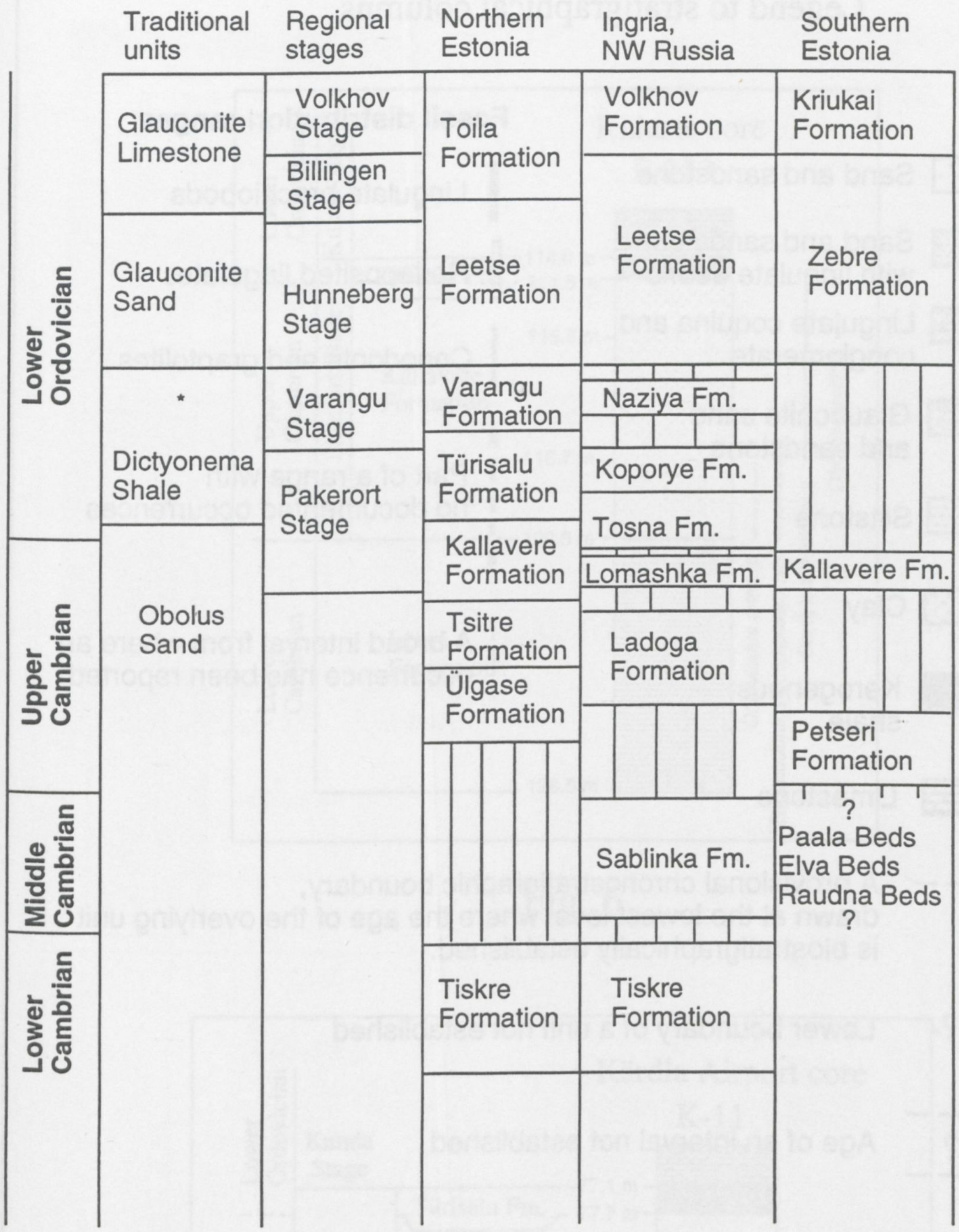

Traditional units
Regional stages
Northern Estonia
Ingria, NW Russia
Southern Estonia
Lower Ordovician
Upper Cambrian
Middle Cambrian
Lower Cambrian
Glauconite Limestone
Glauconite Sand
*
Dictyonema Shale
Obolus Sand
Volkhov Stage
Billingen Stage
Hunneberg Stage
Varangu Stage
Pakerort Stage
Toila Formation
Leetse Formation
Varangu Formation
Türisalu Formation
Kallavere Formation
Tsitre Formation
Ülgase Formation
Tiskre Formation
Volkhov Formation
Leetse Formation
Naziya Fm.
Koporye Fm.
Tosna Fm.
Lomashka Fm.
Ladoga Formation
Sablinka Fm.
Tiskre Formation
Kriukai Formation
Zebre Formation
Kallavere Fm.
Petseri Formation
?
Paala Beds
Elva Beds
Raudna Beds
?

Fig. 4

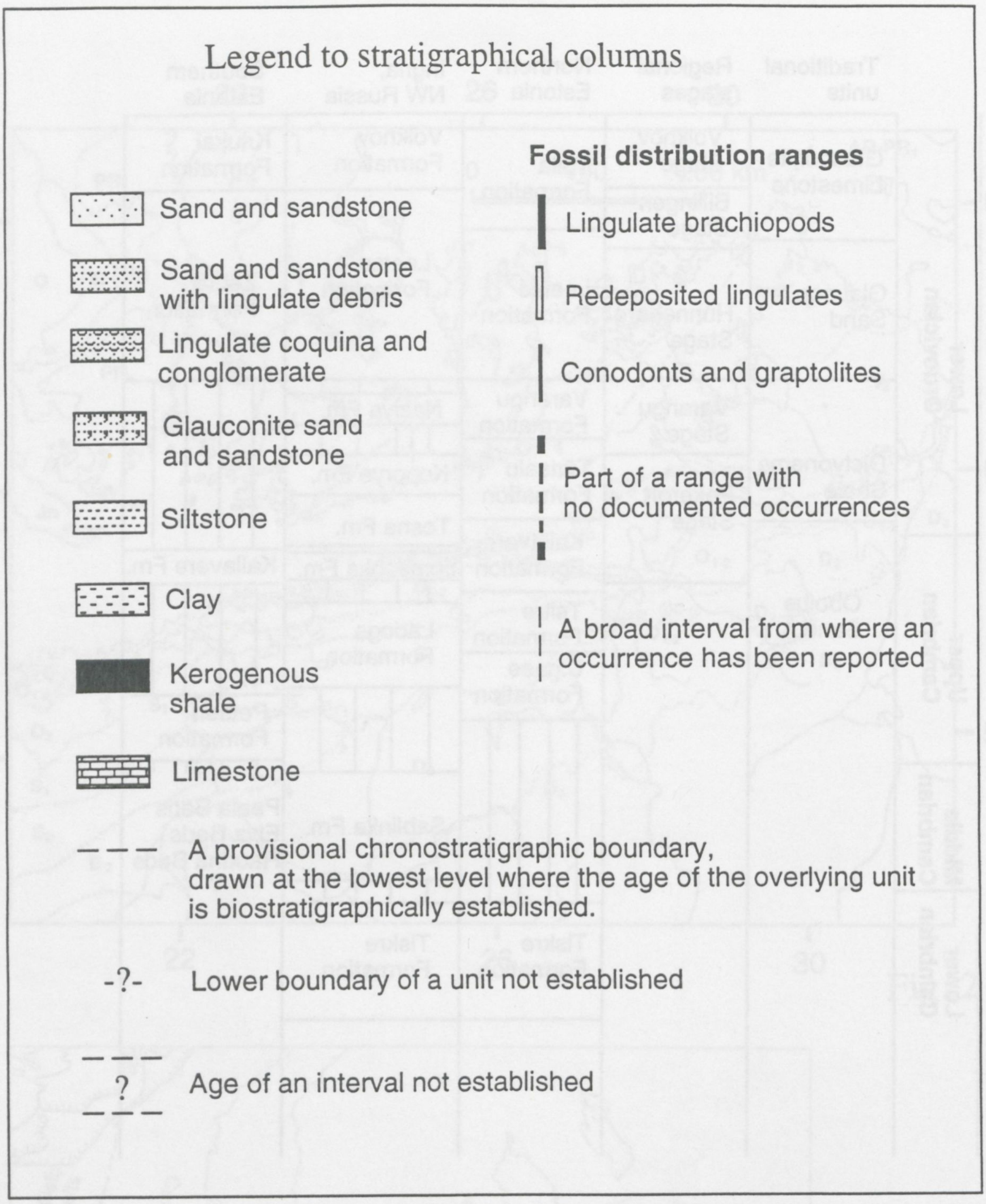

Legend to stratigraphical columns
Sand and sandstone
Sand and sandstone with lingulate debris
Lingulate coquina and conglomerate
Glauconite sand and sandstone
Siltstone
Clay
Kerogenous shale
Limestone
Fossil distribution ranges
Lingulate brachiopods
Redeposited lingulates
Conodonts and graptolites
Part of a range with no documented occurrences
A broad interval from where an occurrence has been reported
A provisional chronostratigraphic boundary, drawn at the lowest level where the age of the overlying unit is biostratigraphically established.
-?-
Lower boundary of a unit not established
?
Age of an interval not established

Fig. 5

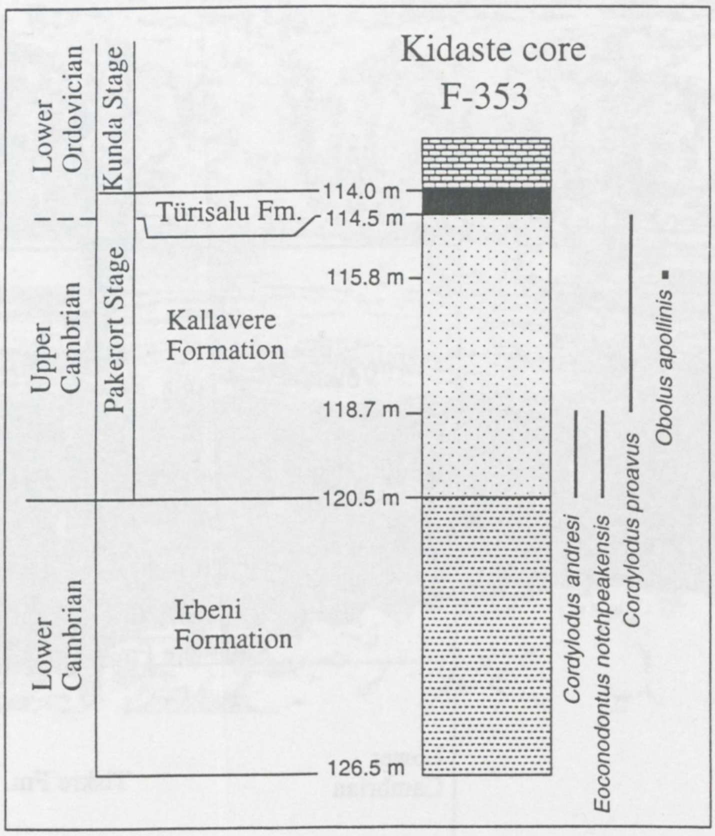

Kidaste core
F-353
Lower Ordovician
Kunda Stage
Upper Cambrian
Pakerort Stage
Türisalu Fm.
Kallavere Formation
Lower Cambrian
Irbeni Formation
114.0 m
114.5 m
115.8 m
118.7 m
120.5 m
126.5 m
Cordylodus andresi
Eoconodontus notchpeakensis
Cordylodus proavus
Obolus apollinis

Fig. 6

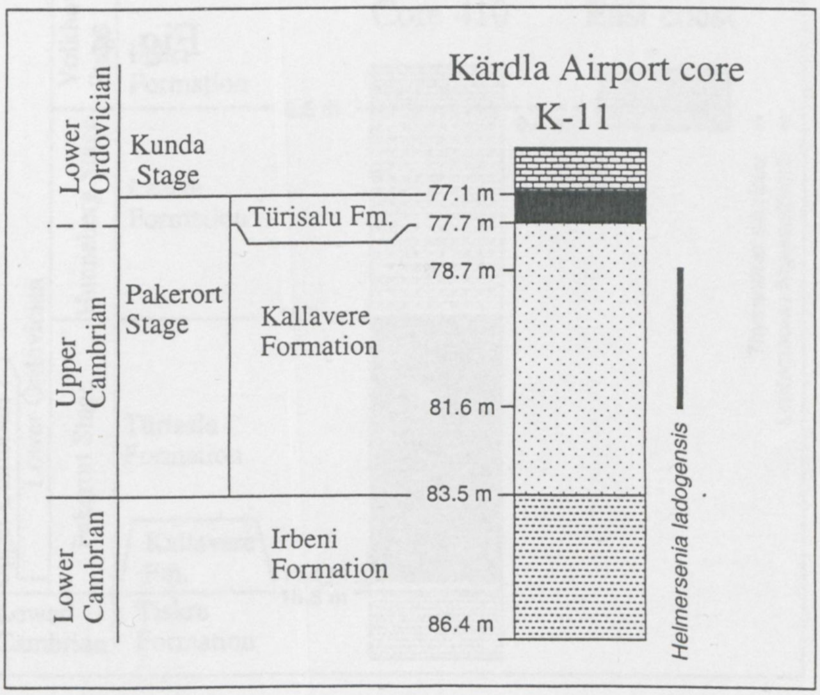

Kärdla Airport core
K-11
Lower Ordovician
Kunda Stage
Upper Cambrian
Pakerort Stage
Türisalu Fm.
Kallavere Formation
Lower Cambrian
Irbeni Formation
77.1 m
77.7 m
78.7 m
81.6 m
83.5 m
86.4 m
Helmersenia ladogensis

Fig. 7

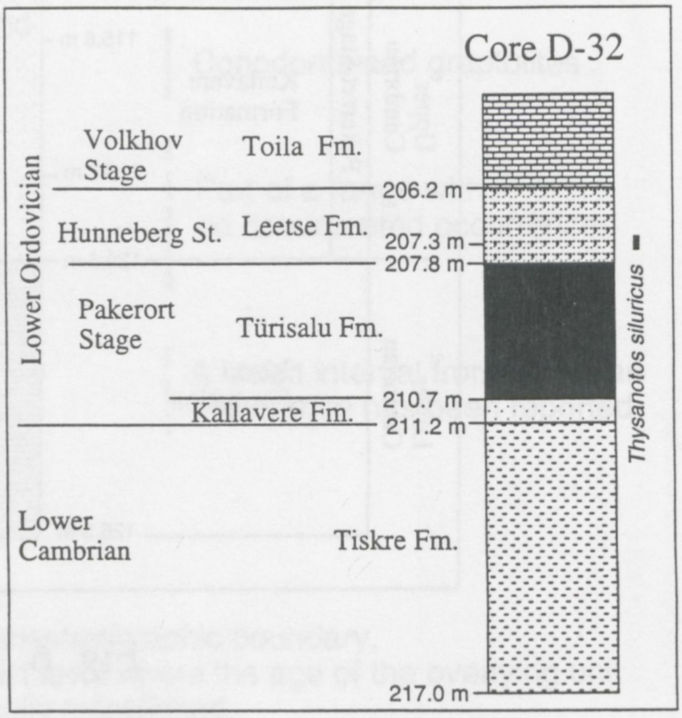

Core D-32
Lower Ordovician
Volkhov Stage
Toila Fm.
206.2 m
Hunneberg St.
Leetse Fm.
207.3 m
207.8 m
Pakerort Stage
Türisalu Fm.
210.7 m
Kallavere Fm.
211.2 m
Lower Cambrian
Tiskre Fm.
217.0 m
Thysanotos siluricus

Fig. 8

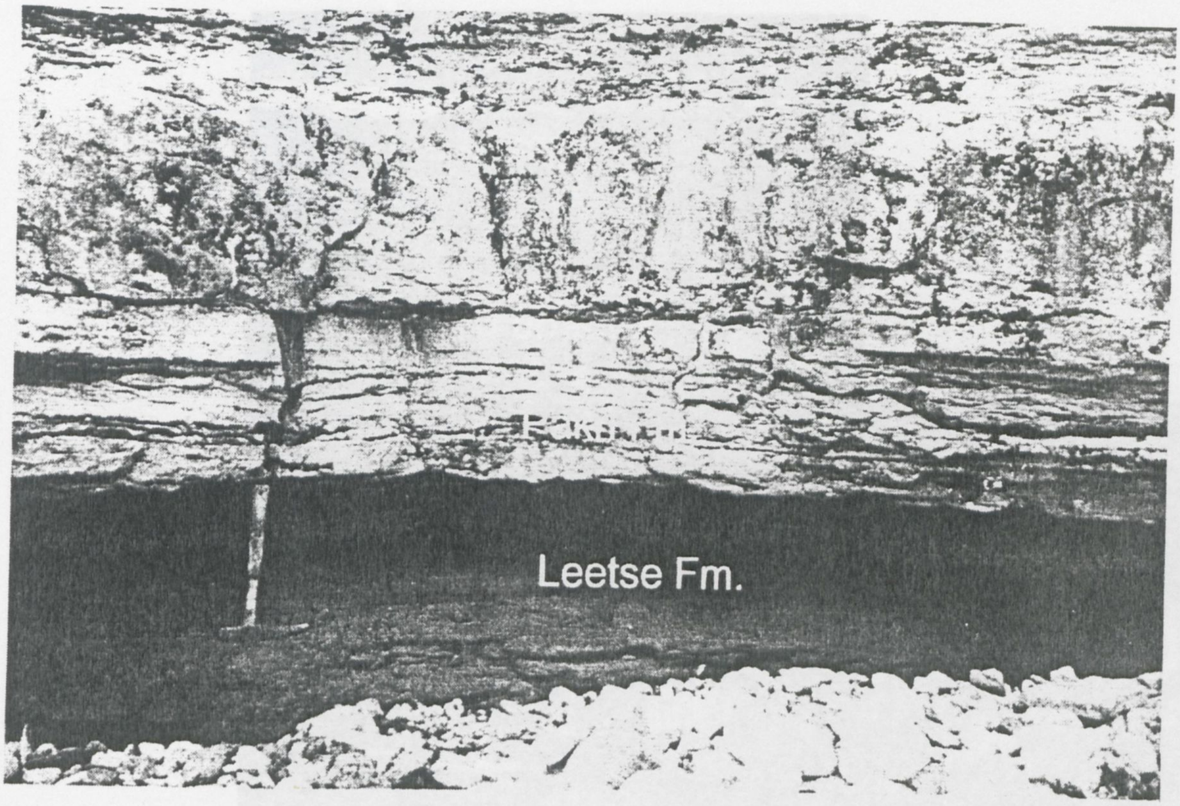

Leetse Fm.

Fig. 9

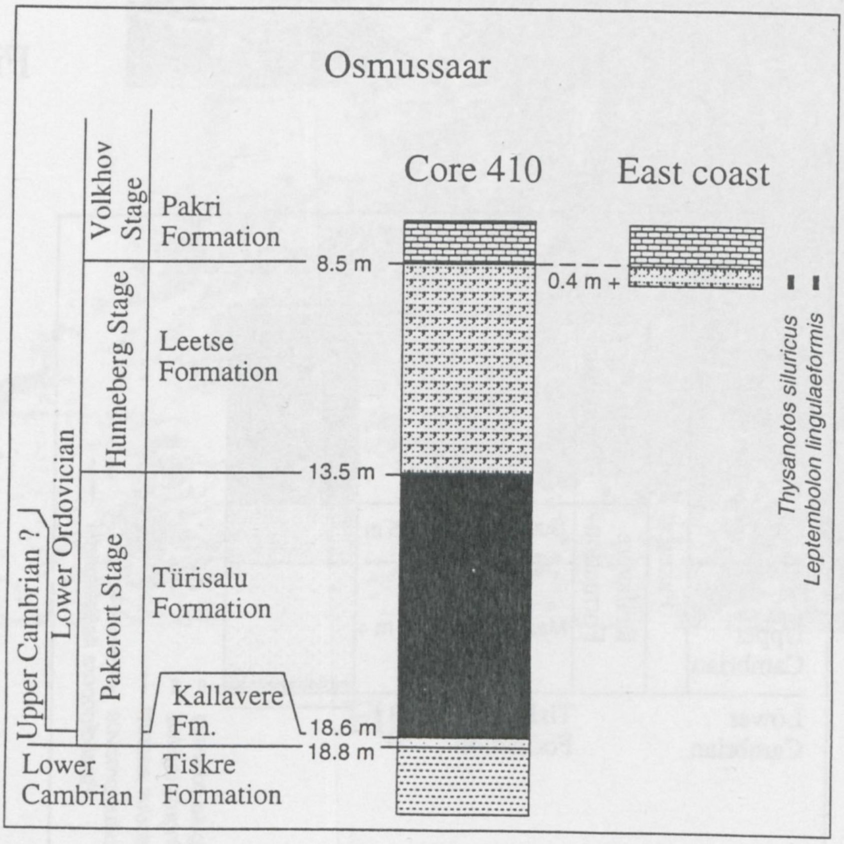
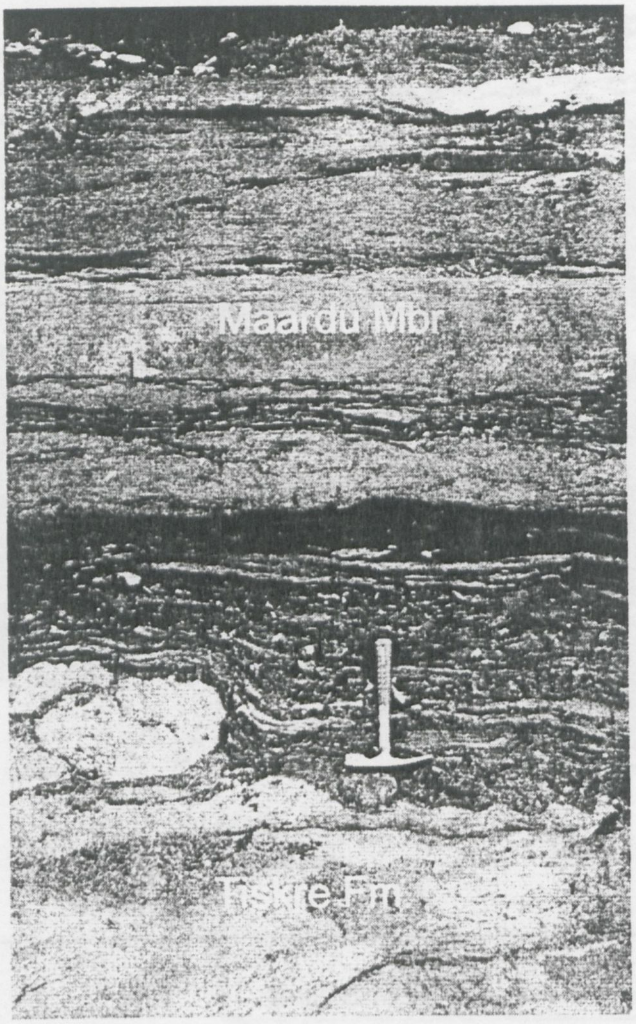
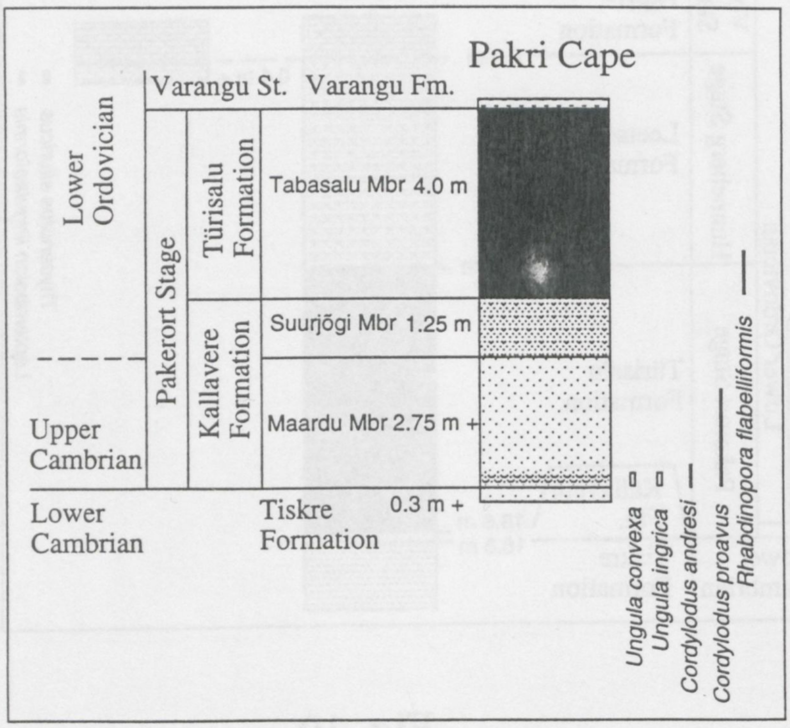

Osmussaar
Core 410
East coast
Volkhov Stage
Pakri Formation
Hunneberg Stage
Leetse Formation
Upper Cambrian ?
Lower Ordovician
Pakerort Stage
Türisalu Formation
Kallavere Fm.
Lower Cambrian
Tiskre Formation
8.5 m
13.5 m
18.6 m
18.8 m
0.4 m +
Thysanotos siluricus
Leptembolon lingulaeformis

Fig. 10



Maardu Mbr
Tiskre Fm

Fig. 11



Pakri Cape
Varangu St.
Varangu Fm.
Lower Ordovician
Pakerort Stage
Türisalu Formation
Tabasalu Mbr 4.0 m
Kallavere Formation
Suurjõgi Mbr 1.25 m
Maardu Mbr 2.75 m +
Upper Cambrian
Lower Cambrian
Tiskre Formation
0.3 m +
Ungula convexa
Ungula ingrica
Cordylodus andresi
Cordylodus proavus
Rhabdinopora flabelliformis

Fig. 12

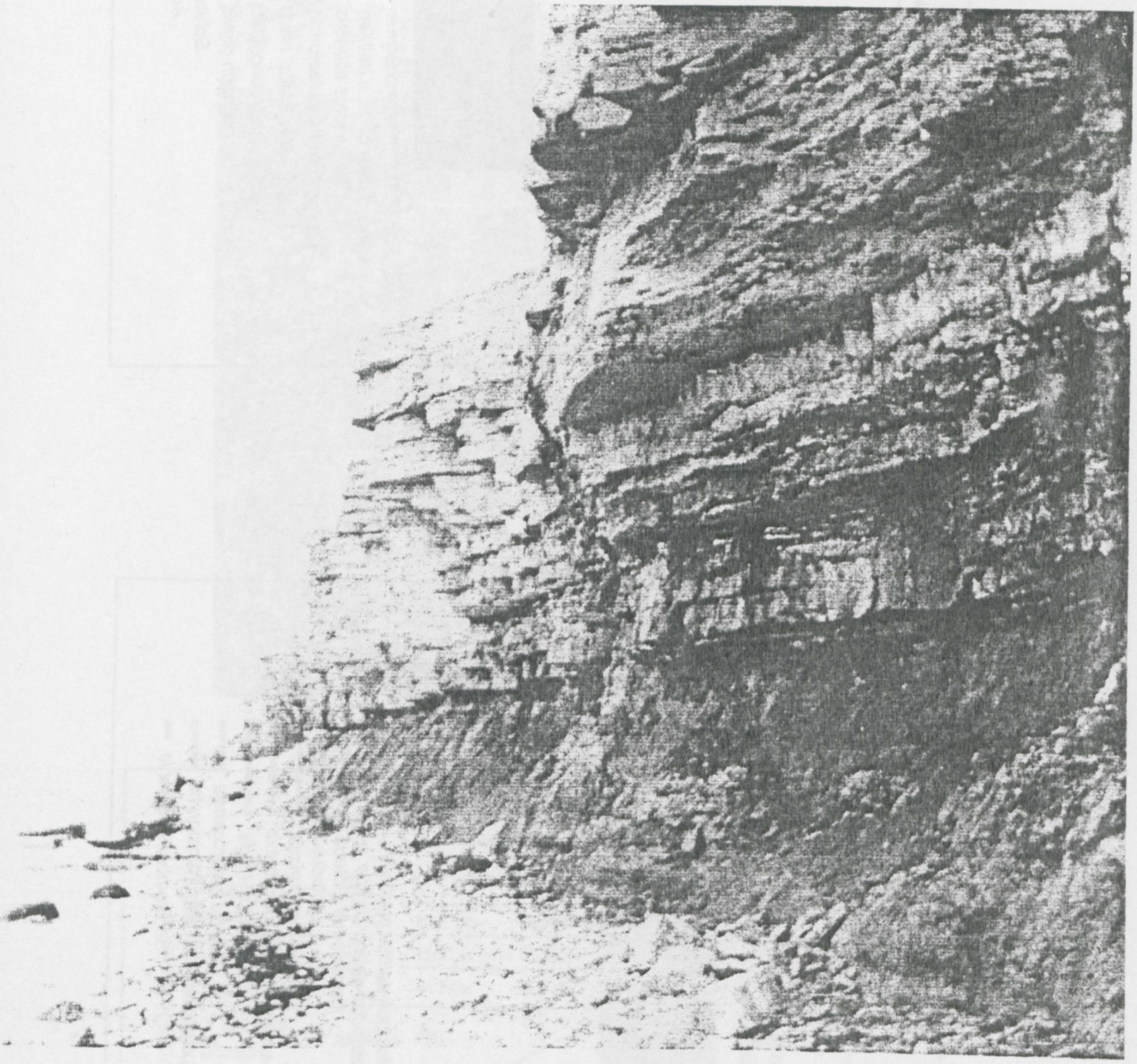


Fig. 13

153

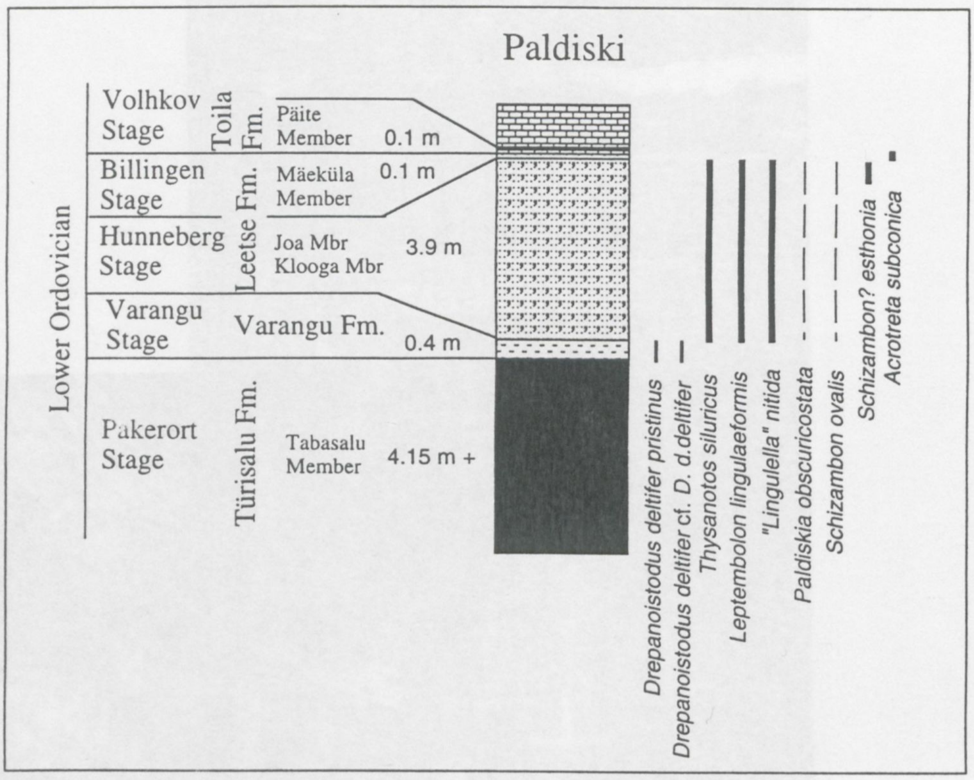

Paldiski
Lower Ordovician
Volhkov Stage
Billingen Stage
Hunneberg Stage
Varangu Stage
Pakerort Stage
Toila Fm.
Leetse Fm.
Varangu Fm.
Türisalu Fm.
Päite Member
Mäeküla Member
Joa Mbr
Klooga Mbr
Tabasalu Member
0.1 m
0.1 m
3.9 m
0.4 m
4.15 m +
Drepanoistodus deltifer pristinus
Drepanoistodus deltifer cf. D. d.deltifer
Thysanotos siluricus
Leptembolon lingulaeformis
"Lingulella" nitida
Paldiskia obscuricostata
Schizambon ovalis
Schizambon? esthonia
Acrotreta subconica

Fig. 14

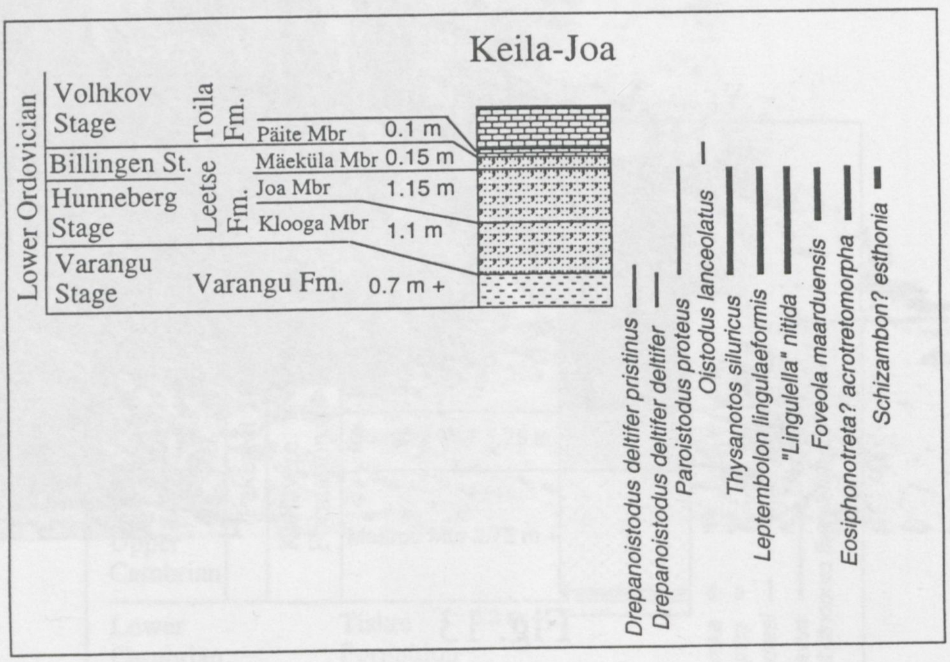

Keila-Joa
Lower Ordovician
Volhkov Stage
Billingen St.
Hunneberg Stage
Varangu Stage
Toila Fm.
Leetse Fm.
Varangu Fm.
Päite Mbr
Mäeküla Mbr
Joa Mbr
Klooga Mbr
0.1 m
0.15 m
1.15 m
1.1 m
0.7 m +
Drepanoistodus deltifer pristinus
Drepanoistodus deltifer deltifer
Paroistodus proteus
Oistodus lanceolatus
Thysanotos siluricus
Leptembolon lingulaeformis
"Lingulella" nitida
Foveola maarduensis
Eosiphonotreta? acrotretomorpha
Schizambon? esthonia

Fig. 15


Mäekula Mbr
Joa Mbr
Varangu Fm.

Fig. 16

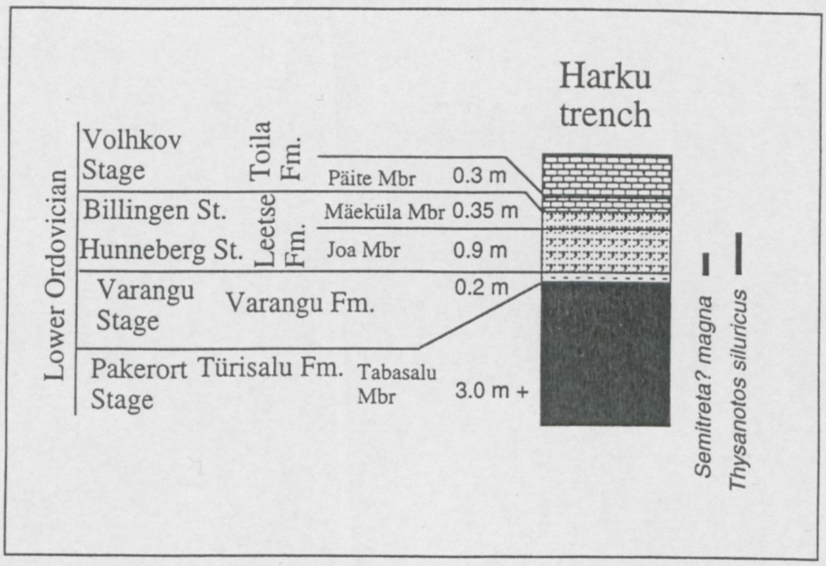
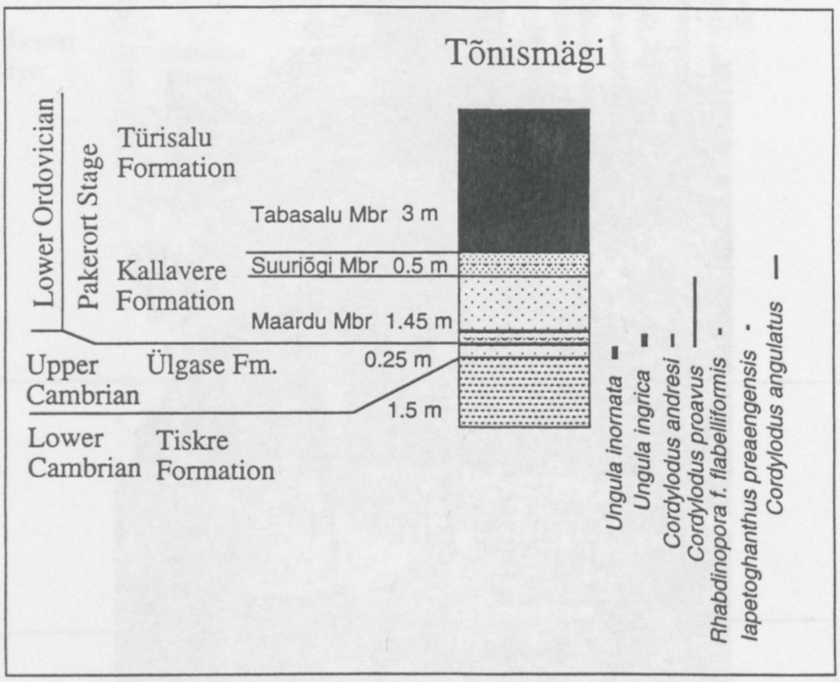

Harku
trench
Lower Ordovician
Volhkov
Stage
Billingen St.
Hunneberg St.
Varangu
Stage
Pakerort
Stage
Toila
Fm.
Leetse
Fm.
Varangu Fm.
Türisalu Fm.
Päite Mbr
Mäeküla Mbr
Joa Mbr
Tabasalu
Mbr
0.3 m
0.35 m
0.9 m
0.2 m
3.0 m +
Semitreta? magna
Thysanotos siluricus

Fig. 17



Tõnismägi
Lower Ordovician
Pakerort Stage
Türisalu Formation
Tabasalu Mbr 3 m
Kallavere Formation
Suurjõgi Mbr 0.5 m
Maardu Mbr 1.45 m
Upper Cambrian
Ülgase Fm.
0.25 m
1.5 m
Lower Cambrian
Tiskre Formation
Ungula inornata
Ungula ingrica
Cordylodus andresi
Cordylodus proavus
Rhabdinopora f. flabelliformis
Iapetoghanthus preaengensis
Cordylodus angulatus

Fig. 18

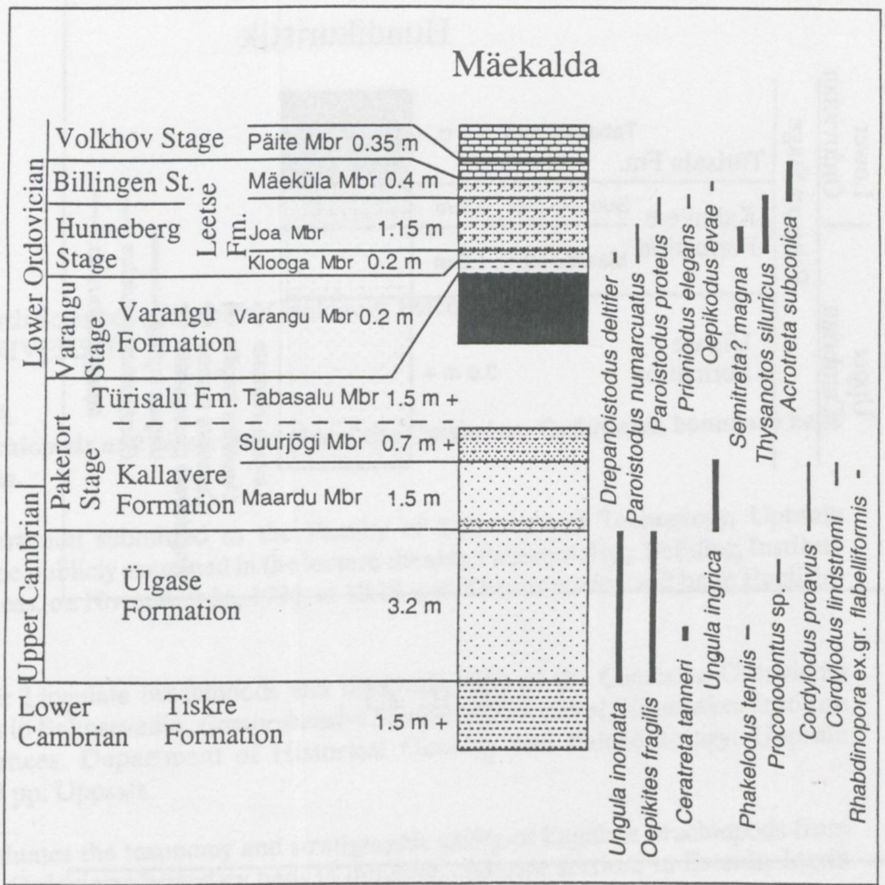

Mäekalda
Volkhov Stage
Billingen St.
Hunneberg Stage
Varangu Stage
Lower Ordovician
Leetse Fm.
Päite Mbr 0.35 m
Mäeküla Mbr 0.4 m
Joa Mbr 1.15 m
Klooga Mbr 0.2 m
Varangu Formation
Varangu Mbr 0.2 m
Türisalu Fm.
Tabasalu Mbr 1.5 m +
Pakerort Stage
Kallavere Formation
Suurjõgi Mbr 0.7 m +
Maardu Mbr 1.5 m
Upper Cambrian
Ülgase Formation
3.2 m
Lower Cambrian
Tiskre Formation
1.5 m +
Ungula inornata
Oepikites fragilis
Drepanoistodus deltifer
Paroistodus numarcuatus
Ceratreta tanneri
Paroistodus proteus
Prioniodus elegans
Ungula ingrica
Oepikodus evae
Phakelodus tenuis
Semitreta? magna
Proconodontus sp.
Thysanotos siluricus
Cordylodus proavus
Acrotreta subconica
Cordylodus lindstromi
Rhabdinopora ex.gr. flabelliformis

Fig. 19

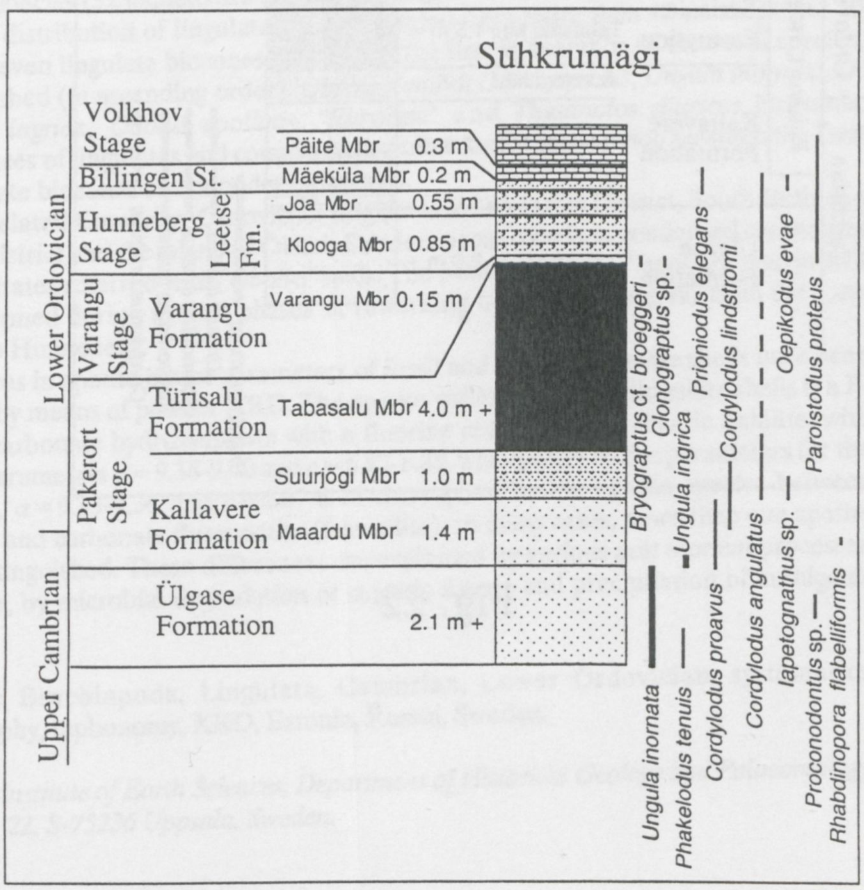

Suhkrumägi
Volkhov Stage
Billingen St.
Hunneberg Stage
Lower Ordovician
Leetse Fm.
Päite Mbr 0.3 m
Mäeküla Mbr 0.2 m
Joa Mbr 0.55 m
Klooga Mbr 0.85 m
Varangu Stage
Varangu Formation
Varangu Mbr 0.15 m
Türisalu Formation
Tabasalu Mbr 4.0 m +
Pakerort Stage
Kallavere Formation
Suurjõgi Mbr 1.0 m
Maardu Mbr 1.4 m
Upper Cambrian
Ülgase Formation
2.1 m +
Ungula inornata
Phakelodus tenuis
Bryograptus cf. broeggeri
Clonograptus sp.
Ungula ingrica
Prioniodus elegans
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
Oepikodus evae
Iapetognathus sp.
Paroistodus proteus
Proconodontus sp.
Rhabdinopora flabelliformis

Fig. 20

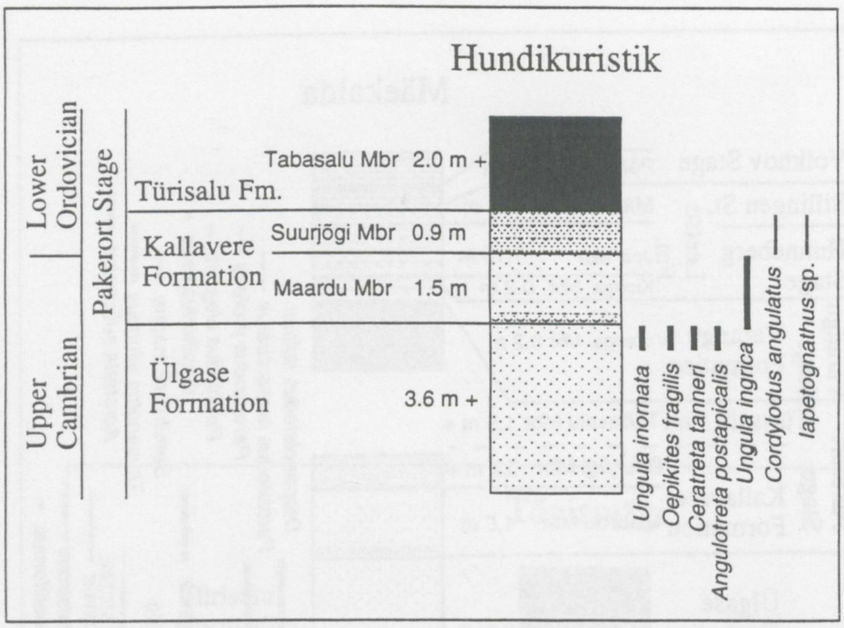

Hundikuristik
Lower Ordovician
Upper Cambrian
Pakerort Stage
Türisalu Fm.
Tabasalu Mbr 2.0 m +
Kallavere Formation
Suurjõgi Mbr 0.9 m
Maardu Mbr 1.5 m
Ülgase Formation
3.6 m +
Ungula inornata
Oepikites fragilis
Ceratreta tanneri
Angulotreta postapicalis
Ungula ingrica
Cordylodus angulatus
Iapetognathus sp.

Fig. 21

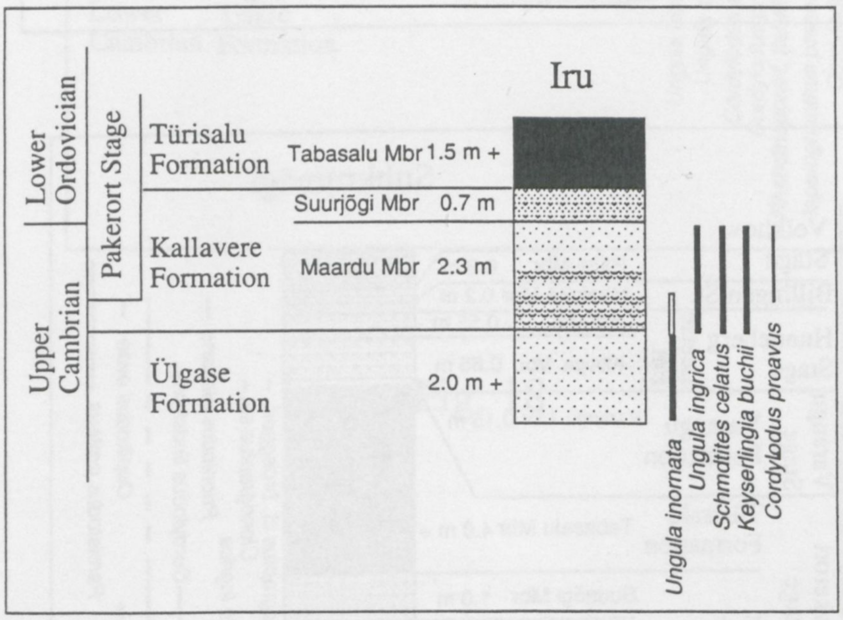

Iru
Lower Ordovician
Upper Cambrian
Pakerort Stage
Türisalu Formation
Tabasalu Mbr 1.5 m +
Suurjõgi Mbr 0.7 m
Kallavere Formation
Maardu Mbr 2.3 m
Ülgase Formation
2.0 m +
Ungula inornata
Ungula ingrica
Schmidtites celatus
Keyserlingia buchii
Cordylodus proavus

Fig. 22

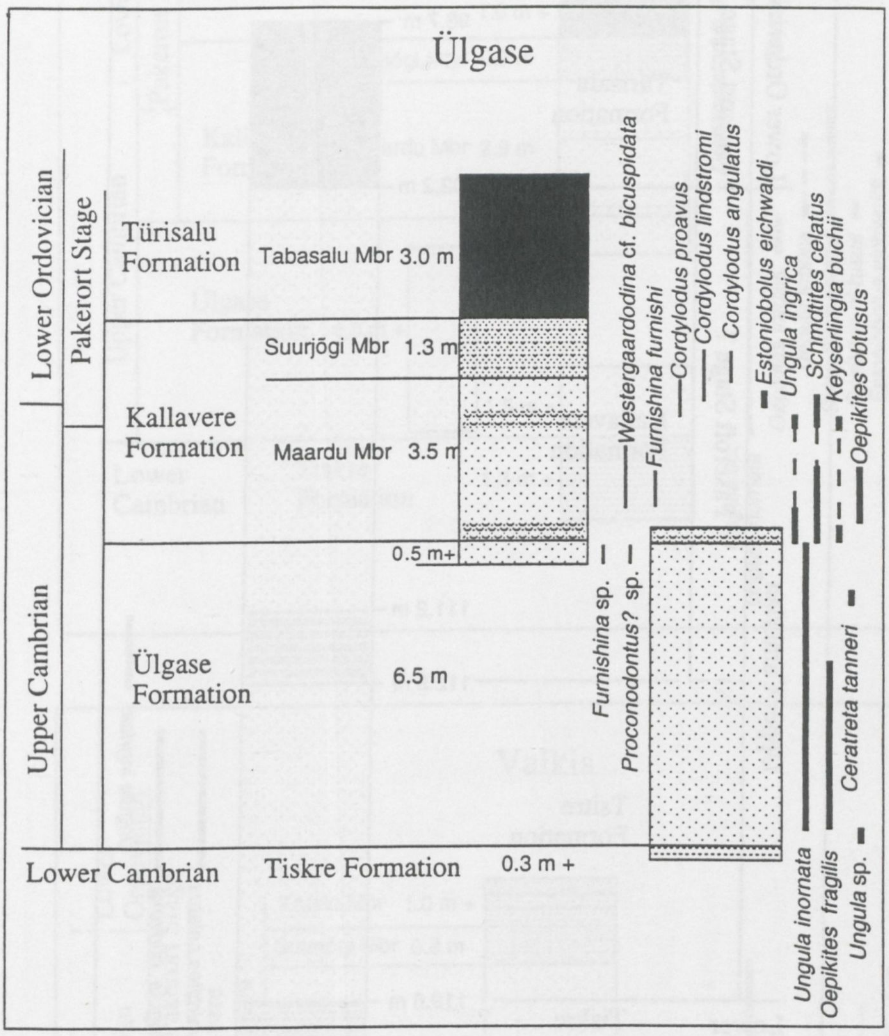
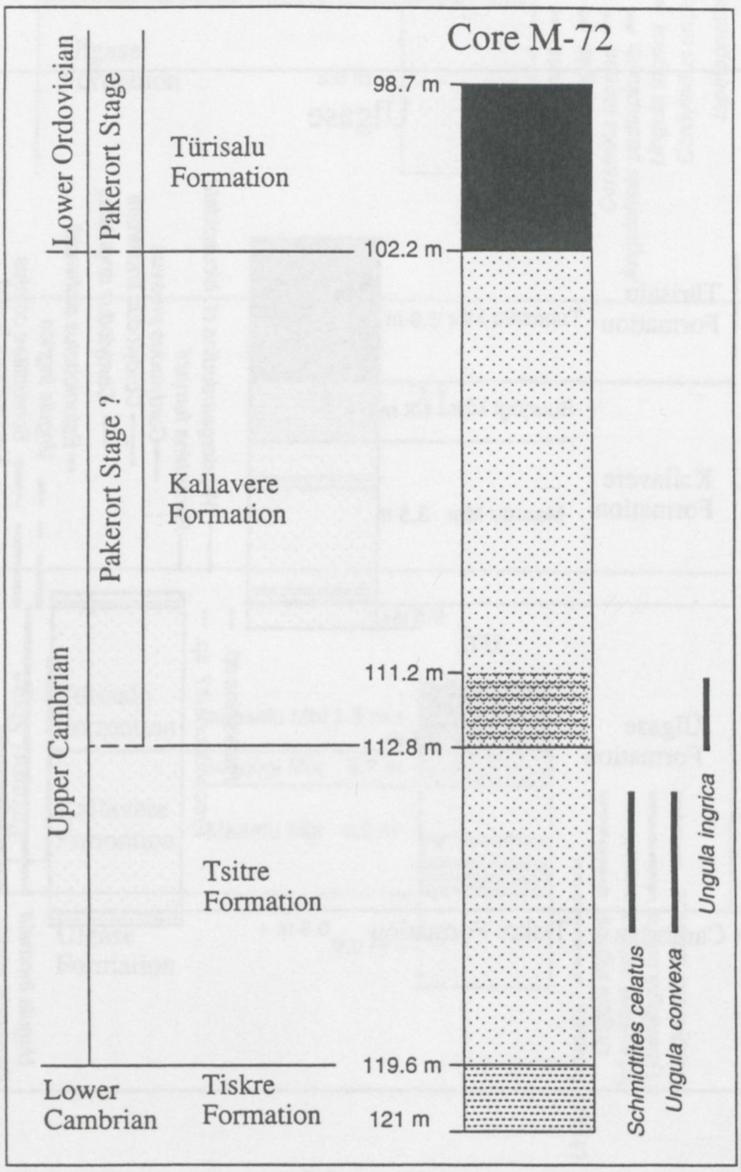

Ülgase
Lower Ordovician
Pakerort Stage
Türisalu Formation
Tabasalu Mbr 3.0 m
Suurjõgi Mbr 1.3 m
Kallavere Formation
Maardu Mbr 3.5 m
0.5 m+
Upper Cambrian
Ülgase Formation
6.5 m
Lower Cambrian
Tiskre Formation
0.3 m +
Furnishina sp.
Proconodontus? sp.
Westergaardodina cf. bicuspidata
Furnishina furnishi
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
Estoniobolus eichwaldi
Ungula ingrica
Schmidtites celatus
Keyserlingia buchii
Oepikites obtusus
Ungula inornata
Oepikites fragilis
Ceratreta tanneri
Ungula sp.

Fig. 23



Core M-72
Lower Ordovician
Pakerort Stage
Türisalu Formation
Pakerort Stage ?
Kallavere Formation
Upper Cambrian
Tsitre Formation
Lower Cambrian
Tiskre Formation
98.7 m
102.2 m
111.2 m
112.8 m
119.6 m
121 m
Schmidtites celatus
Ungula convexa
Ungula ingrica

Fig. 24

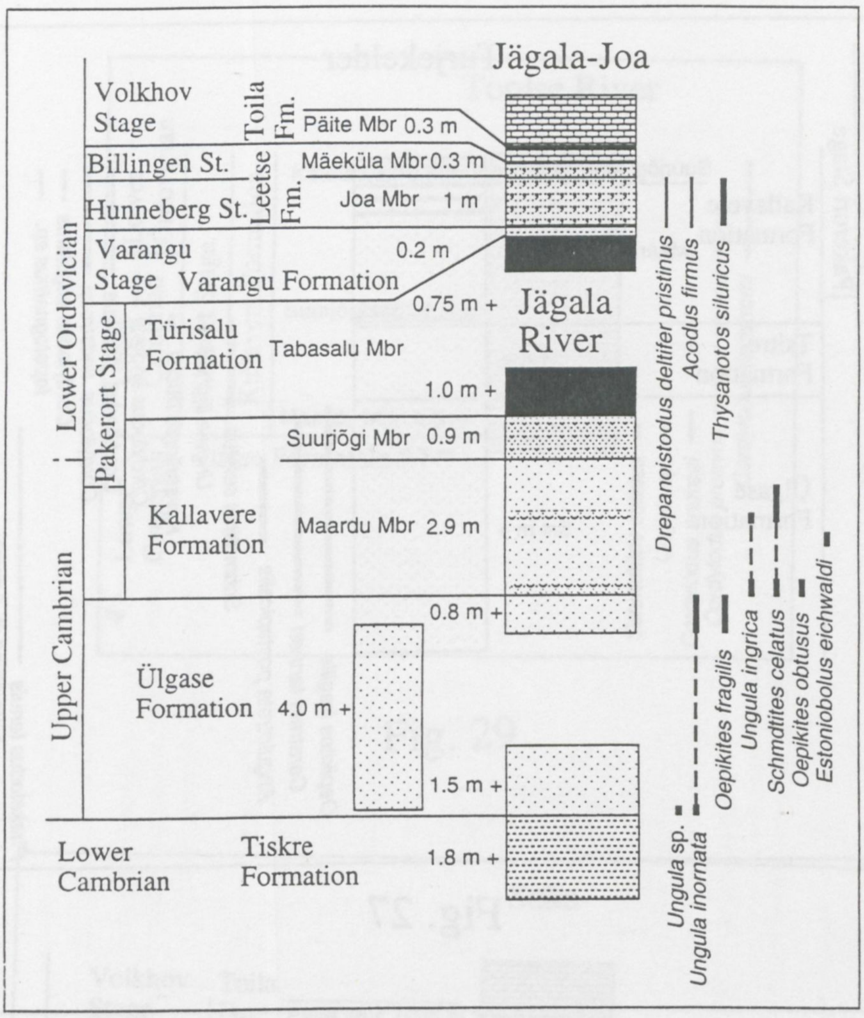

Jägala-Joa
Volkhov Stage
Billingen St.
Hunneberg St.
Varangu Stage
Lower Ordovician
Pakerort Stage
Upper Cambrian
Lower Cambrian
Toila Fm.
Leetse Fm.
Päite Mbr 0.3 m
Mäeküla Mbr 0.3 m
Joa Mbr 1 m
0.2 m
Varangu Formation
0.75 m +
Jägala River
Türisalu Formation
Tabasalu Mbr
1.0 m +
Suurjõgi Mbr 0.9 m
Kallavere Formation
Maardu Mbr 2.9 m
0.8 m +
Ülgase Formation
4.0 m +
1.5 m +
Tiskre Formation
1.8 m +
Ungula sp.
Ungula inornata
Drepanoistodus deltifer pristinus
Acodus firmus
Thysanotos siluricus
Oepikites fragilis
Ungula ingrica
Schmdtites celatus
Oepikites obtusus
Estoniobolus eichwaldi

Fig. 25

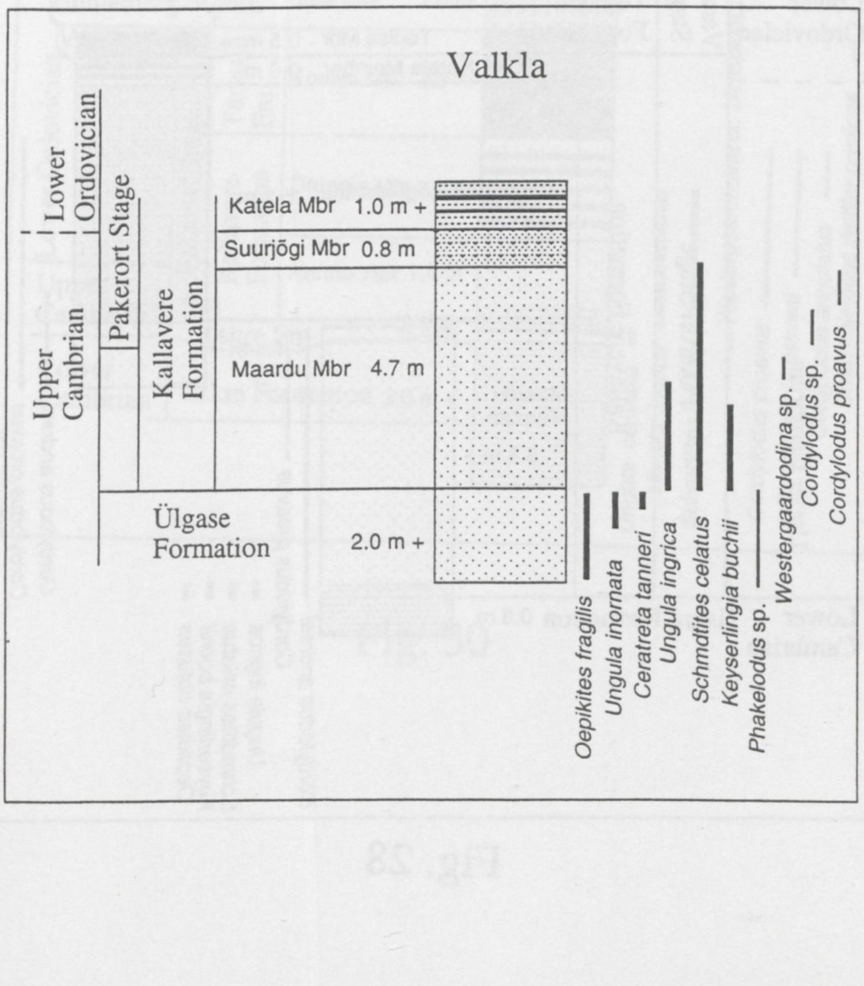
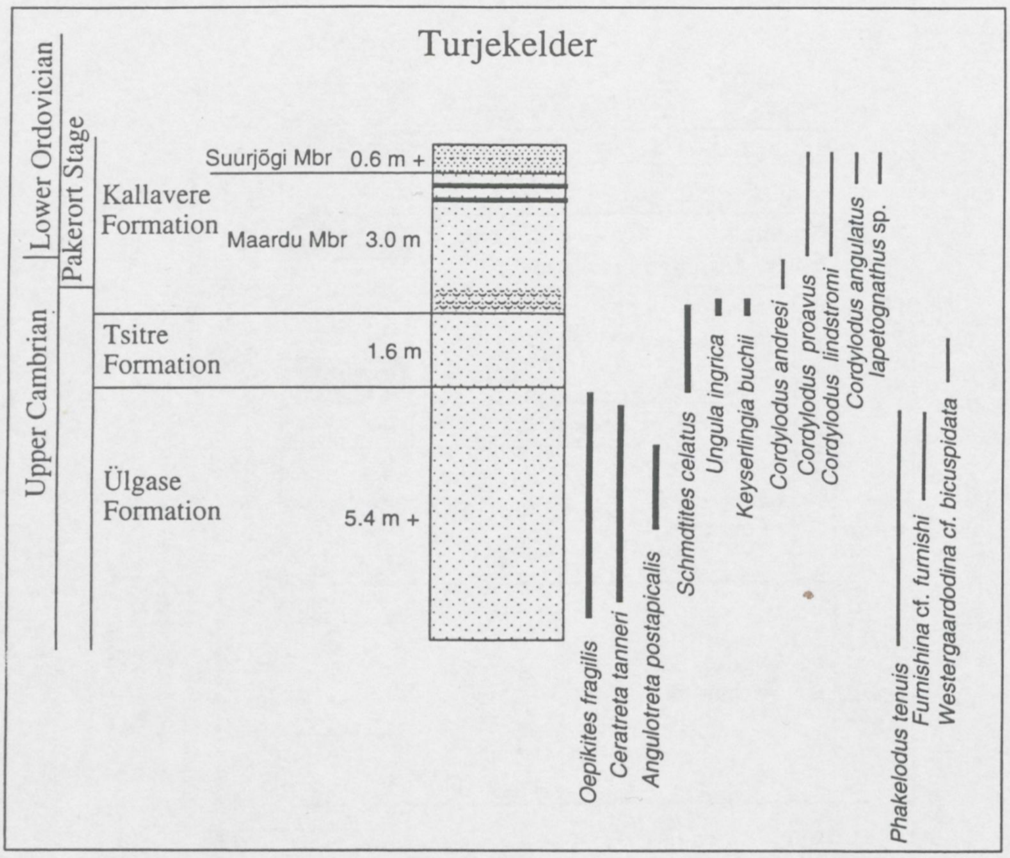
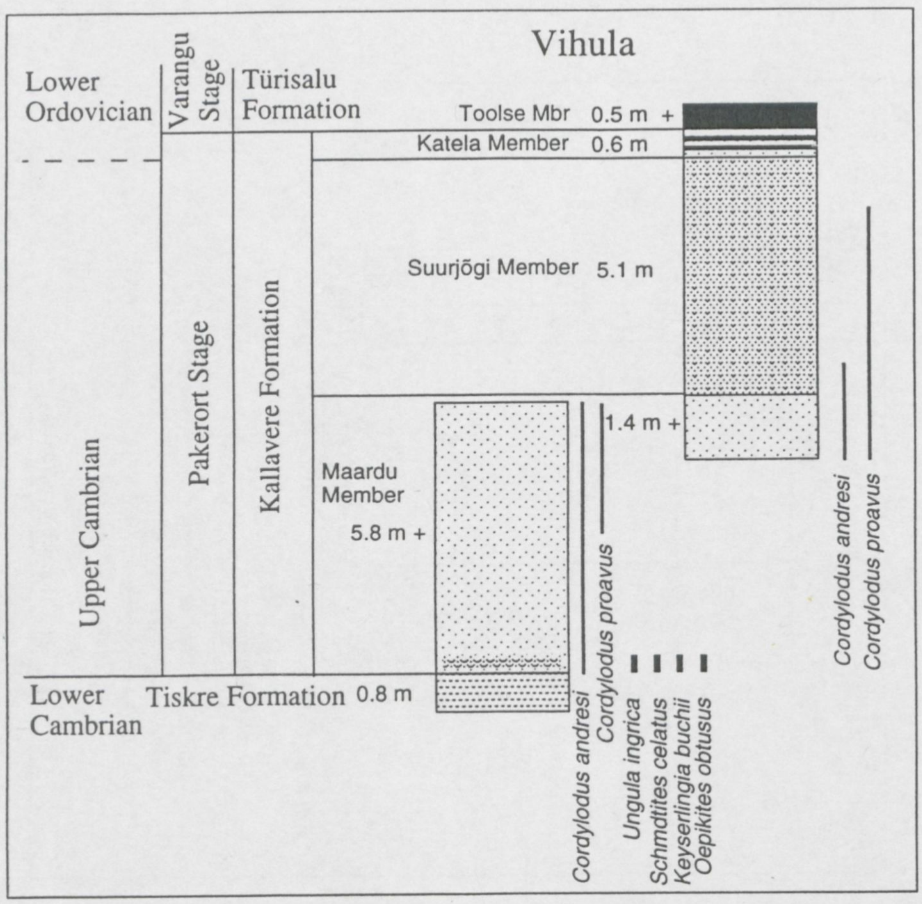

Valkla
Upper Cambrian
Lower Ordovician
Pakerort Stage
Kallavere Formation
Katela Mbr 1.0 m +
Suurjõgi Mbr 0.8 m
Maardu Mbr 4.7 m
Ülgase Formation
2.0 m +
Oepikites fragilis
Ungula inornata
Ceratreta tanneri
Ungula ingrica
Schmdtites celatus
Keyserlingia buchii
Phakelodus sp.
Westergaardodina sp.
Cordylodus sp.
Cordylodus proavus

Fig. 26



Turjekelder
Lower Ordovician
Upper Cambrian
Pakerort Stage
Kallavere Formation
Suurjõgi Mbr 0.6 m +
Maardu Mbr 3.0 m
Tsitre Formation
1.6 m
Ülgase Formation
5.4 m +
Oepikites fragilis
Ceratreta tanneri
Angulotreta postapicalis
Schmdtites celatus
Ungula ingrica
Keyserlingia buchii
Cordylodus andresi
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
Iapetognathus sp.
Phakelodus tenuis
Furnishina cf. furnishi
Westergaardodina cf. bicuspidata

Fig. 27



Vihula
Lower Ordovician
Varangu Stage
Türisalu Formation
Toolse Mbr 0.5 m +
Katela Member 0.6 m
Suurjõgi Member 5.1 m
Upper Cambrian
Pakerort Stage
Kallavere Formation
Maardu Member
5.8 m +
1.4 m +
Lower Cambrian
Tiskre Formation 0.8 m
Cordylodus andresi
Cordylodus proavus
Ungula ingrica
Schmdtites celatus
Keyserlingia buchii
Oepikites obtusus
Cordylodus andresi
Cordylodus proavus

Fig. 28

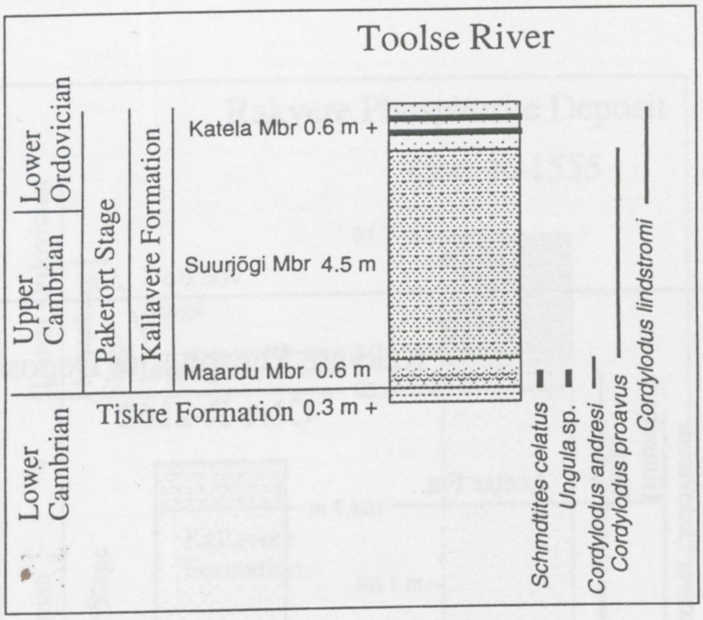

Toolse River
Lower Ordovician
Upper Cambrian
Lower Cambrian
Pakerort Stage
Kallavere Formation
Katela Mbr 0.6 m +
Suurjõgi Mbr 4.5 m
Maardu Mbr 0.6 m
Tiskre Formation 0.3 m +
Schmdtites celatus
Ungula sp.
Cordylodus andresi
Cordylodus proavus
Cordylodus lindstromi

Fig. 29

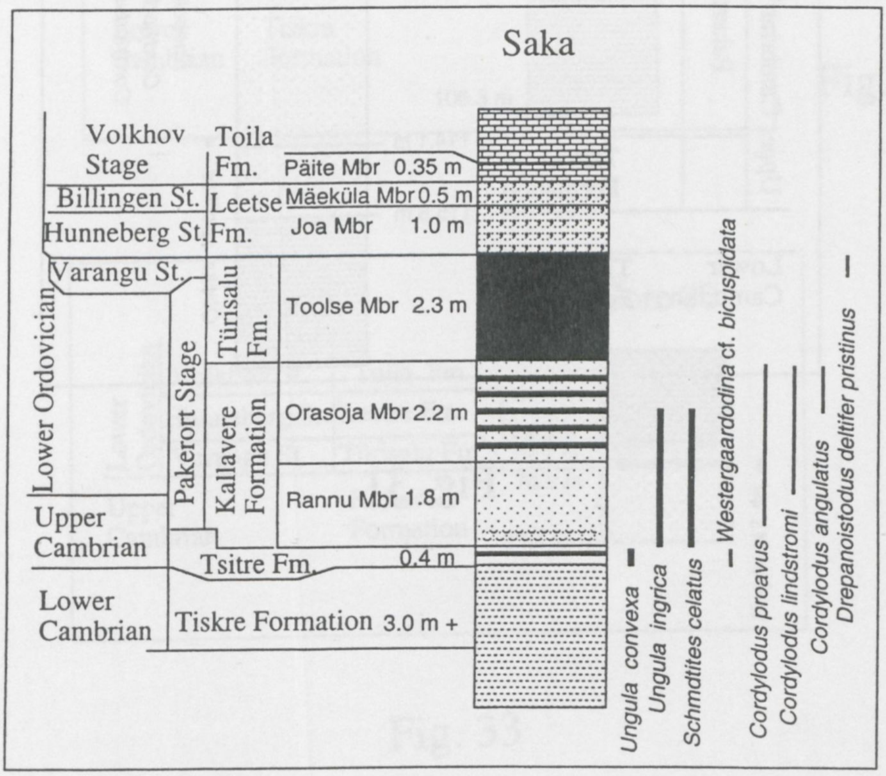
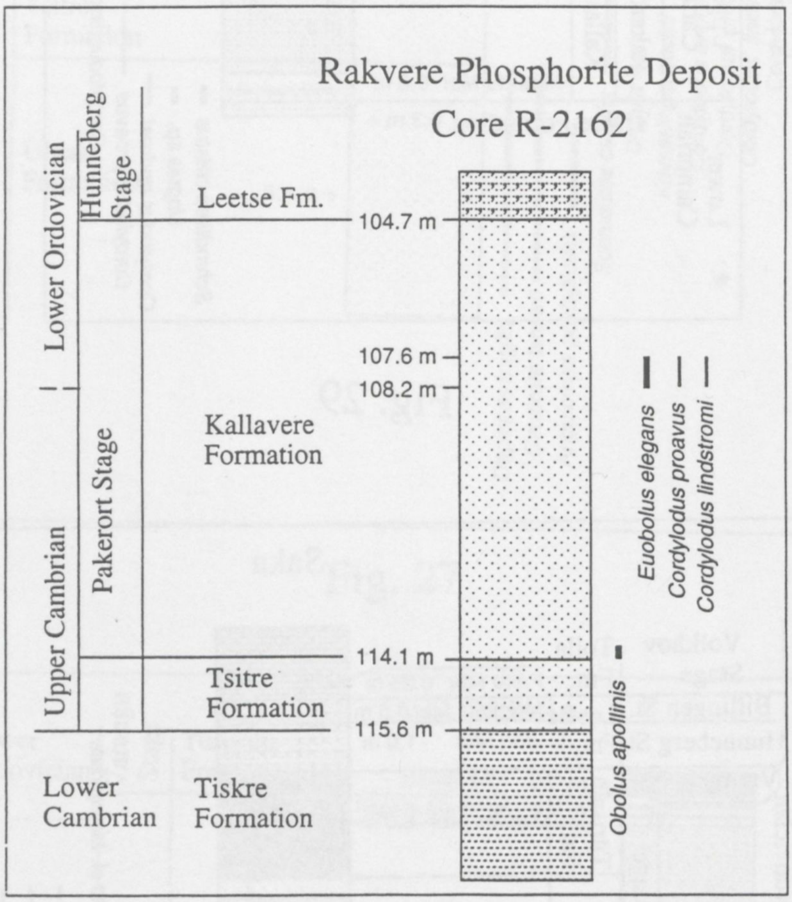
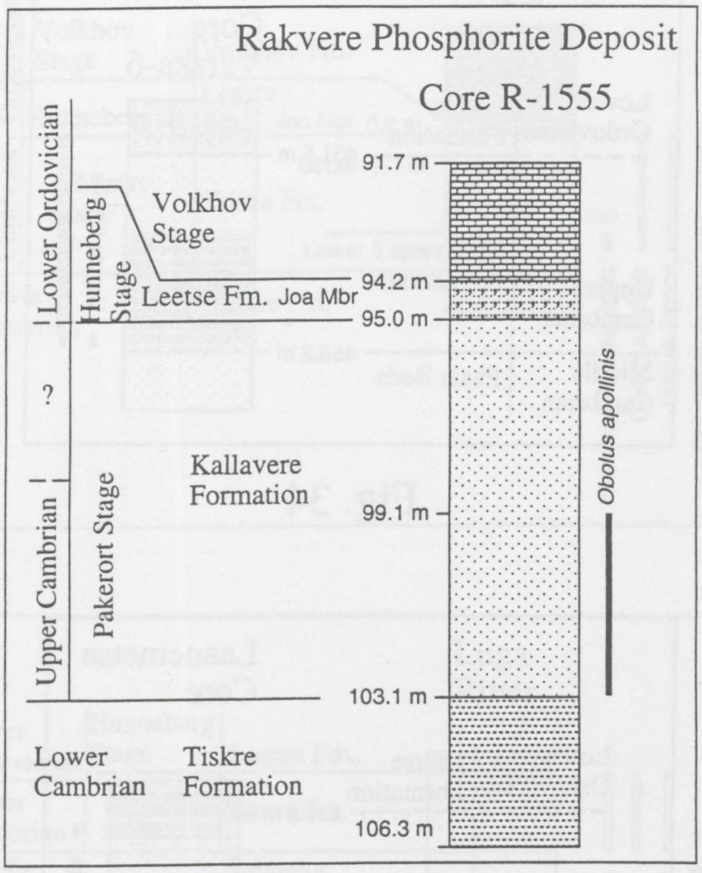

Saka
Volkhov Stage
Toila Fm.
Päite Mbr 0.35 m
Billingen St.
Leetse Fm.
Mäeküla Mbr 0.5 m
Hunneberg St.
Joa Mbr 1.0 m
Varangu St.
Lower Ordovician
Pakerort Stage
Türisalu Fm.
Toolse Mbr 2.3 m
Kallavere Formation
Orasoja Mbr 2.2 m
Rannu Mbr 1.8 m
Upper Cambrian
Tsitre Fm.
0.4 m
Lower Cambrian
Tiskre Formation 3.0 m +
Ungula convexa
Ungula ingrica
Schmdtites celatus
Westergaardodina cf. bicuspidata
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
Drepanoistodus deltifer pristinus

Fig. 30



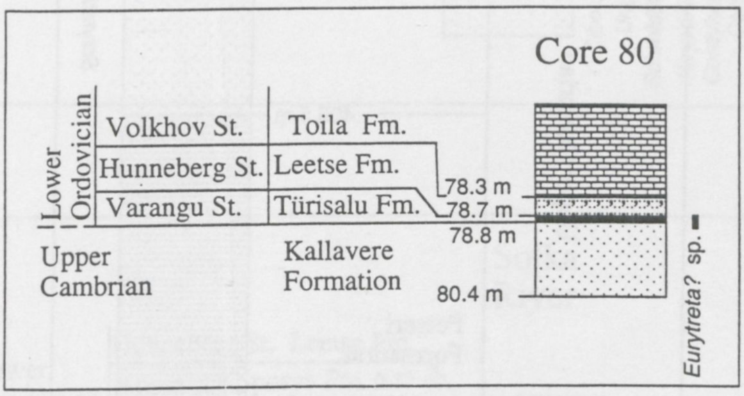
Rakvere Phosphorite Deposit
Core R-2162
Lower Ordovician
Upper Cambrian
Lower Cambrian
Hunneberg Stage
Pakerort Stage
Leetse Fm.
Kallavere Formation
Tsitre Formation
Tiskre Formation
104.7 m
107.6 m
108.2 m
114.1 m
115.6 m
Euobolus elegans
Cordylodus proavus
Cordylodus lindstromi
Obolus apollinis

Fig. 31



Rakvere Phosphorite Deposit
Core R-1555
Lower Ordovician
Hunneberg Stage
Volkhov Stage
Leetse Fm.
Joa Mbr
?
Upper Cambrian
Pakerort Stage
Kallavere Formation
Lower Cambrian
Tiskre Formation
91.7 m
94.2 m
95.0 m
99.1 m
103.1 m
106.3 m
Obolus apollinis

Fig. 32



Core 80
Lower Ordovician
Volkhov St.
Hunneberg St.
Varangu St.
Toila Fm.
Leetse Fm.
Türisalu Fm.
Upper Cambrian
Kallavere Formation
78.3 m
78.7 m
78.8 m
80.4 m
Eurytreta? sp.

Fig. 33

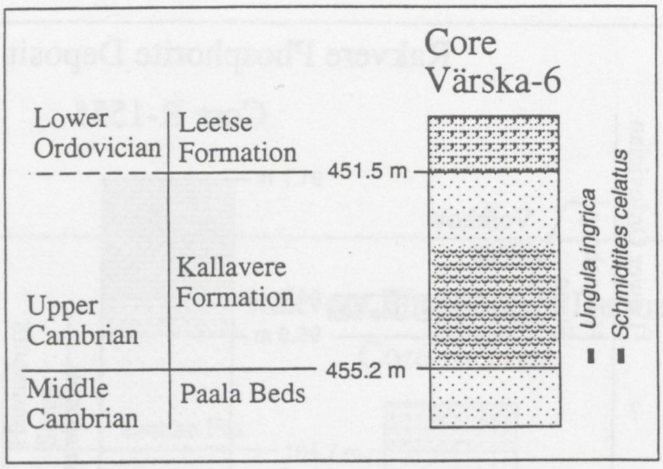

Core
Värska-6
Lower
Ordovician
Leetse
Formation
451.5 m
Kallavere
Formation
Upper
Cambrian
455.2 m
Middle
Cambrian
Paala Beds
Ungula ingrica
Schmidtites celatus

Fig. 34

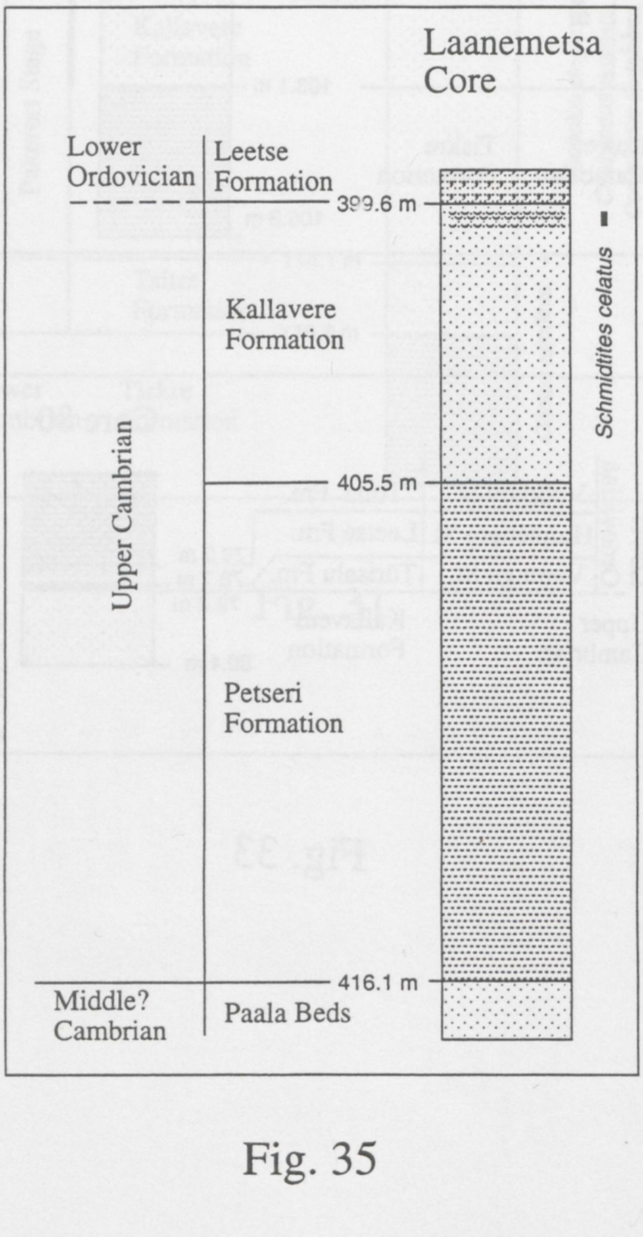

Laanemetsa
Core
Lower
Ordovician
Leetse
Formation
399.6 m
Kallavere
Formation
Schmidtites celatus
Upper Cambrian
405.5 m
Petseri
Formation
416.1 m
Middle?
Cambrian
Paala Beds

Fig. 35

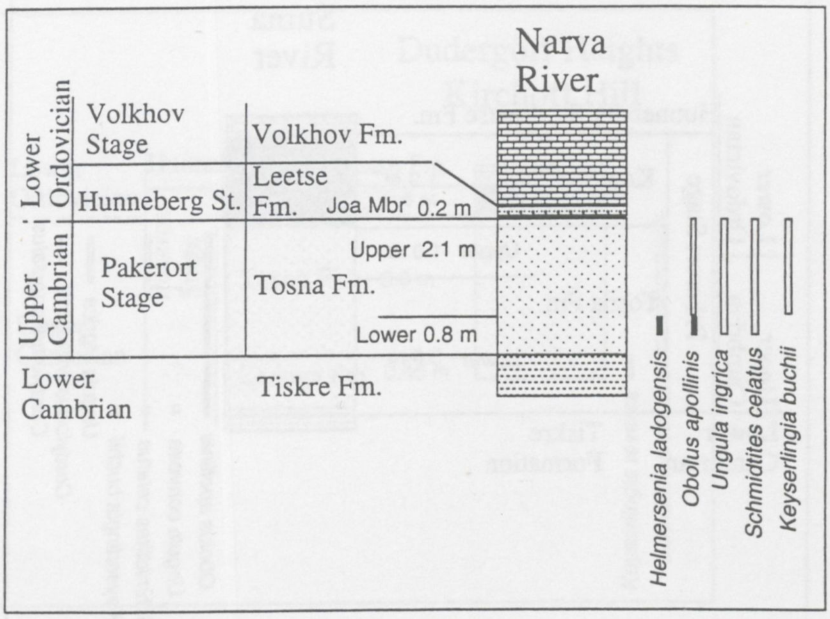


Fig. 36

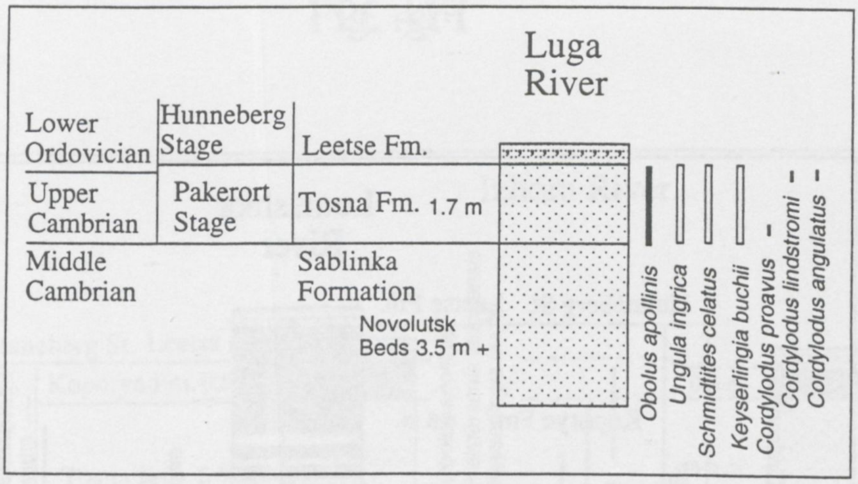


Fig. 37

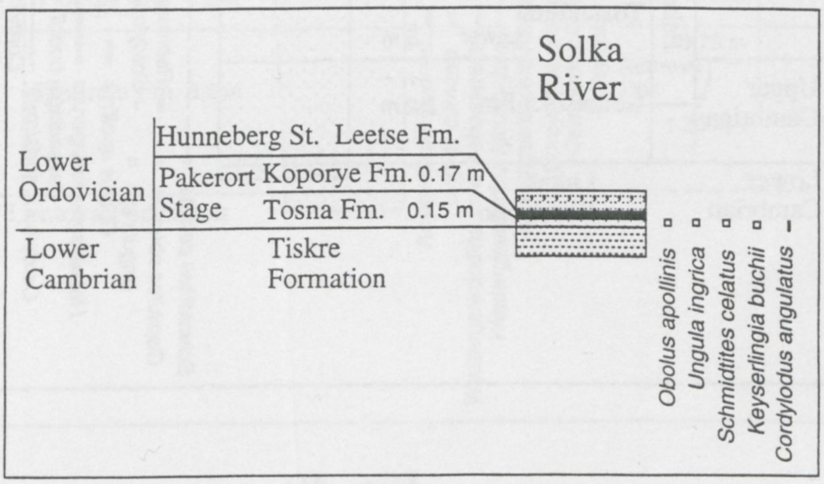


Fig. 38

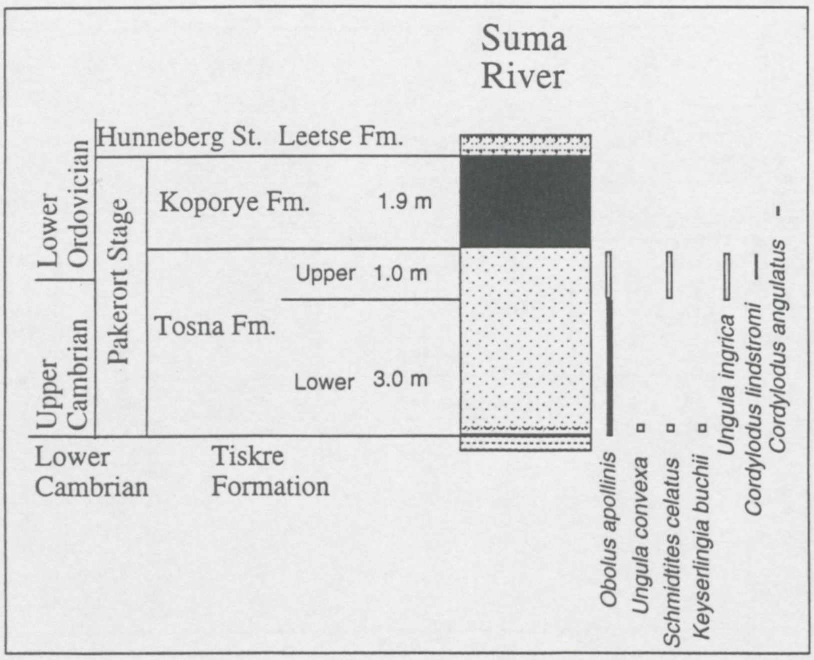

Suma
River
Hunneberg St.
Leetse Fm.
Lower Ordovician
Upper Cambrian
Pakerort Stage
Koporye Fm.
1.9 m
Upper
1.0 m
Tosna Fm.
Lower
3.0 m
Lower Cambrian
Tiskre Formation
Obolus apollinis
Ungula convexa
Schmidtites celatus
Keyserlingia buchii
Ungula ingrica
Cordylodus lindstromi
Cordylodus angulatus

Fig. 39

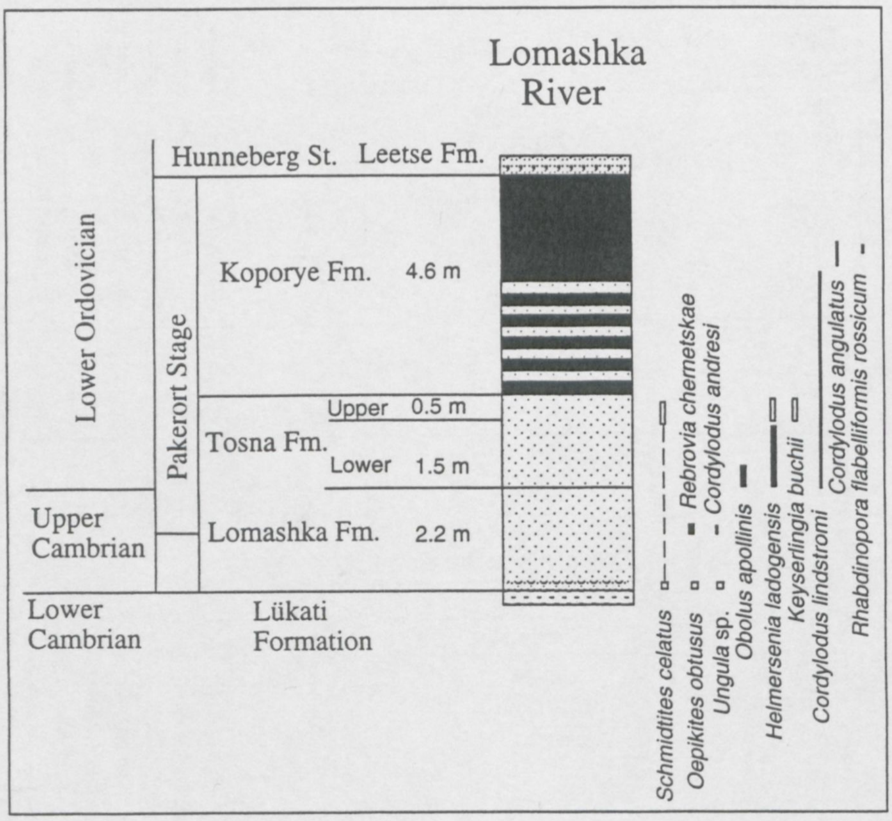

Lomashka
River
Hunneberg St.
Leetse Fm.
Lower Ordovician
Upper Cambrian
Pakerort Stage
Koporye Fm.
4.6 m
Upper
0.5 m
Tosna Fm.
Lower
1.5 m
Lomashka Fm.
2.2 m
Lower Cambrian
Lükati Formation
Schmidtites celatus
Oepikites obtusus
Ungula sp.
Obolus apollinis
Helmersenia ladogensis
Cordylodus lindstromi
Rebrovia chernetskae
Cordylodus andresi
Keyserlingia buchii
Cordylodus angulatus
Rhabdinopora flabelliformis rossicum

Fig. 40

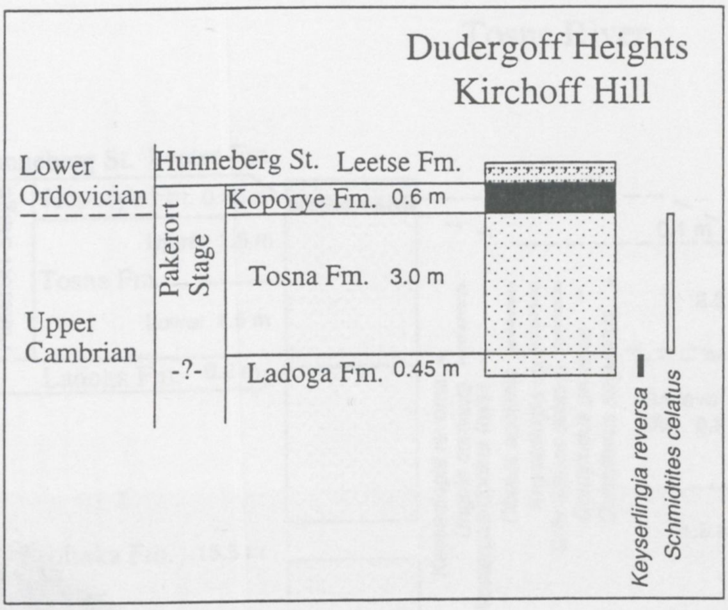

Dudergoff Heights
Kirchoff Hill
Lower Ordovician
Upper Cambrian
Hunneberg St.
Leetse Fm.
Pakerort Stage
Koporye Fm. 0.6 m
Tosna Fm. 3.0 m
-?-
Ladoga Fm. 0.45 m
Keyserlingia reversa
Schmidtites celatus

Fig. 41

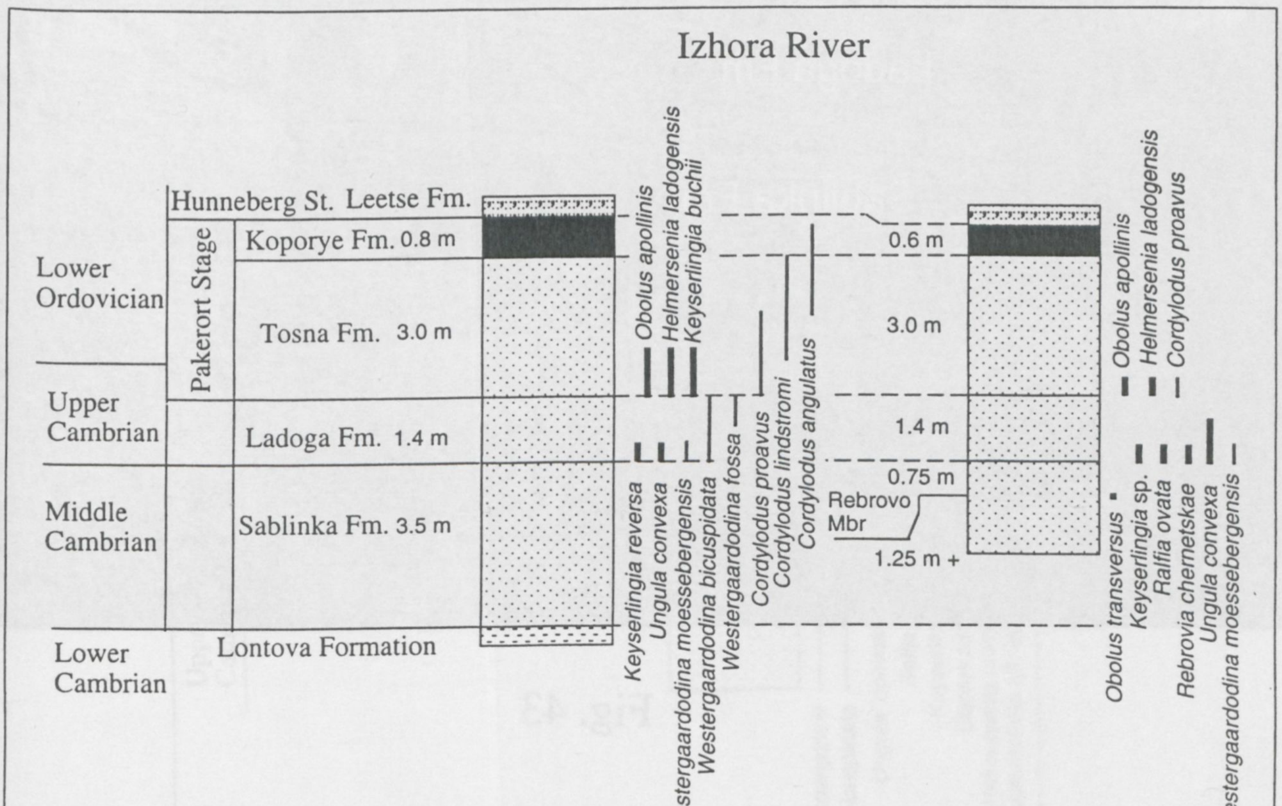

Izhora River
Lower Ordovician
Upper Cambrian
Middle Cambrian
Lower Cambrian
Hunneberg St.
Leetse Fm.
Pakerort Stage
Koporye Fm. 0.8 m
Tosna Fm. 3.0 m
Ladoga Fm. 1.4 m
Sablinka Fm. 3.5 m
Lontova Formation
Obolus apollinis
Helmersenia ladogensis
Keyserlingia buchii
Keyserlingia reversa
Ungula convexa
Westergaardodina moessebergensis
Westergaardodina bicuspidata
Westergaardodina fossa
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
0.6 m
3.0 m
1.4 m
0.75 m
Rebrovo Mbr
1.25 m +
Obolus apollinis
Helmersenia ladogensis
Cordylodus proavus
Obolus transversus
Keyserlingia sp.
Ralfia ovata
Rebrovia chernetskae
Ungula convexa
Westergaardodina moessebergensis

Fig. 42

Fig. 43

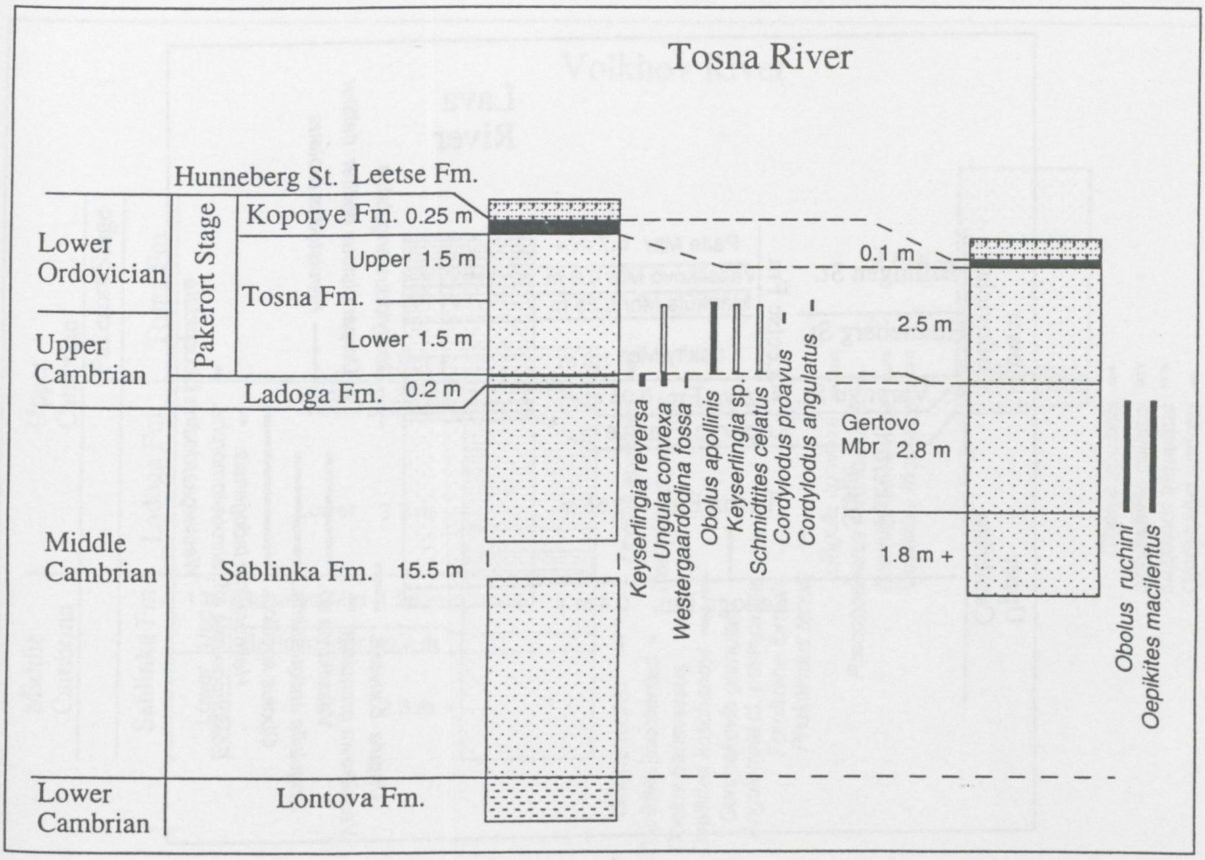

Tosna River
Hunneberg St.
Leetse Fm.
Lower Ordovician
Pakerort Stage
Koporye Fm. 0.25 m
Upper 1.5 m
Tosna Fm.
Lower 1.5 m
Upper Cambrian
Ladoga Fm.
0.2 m
Middle Cambrian
Sablinka Fm.
15.5 m
Lower Cambrian
Lontova Fm.
Keyserlingia reversa
Ungula convexa
Westergaardodina fossa
Obolus apollinis
Keyserlingia sp.
Schmidtites celatus
Cordylodus proavus
Cordylodus angulatus
0.1 m
2.5 m
Gertovo Mbr
2.8 m
1.8 m +
Obolus ruchini
Oepikites macilentus

Fig. 44

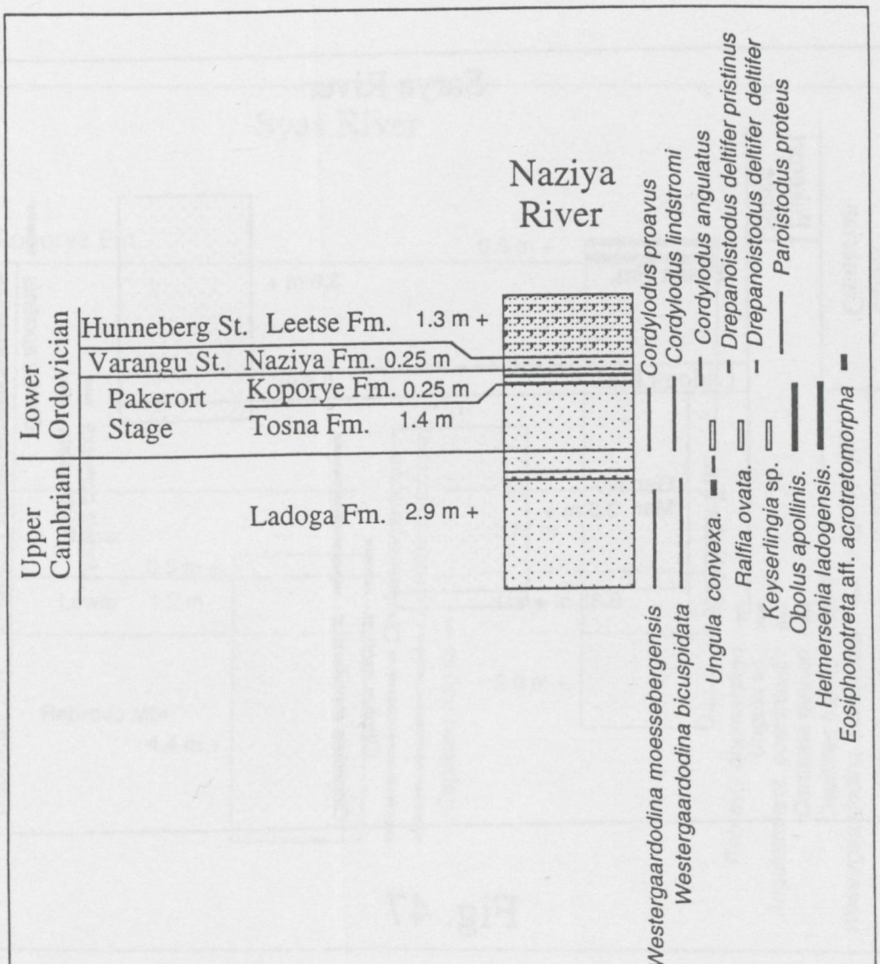

Naziya River
Lower Ordovician
Hunneberg St.
Leetse Fm.
1.3 m +
Varangu St.
Naziya Fm. 0.25 m
Pakerort Stage
Koporye Fm. 0.25 m
Tosna Fm.
1.4 m
Upper Cambrian
Ladoga Fm.
2.9 m +
Cordylodus proavus
Cordylodus lindstromi
Cordylodus angulatus
Drepanoistodus deltifer pristinus
Drepanoistodus deltifer deltifer
Paroistodus proteus
Westergaardodina moessebergensis
Westergaardodina bicuspidata
Ungula convexa.
Ralfia ovata.
Keyserlingia sp.
Obolus apollinis.
Helmersenia ladogensis.
Eosiphonotreta aff. acrotretomorpha

Fig. 45

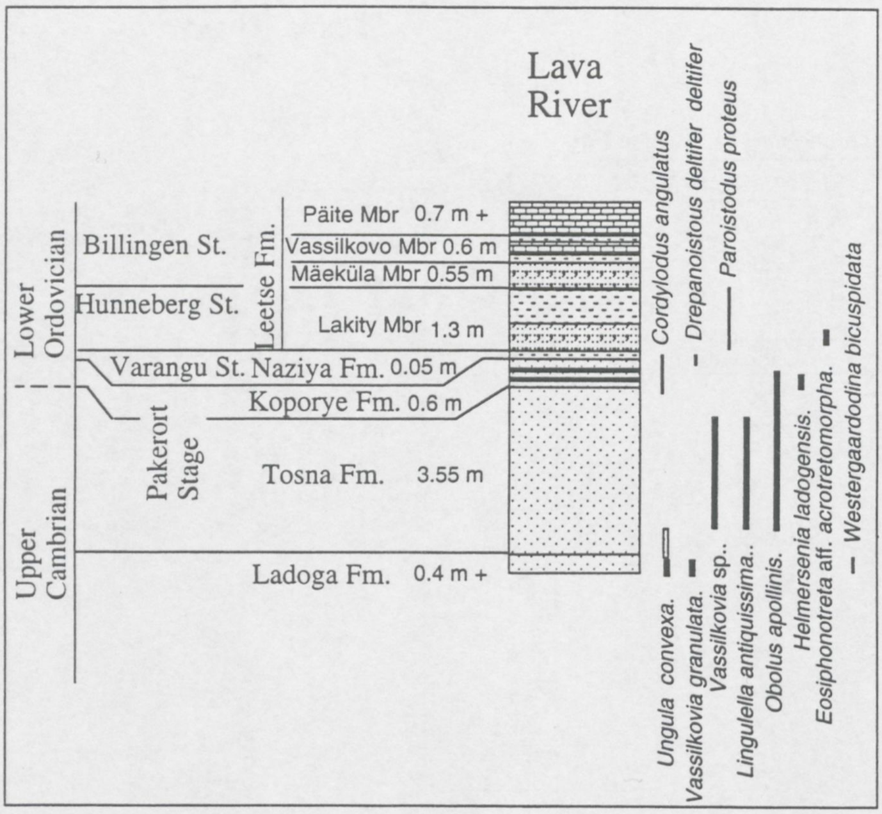

Lava River
Lower Ordovician
Upper Cambrian
Billingen St.
Hunneberg St.
Varangu St.
Pakerort Stage
Leetse Fm.
Päite Mbr 0.7 m +
Vassilkovo Mbr 0.6 m
Mäeküla Mbr 0.55 m
Lakity Mbr 1.3 m
Naziya Fm. 0.05 m
Koporye Fm. 0.6 m
Tosna Fm. 3.55 m
Ladoga Fm. 0.4 m +
Ungula convexa.
Cordylodus angulatus
Vassilkovia granulata.
Drepanoistous deltifer deltifer
Vassilkovia sp..
Paroistodus proteus
Lingulella antiquissima..
Obolus apollinis.
Helmersenia ladogensis.
Eosiphonotreta aff. acrotretomorpha.
Westergaardodina bicuspidata

Fig. 46

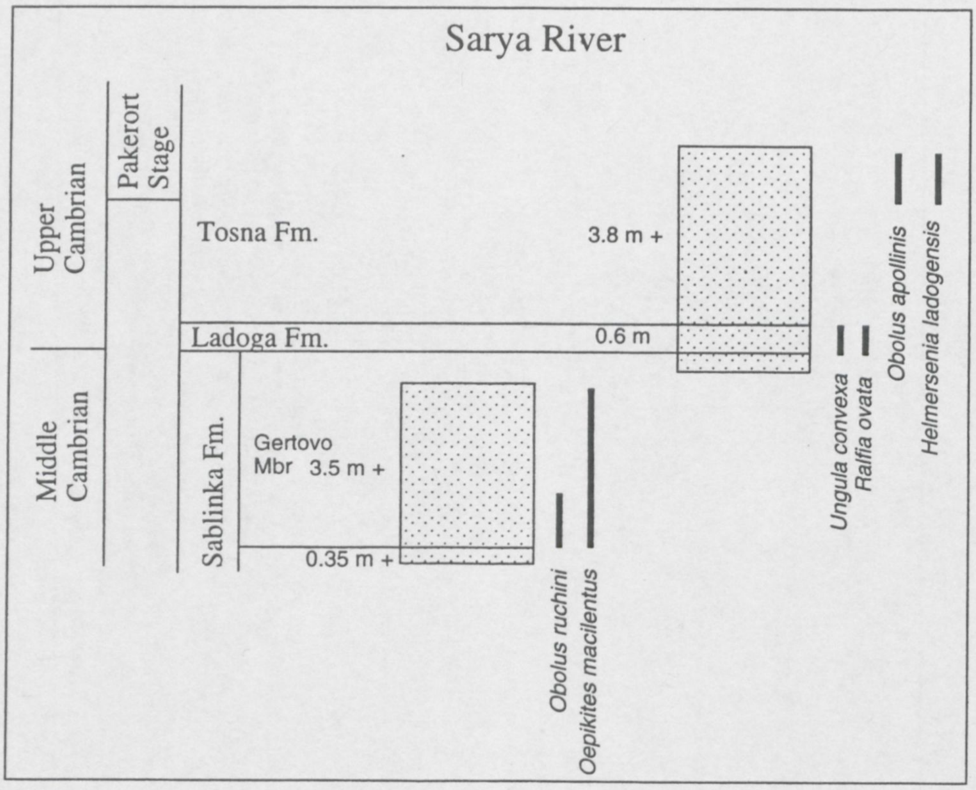

Sarya River
Upper Cambrian
Middle Cambrian
Pakerort Stage
Tosna Fm.
3.8 m +
Ladoga Fm.
0.6 m
Sablinka Fm.
Gertovo Mbr 3.5 m +
0.35 m +
Obolus ruchini
Oepikites macilentus
Ungula convexa
Raffia ovata
Obolus apollinis
Helmersenia ladogensis

Fig. 47

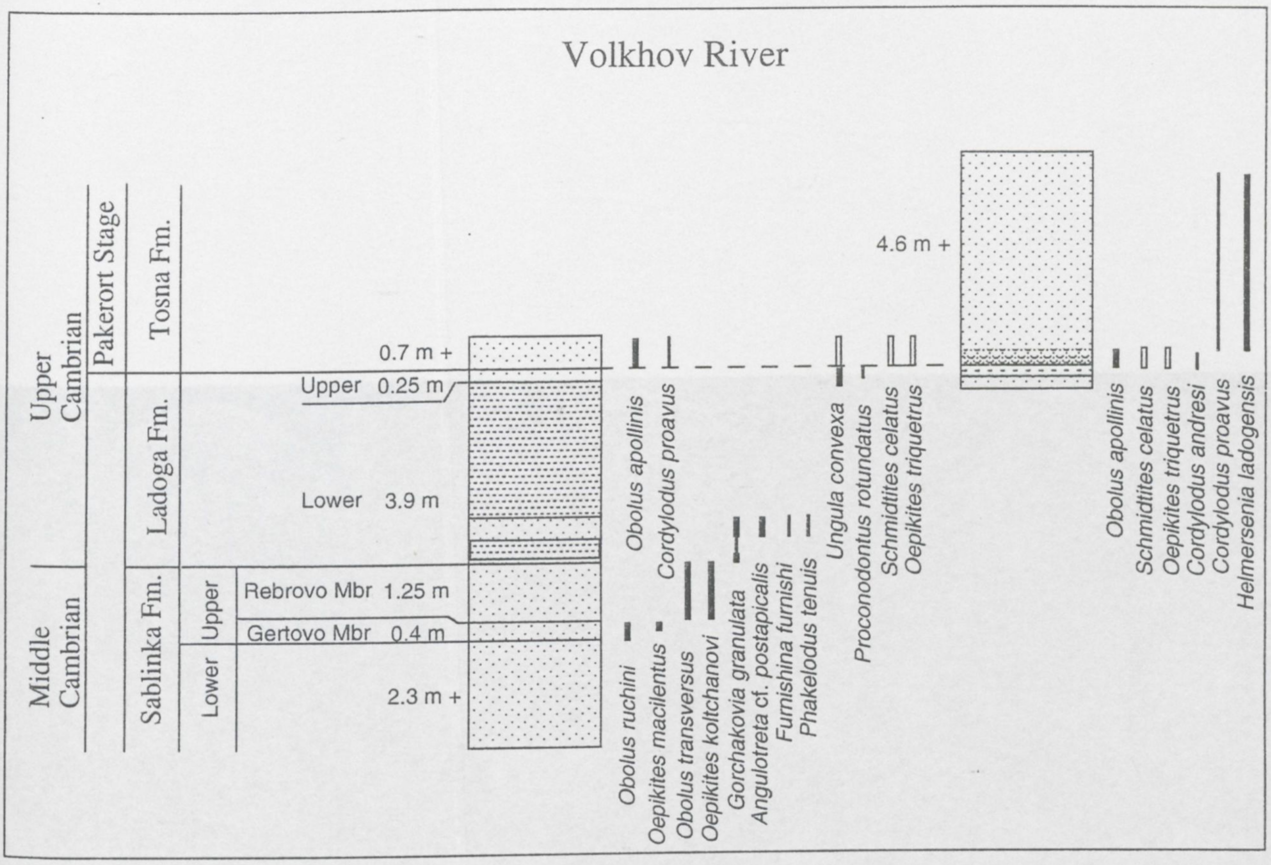

Volkhov River
Upper Cambrian
Middle Cambrian
Pakerort Stage
Tosna Fm.
Ladoga Fm.
Sablinka Fm.
Upper
Lower
Rebrovo Mbr 1.25 m
Gertovo Mbr 0.4 m
0.7 m +
Upper 0.25 m
Lower 3.9 m
2.3 m +
4.6 m +
Obolus ruchini
Oepikites macilentus
Obolus transversus
Oepikites koltchanovi
Gorchakovia granulata
Angulotreta cf. postapicalis
Furnishina furnishi
Phakelodus tenuis
Obolus apollinis
Cordylodus proavus
Ungula convexa
Proconodontus rotundatus
Schmidtites celatus
Oepikites triquetrus
Obolus apollinis
Schmidtites celatus
Oepikites triquetrus
Cordylodus andresi
Cordylodus proavus
Helmersenia ladogensis

Fig. 48

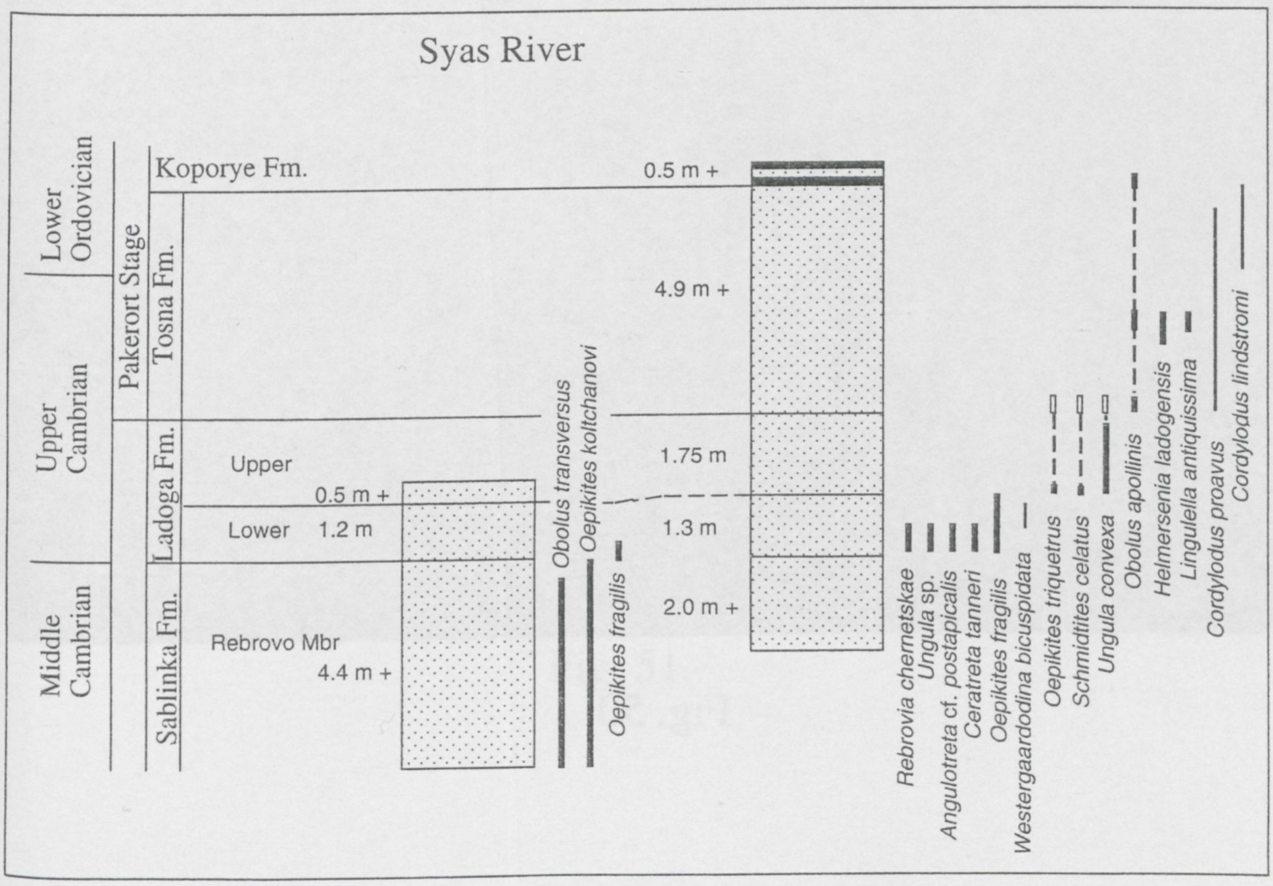

Syas River
Lower Ordovician
Upper Cambrian
Middle Cambrian
Pakerort Stage
Koporye Fm.
Tosna Fm.
Ladoga Fm.
Sablinka Fm.
Upper
Lower 1.2 m
Rebrovo Mbr
0.5 m +
4.4 m +
0.5 m +
4.9 m +
1.75 m
1.3 m
2.0 m +
Obolus transversus
Oepikites koltchanovi
Oepikites fragilis
Rebrovia chernetskae
Ungula sp.
Angulotreta cf. postapicalis
Ceratreta tanneri
Oepikites fragilis
Westergaardodina bicuspidata
Oepikites triquetrus
Schmidtites celatus
Ungula convexa
Obolus apollinis
Helmersenia ladogensis
Lingulella antiquissima
Cordylodus proavus
Cordylodus lindstromi

Fig. 49

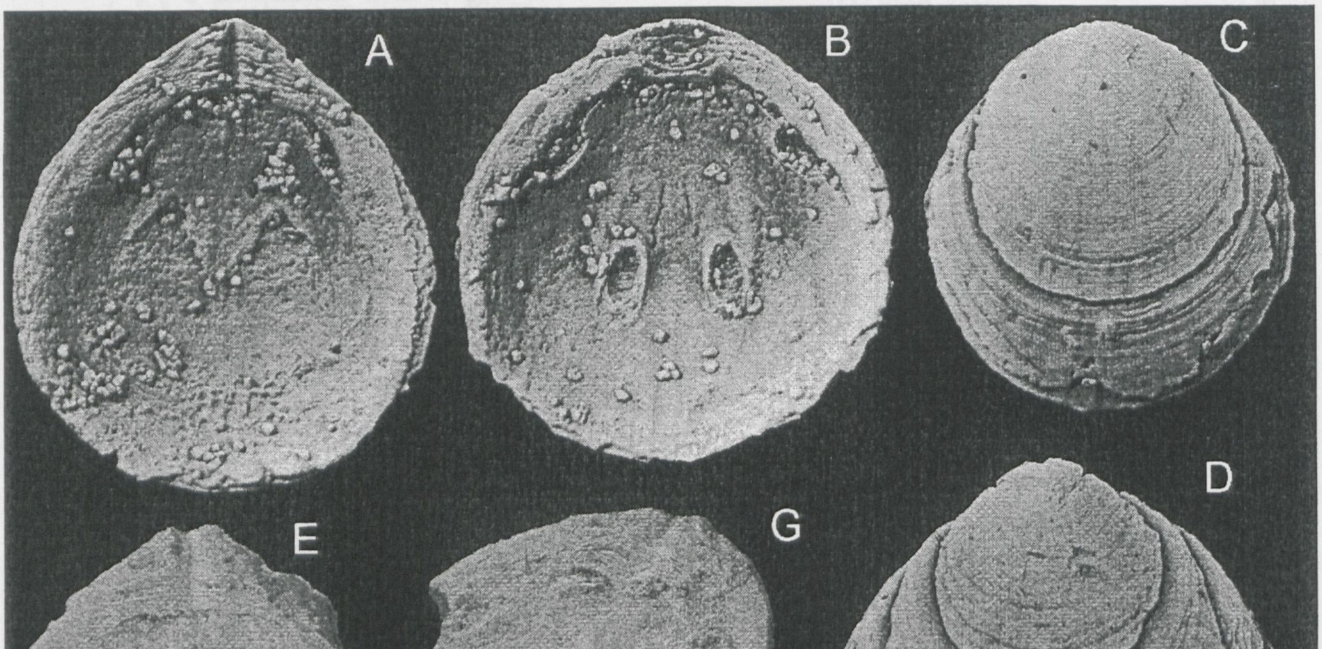


Fig. 50

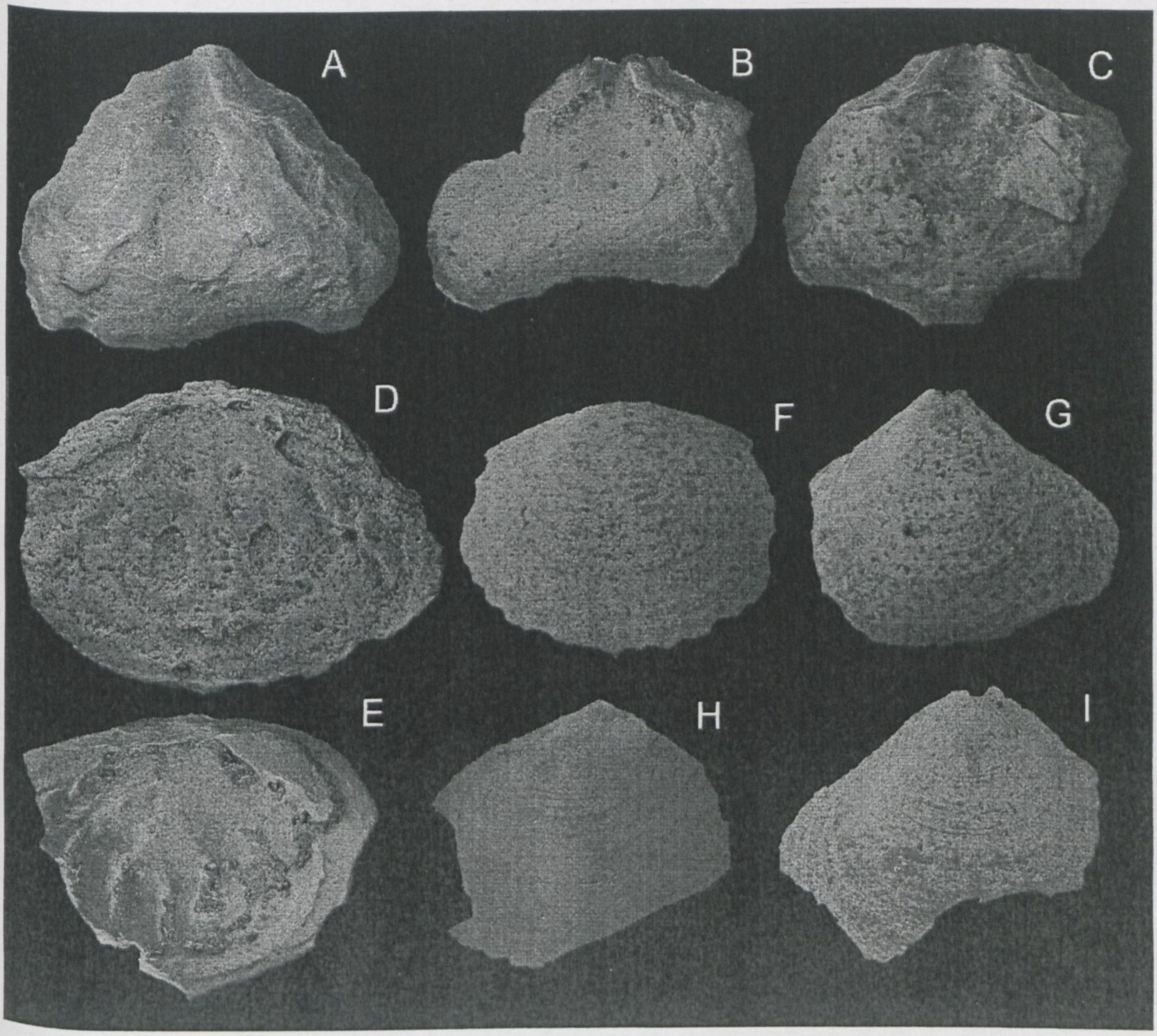


Fig. 51

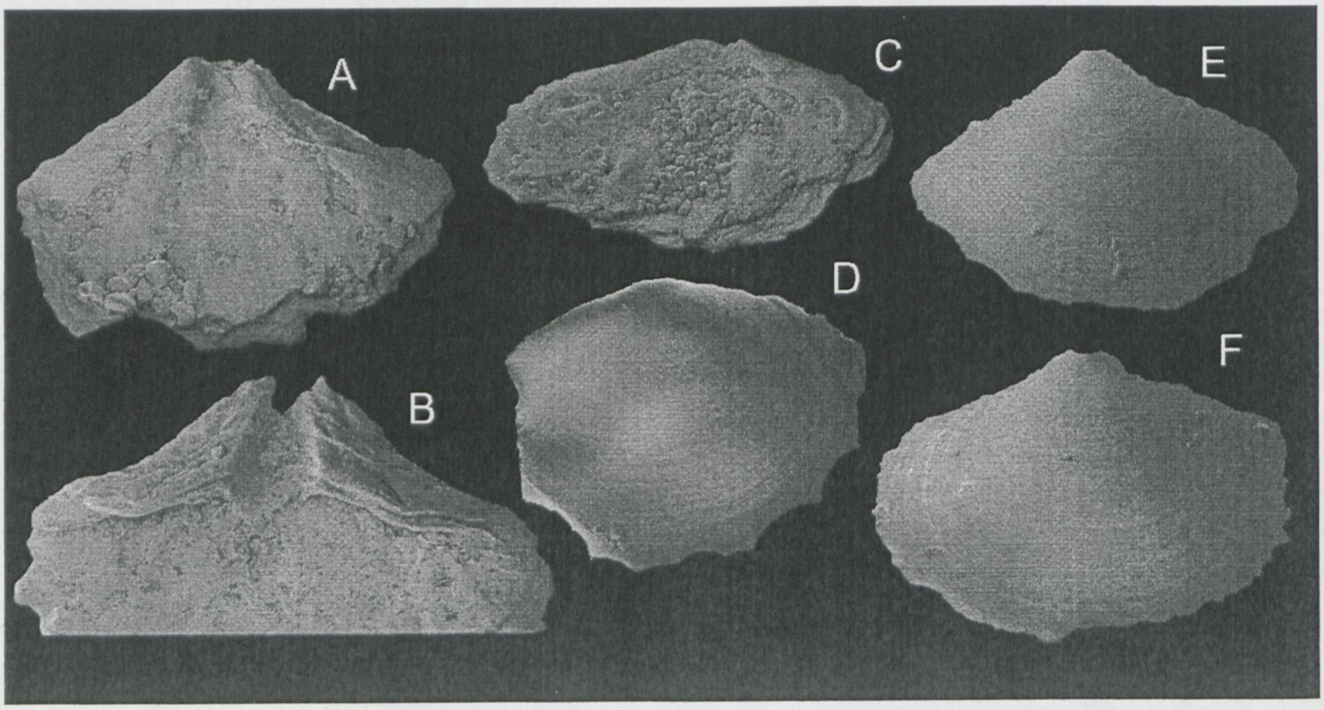


Fig. 52

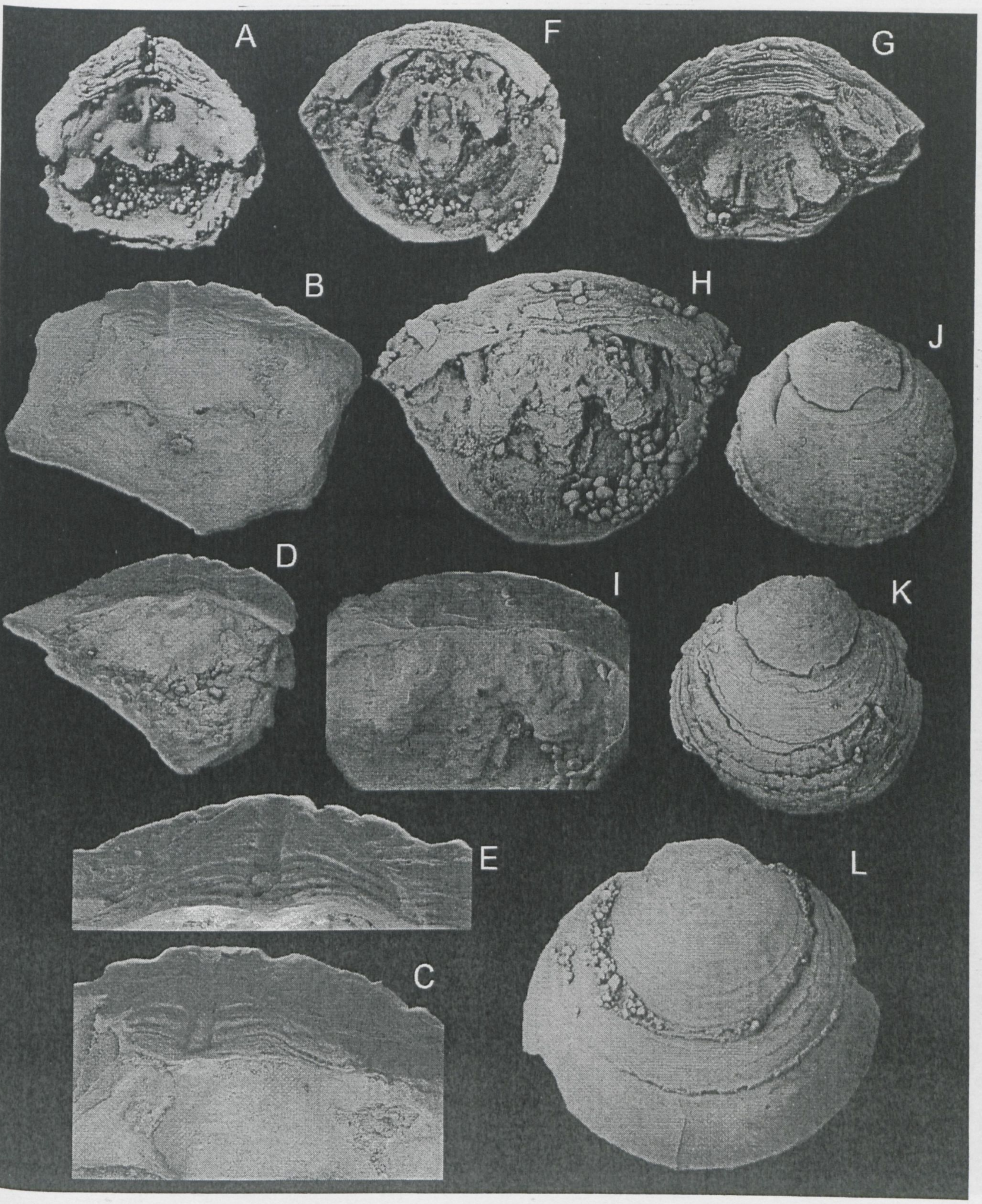


Fig. 53

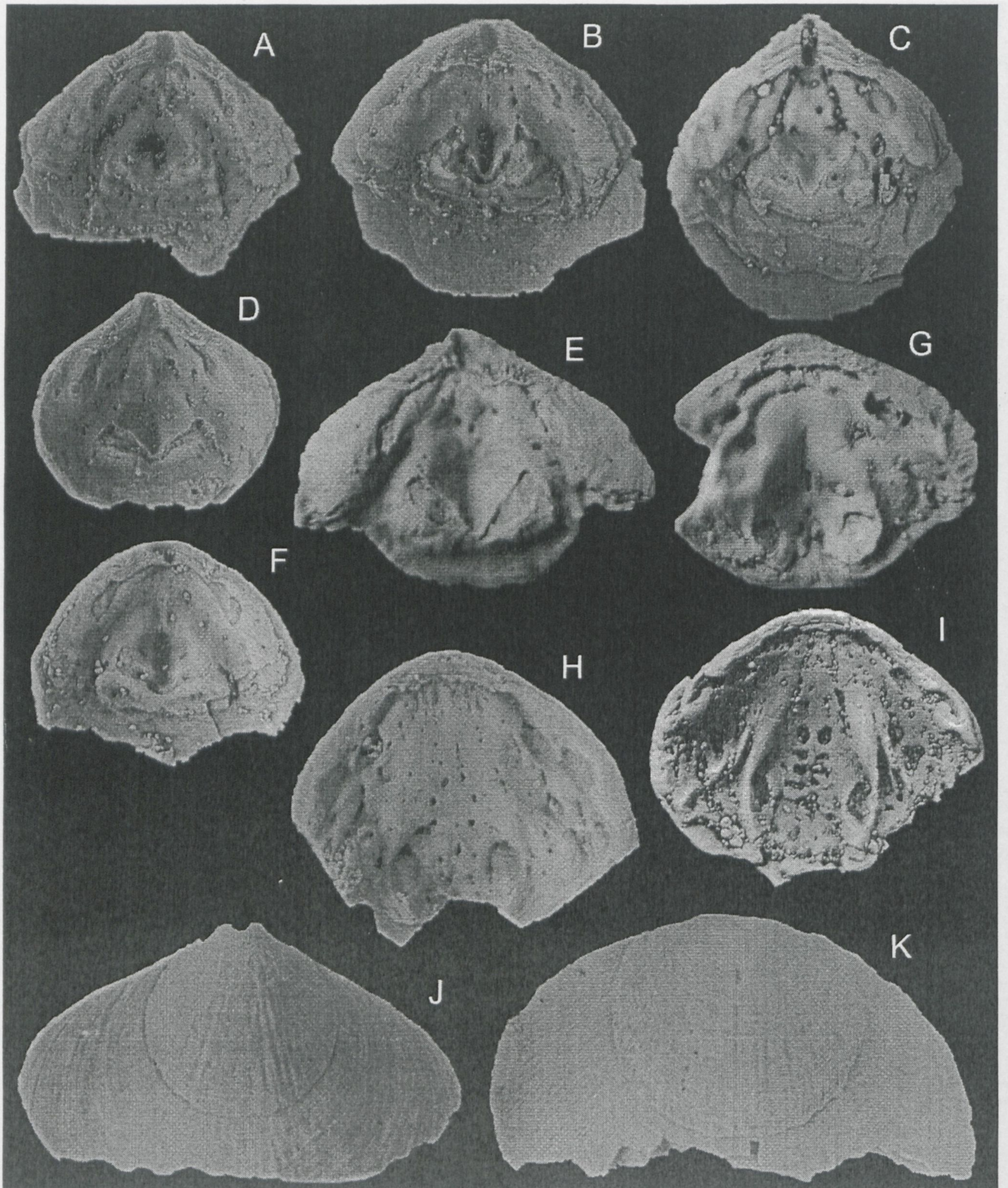


Fig. 54

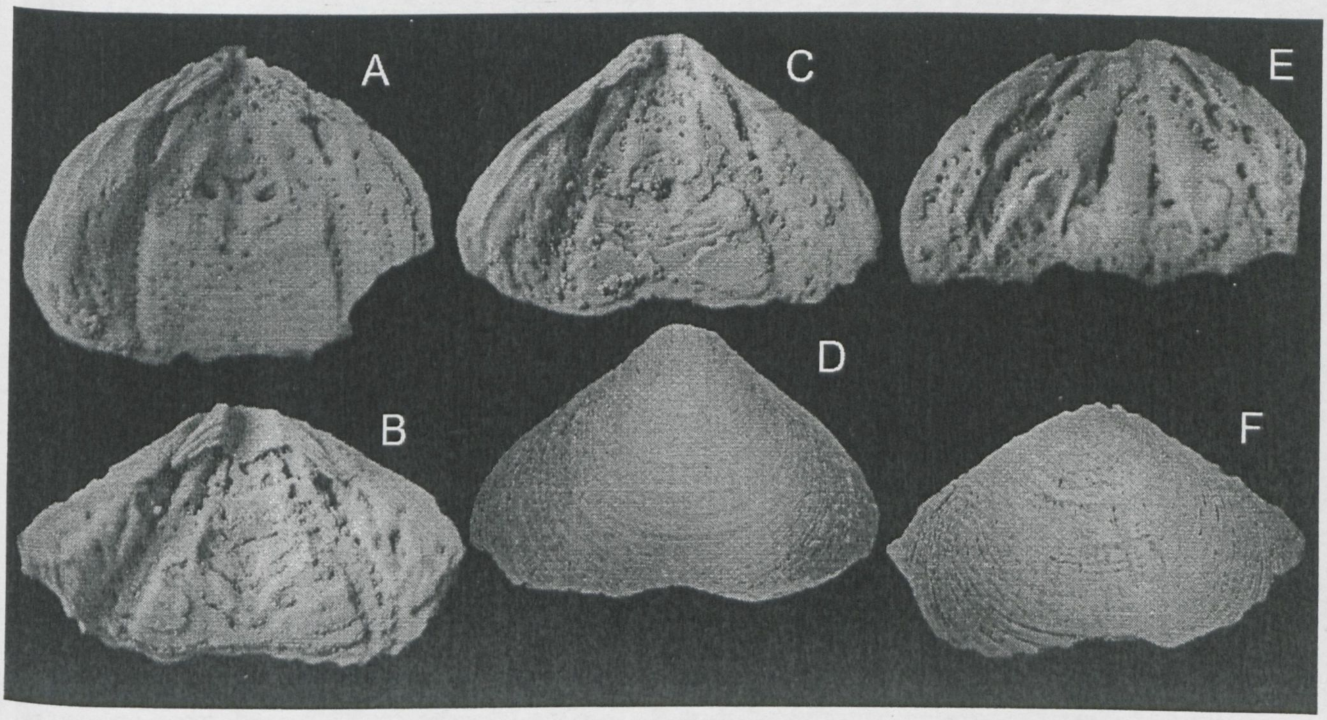


Fig. 55

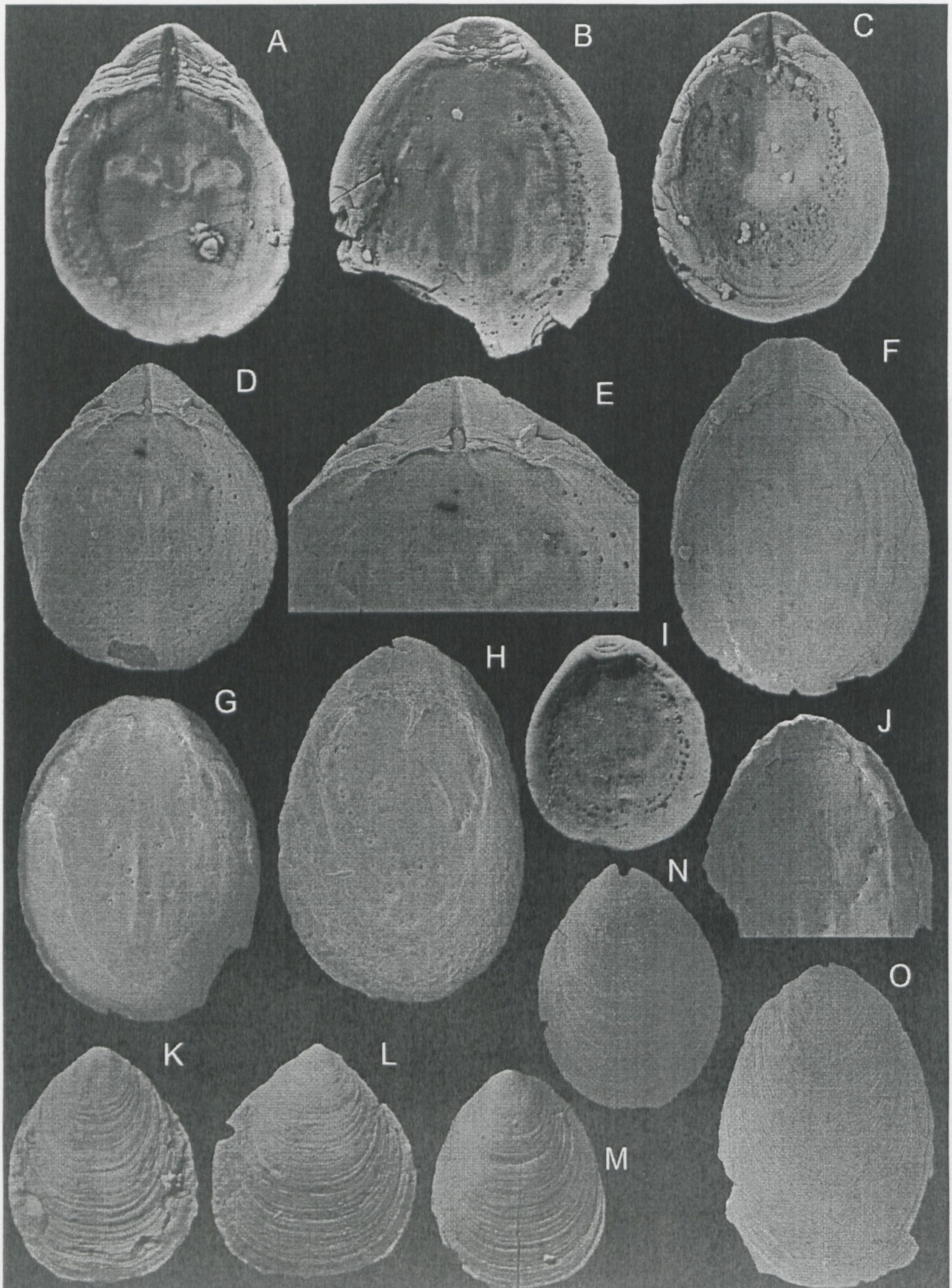


Fig. 56

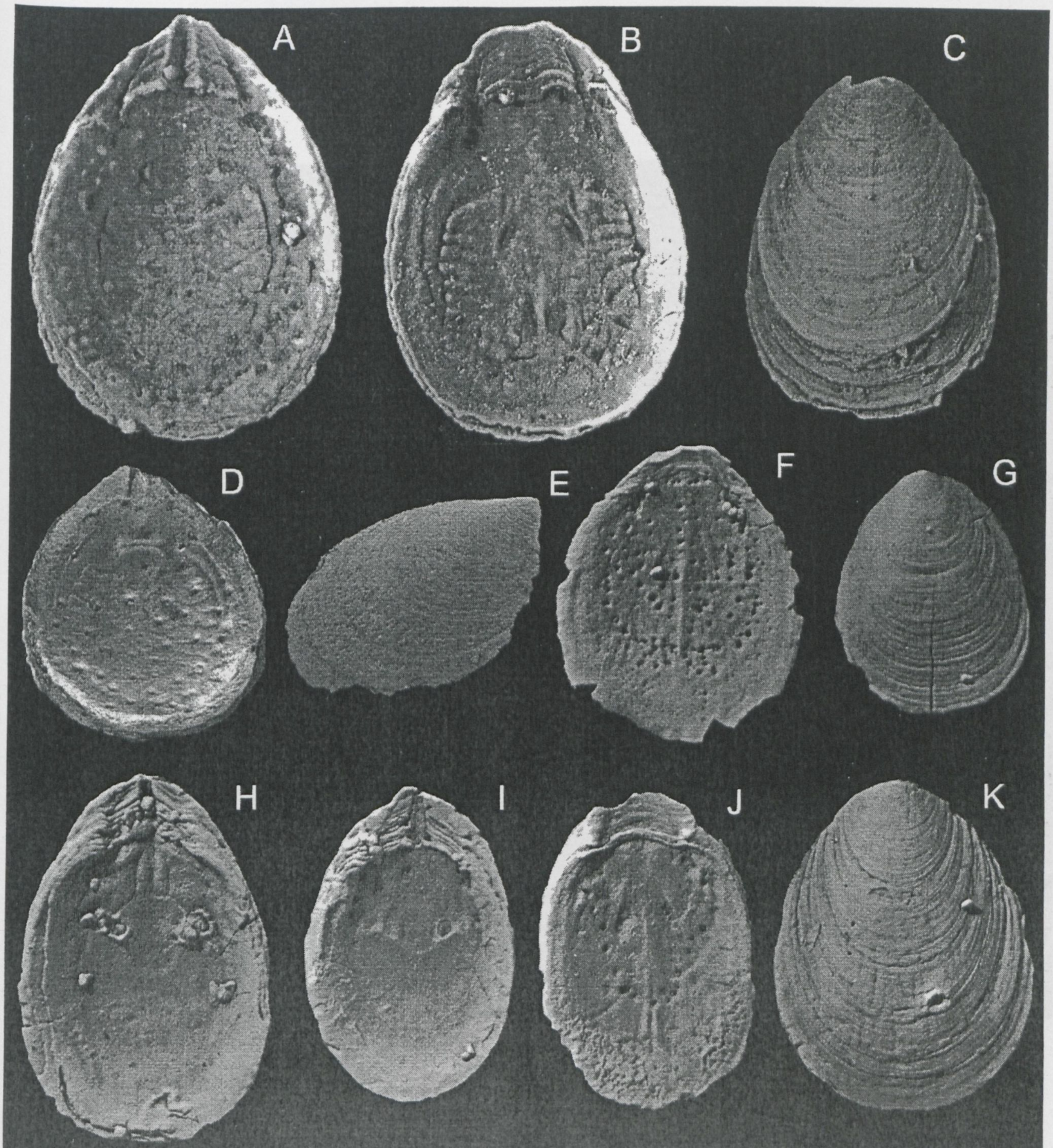


Fig. 57

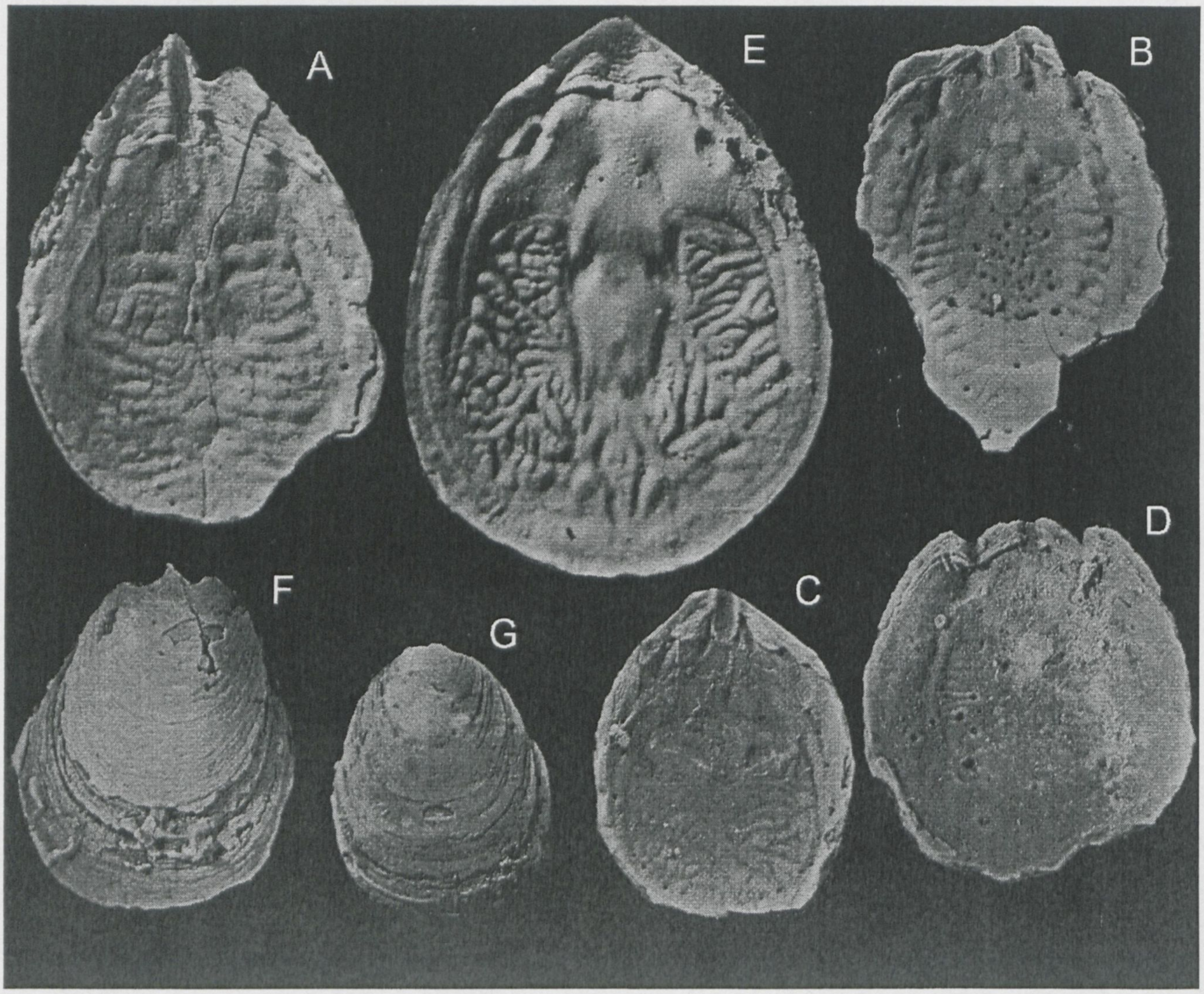


Fig. 58

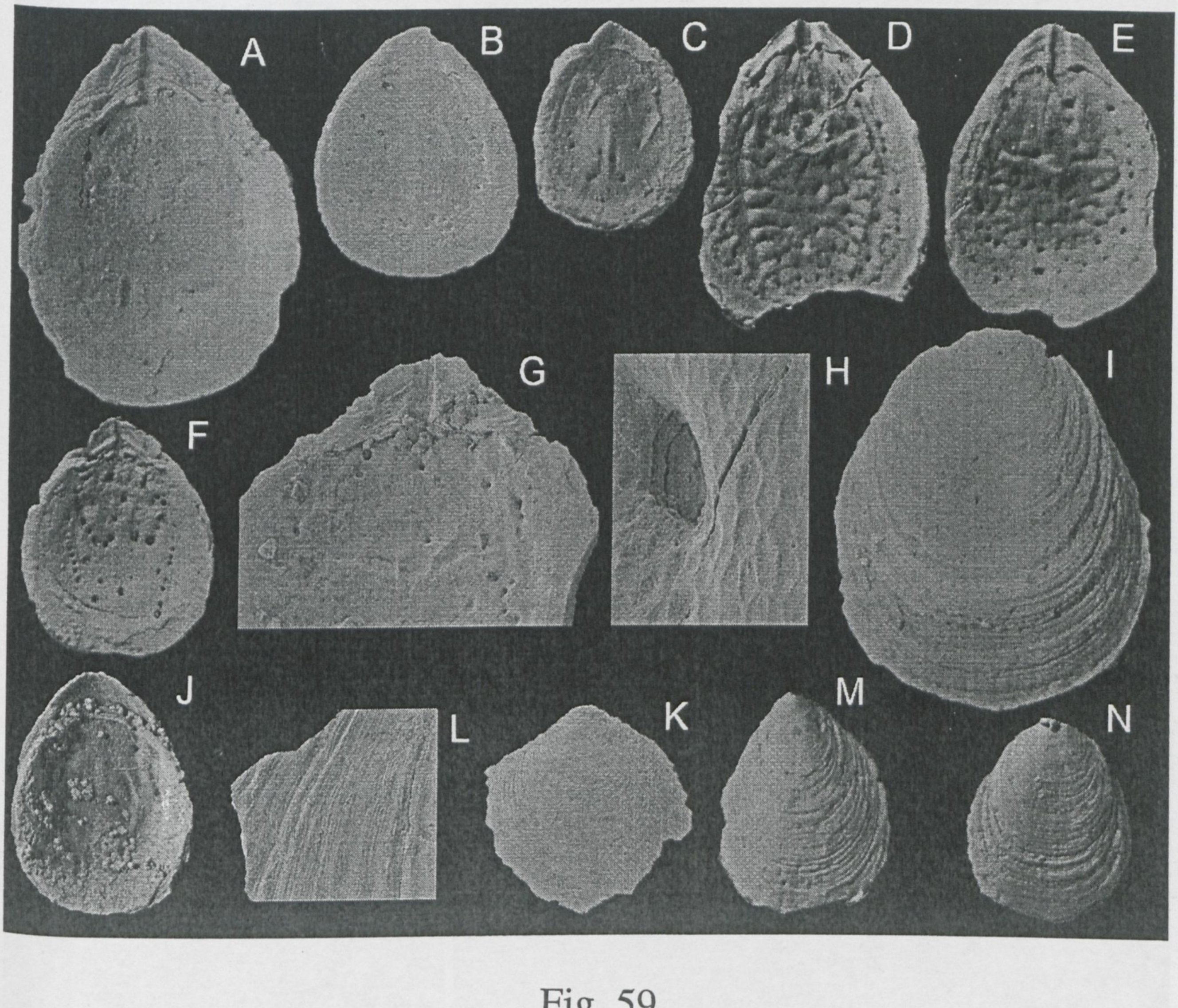


Fig. 59

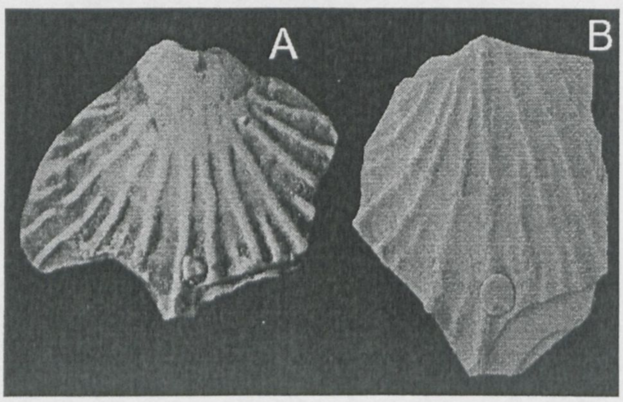


Fig. 60

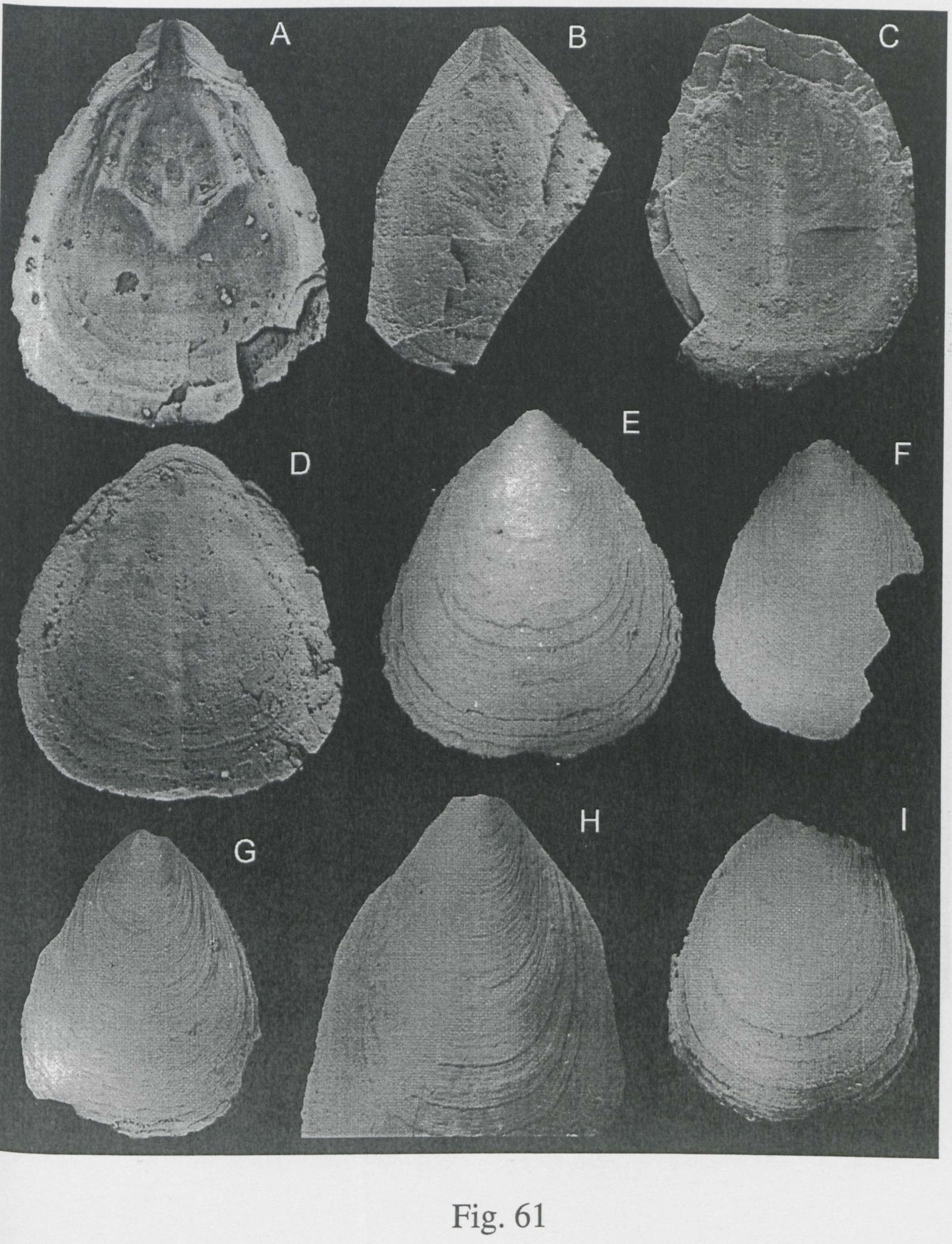


Fig. 61

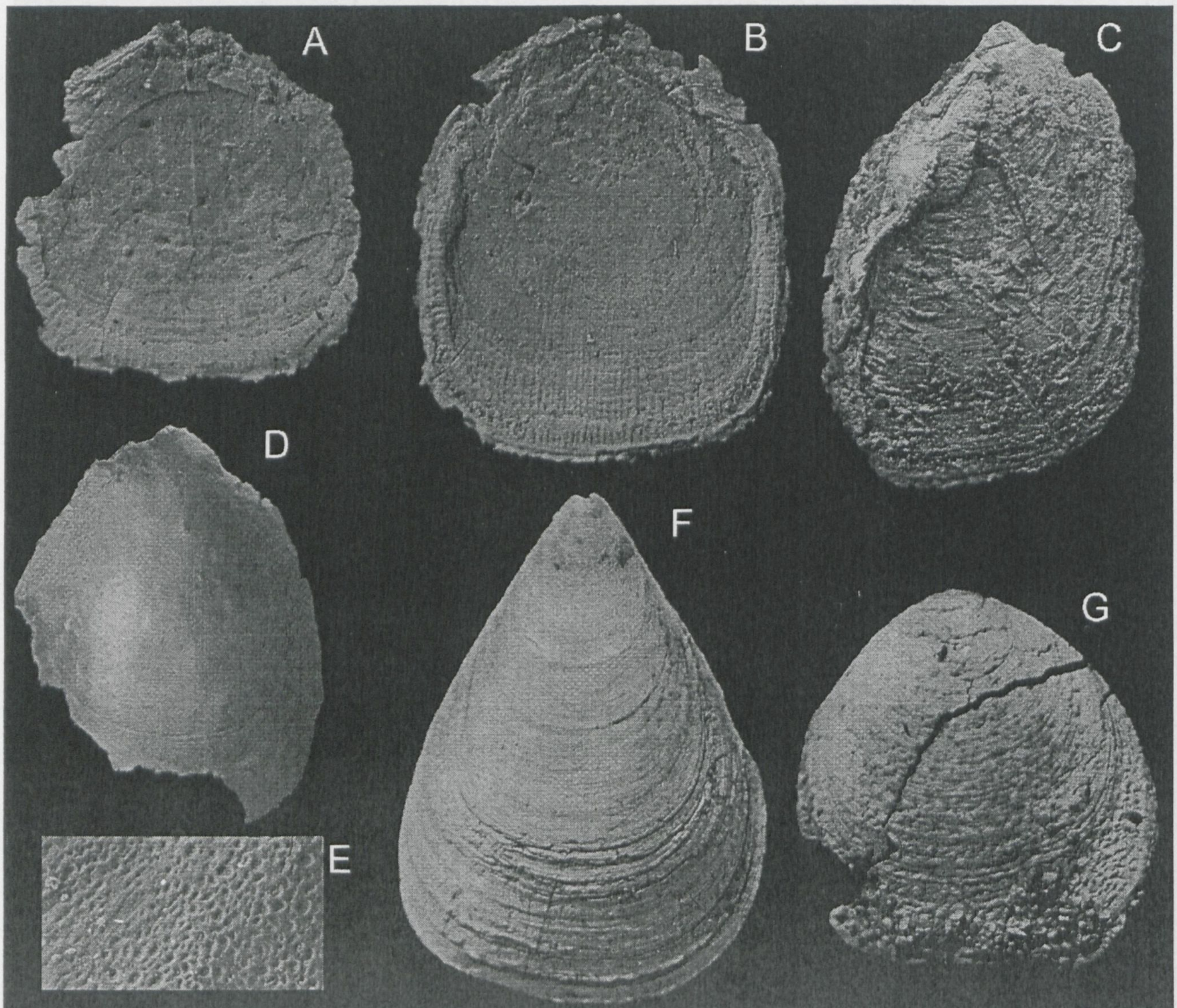


Fig. 62

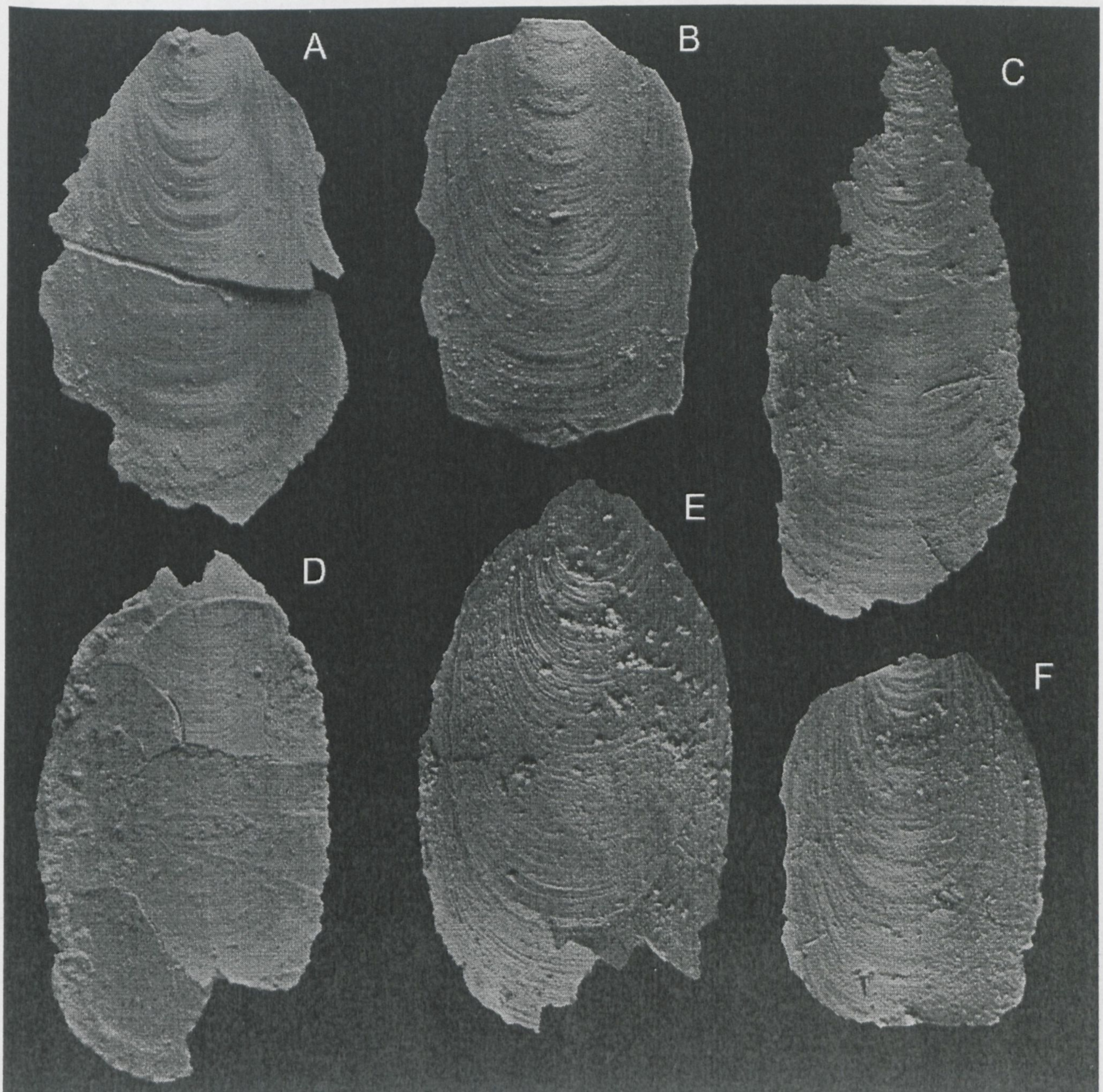


Fig. 63

187

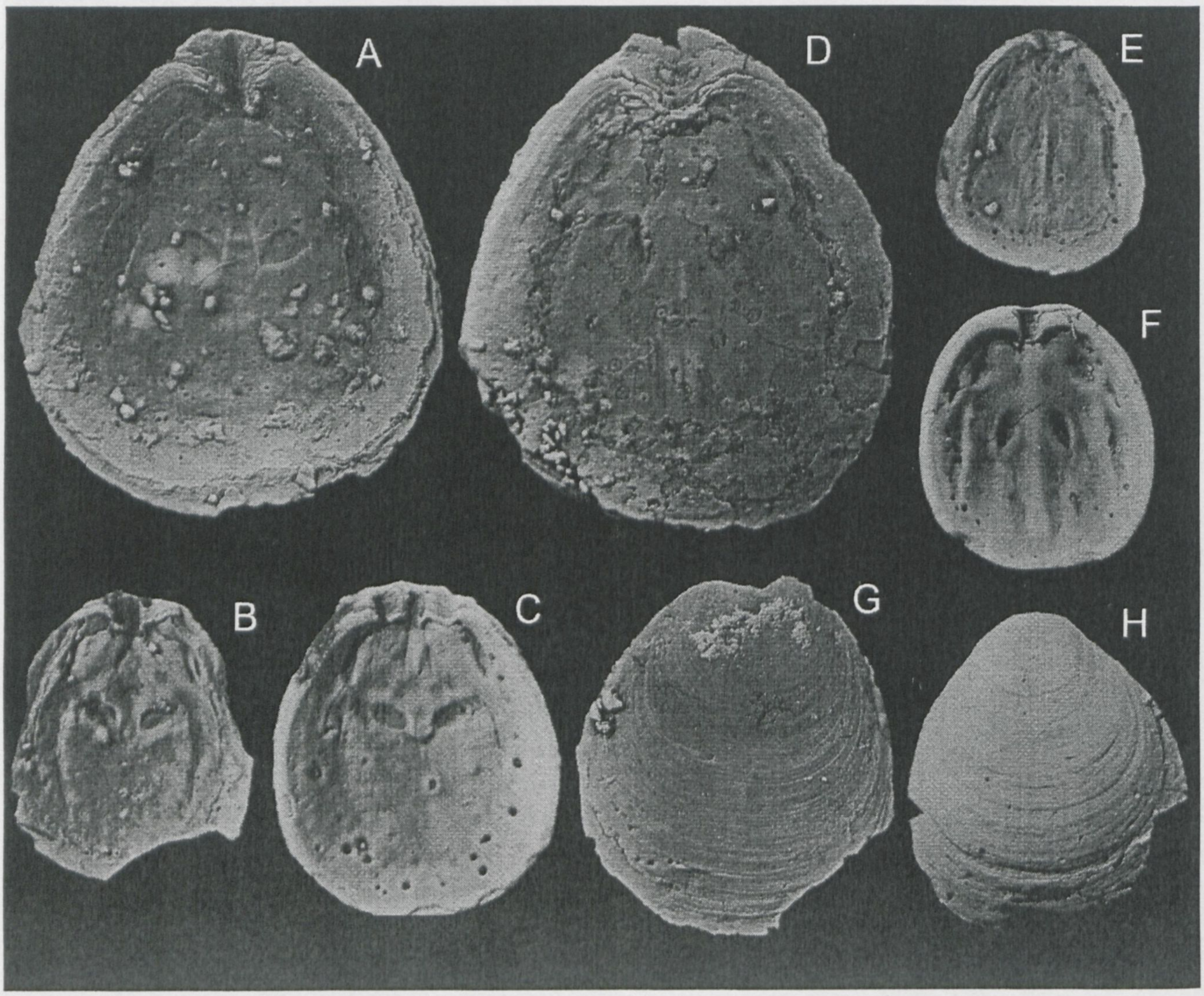


Fig. 64

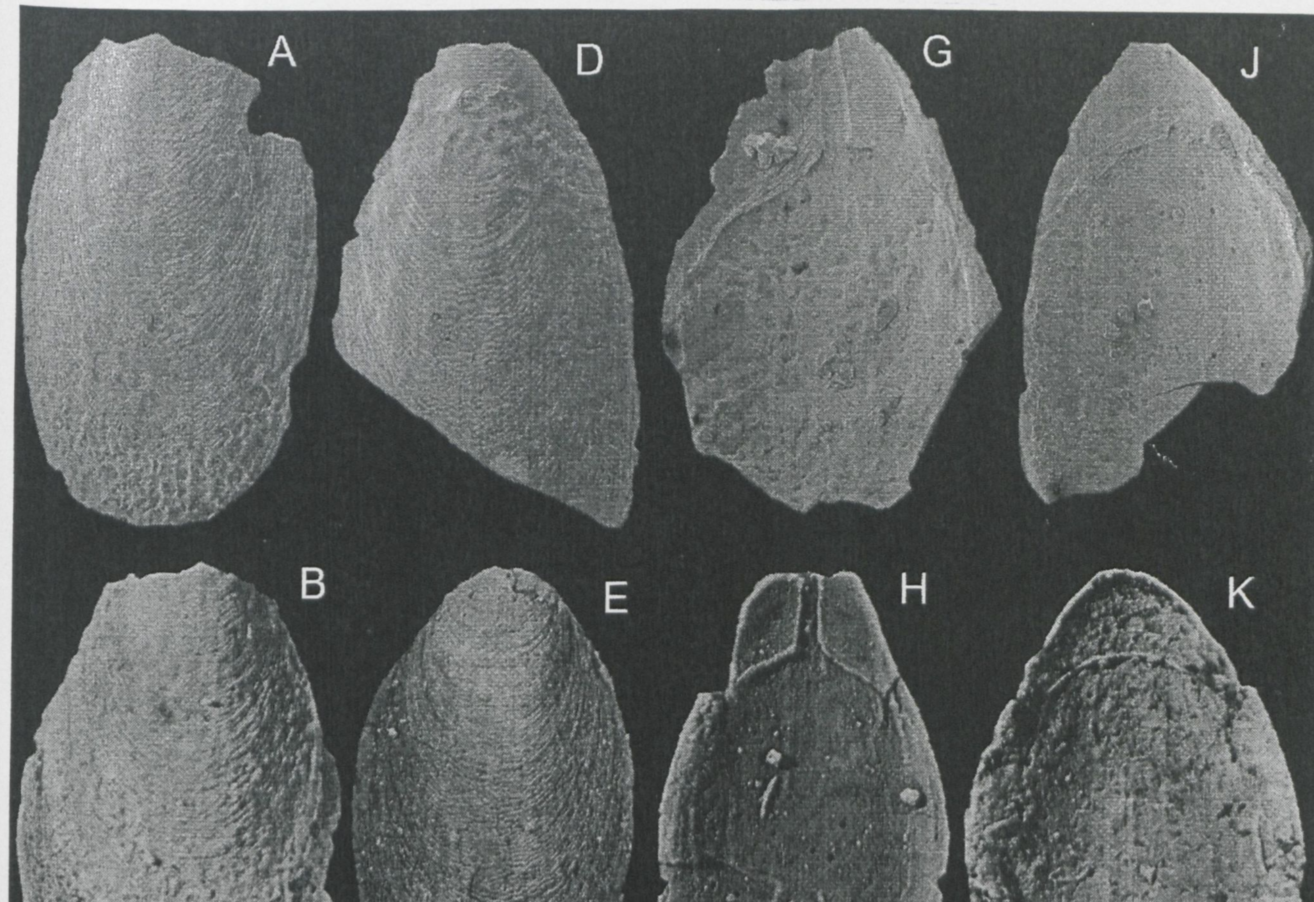


Fig. 65

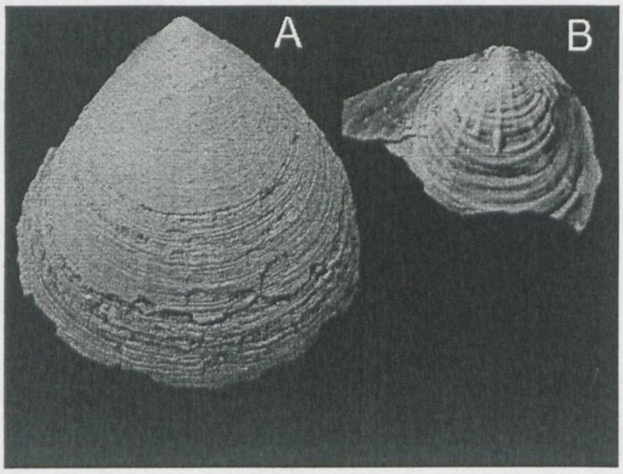
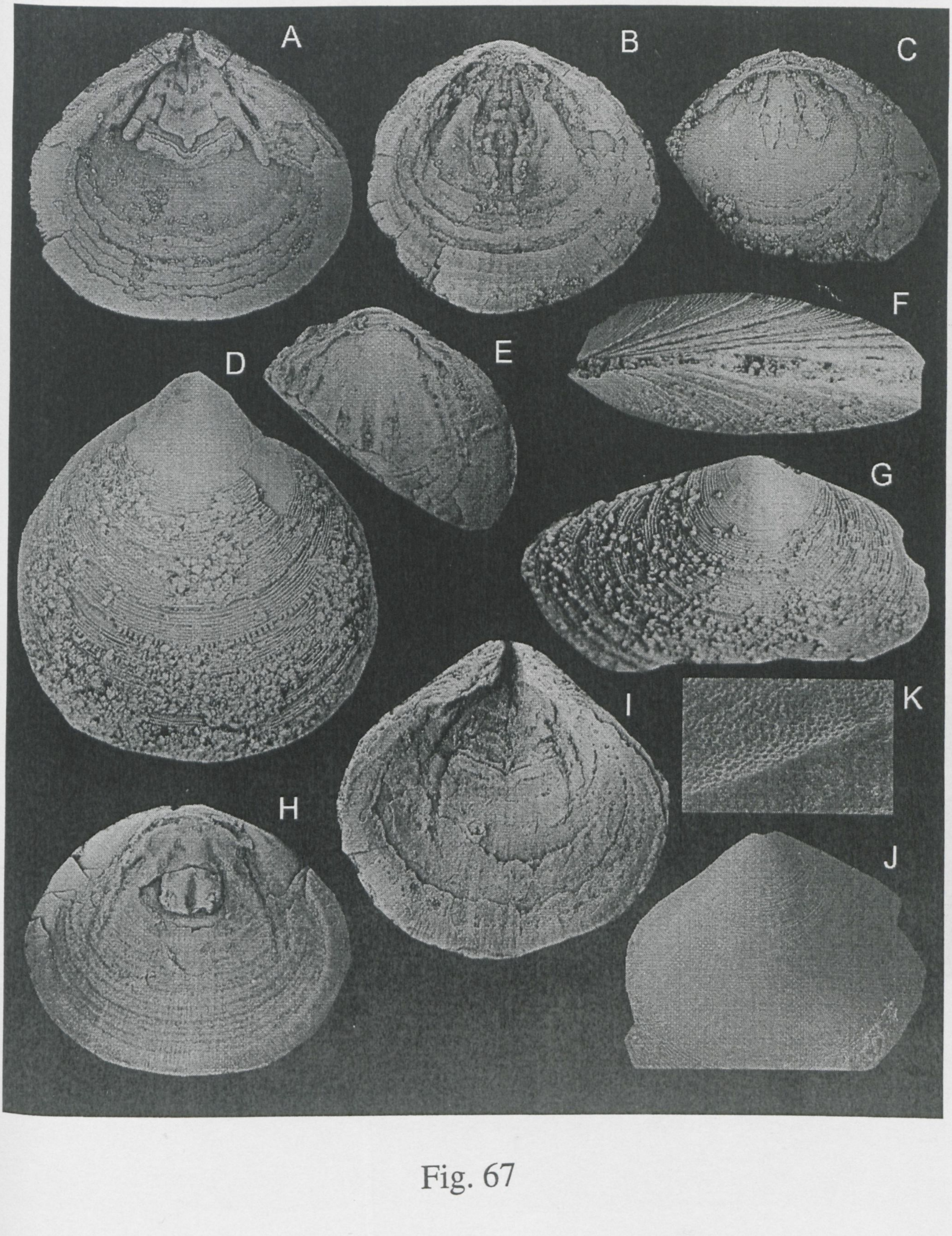


Fig. 66



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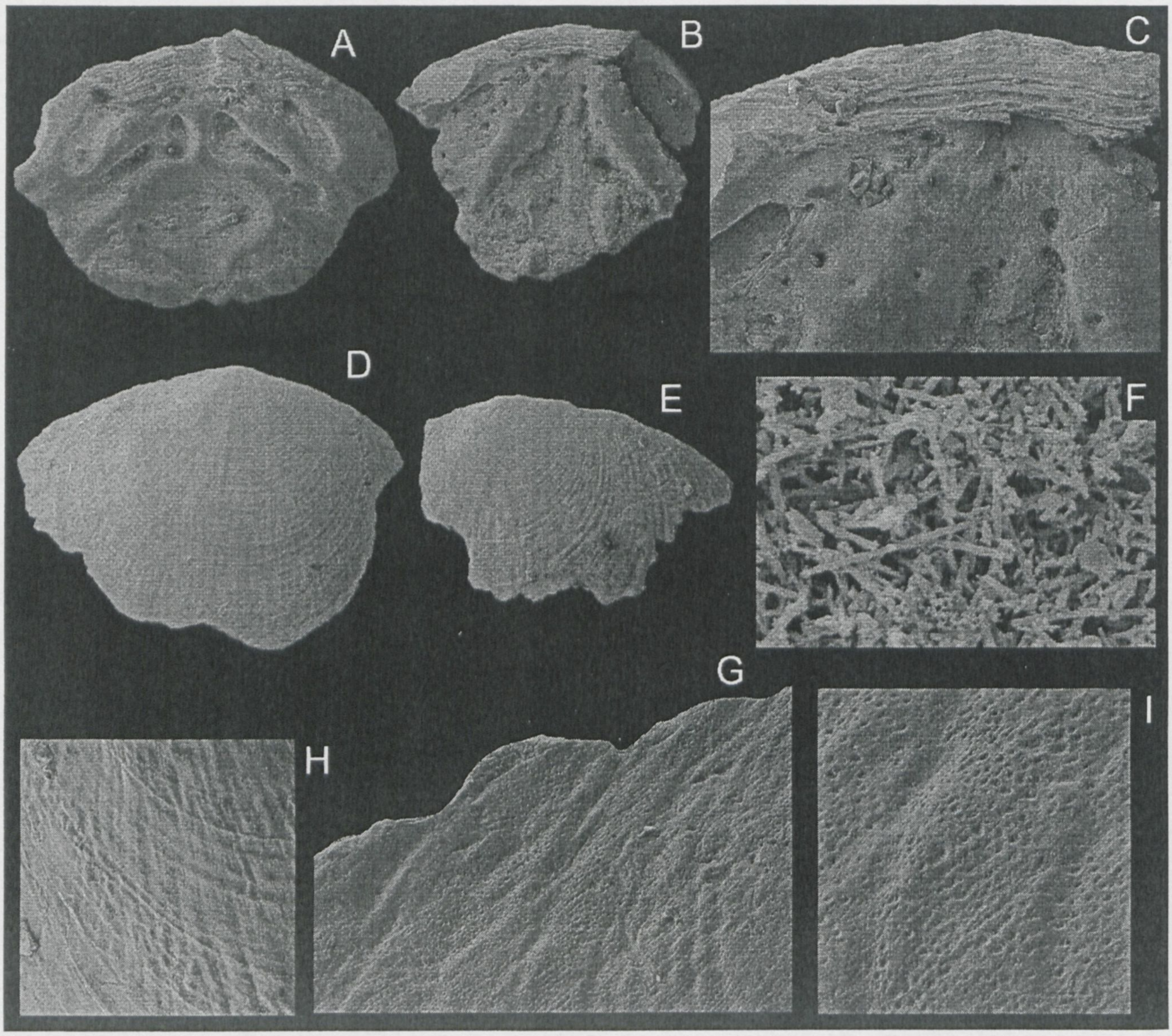

Fig. 68

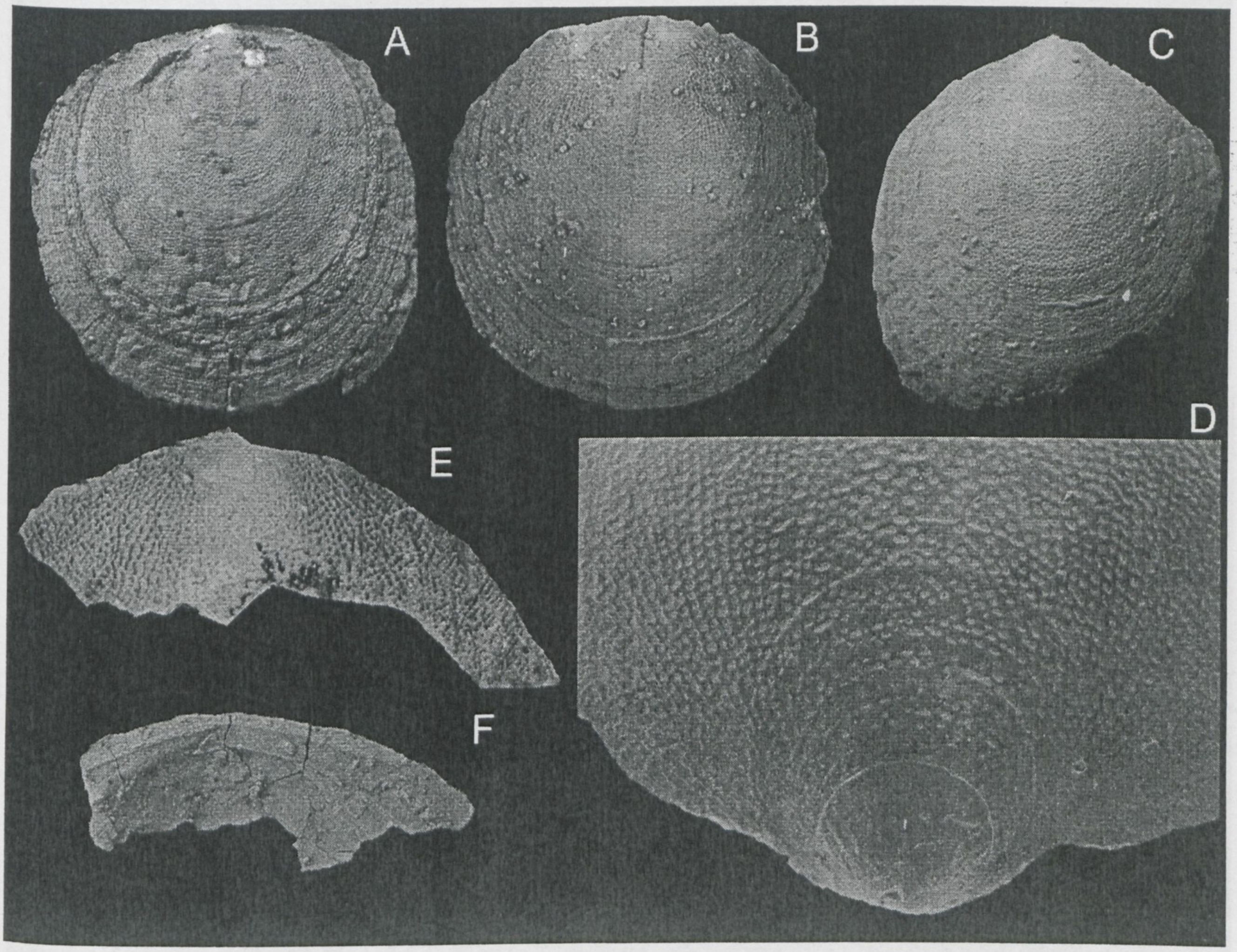

Fig. 69

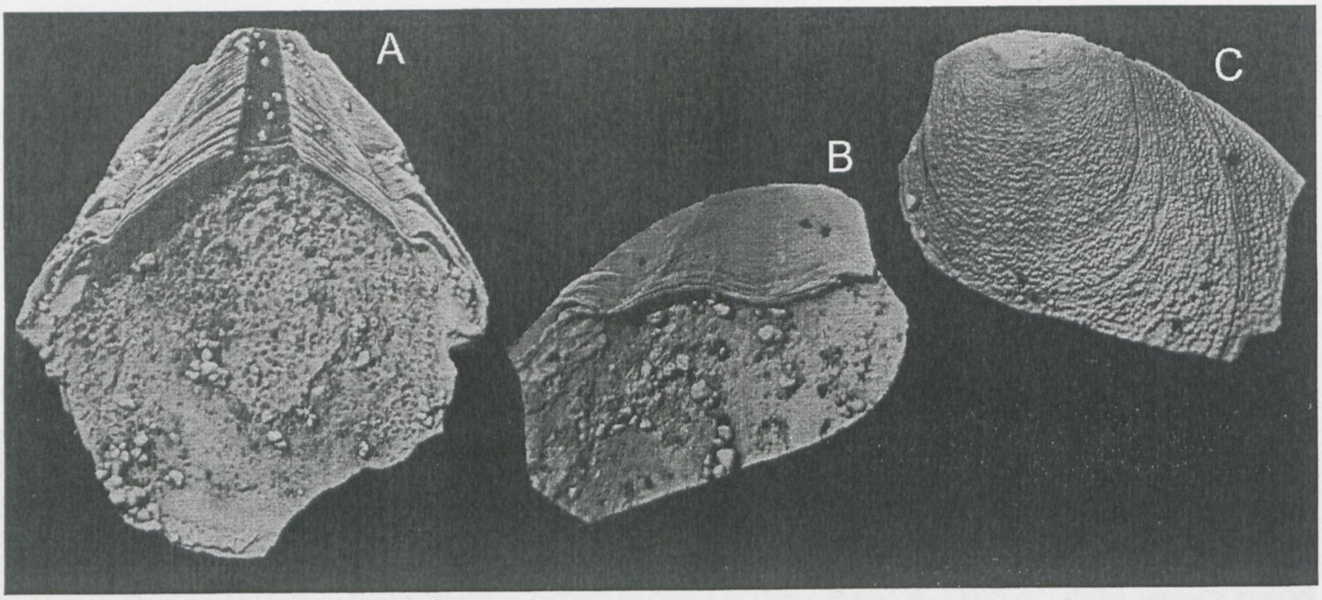

Fig. 70

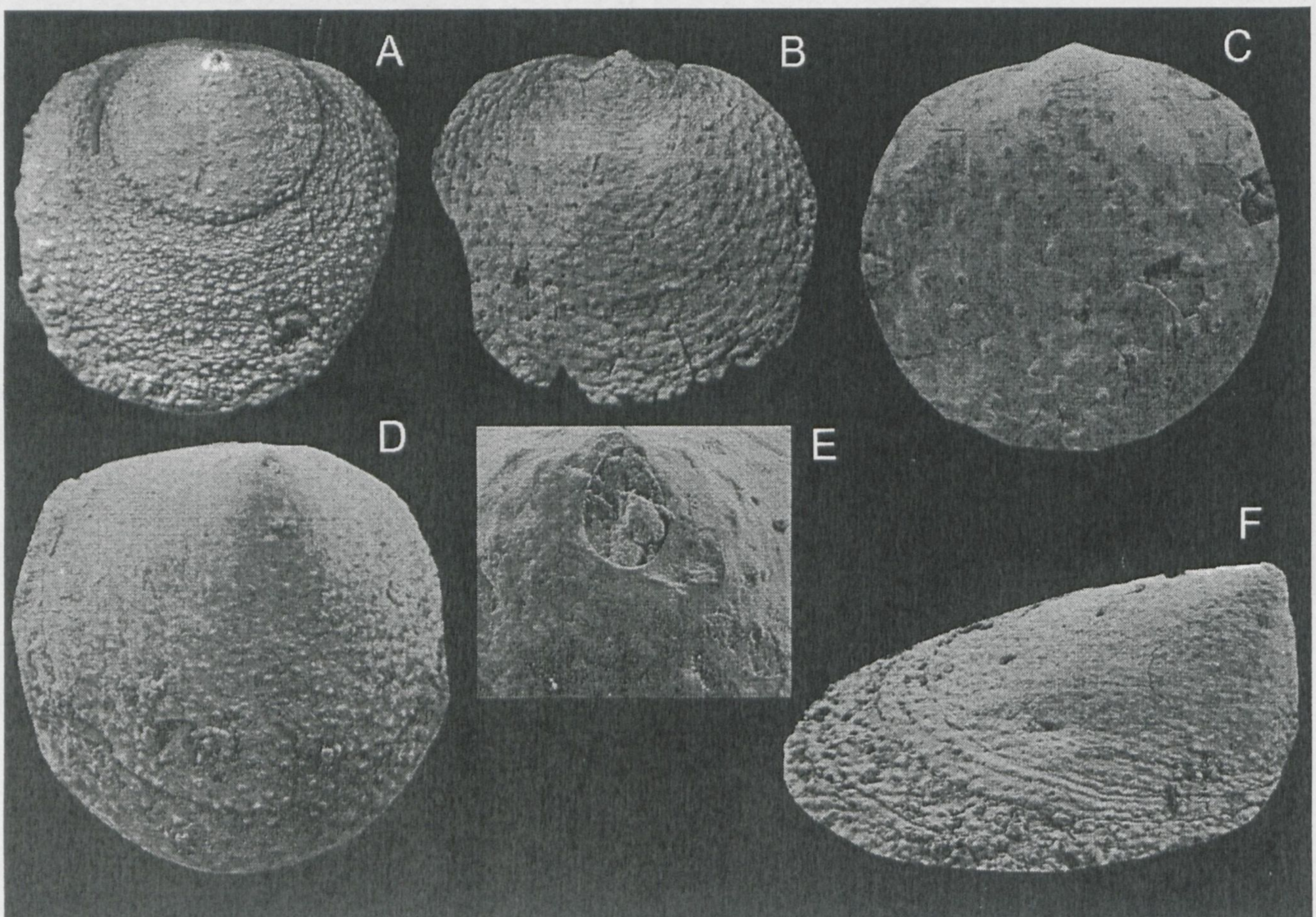

Fig. 71

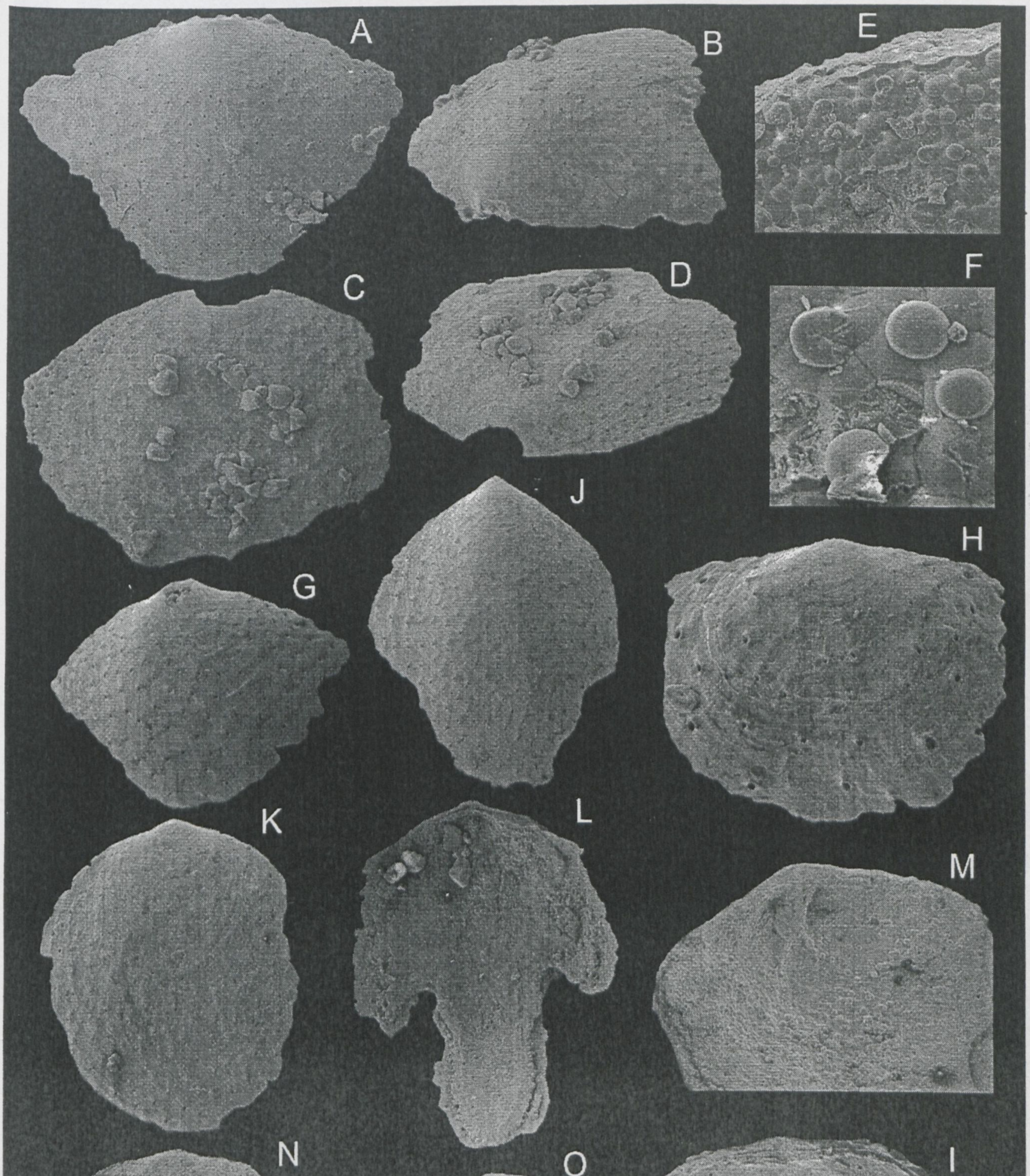

Fig. 72

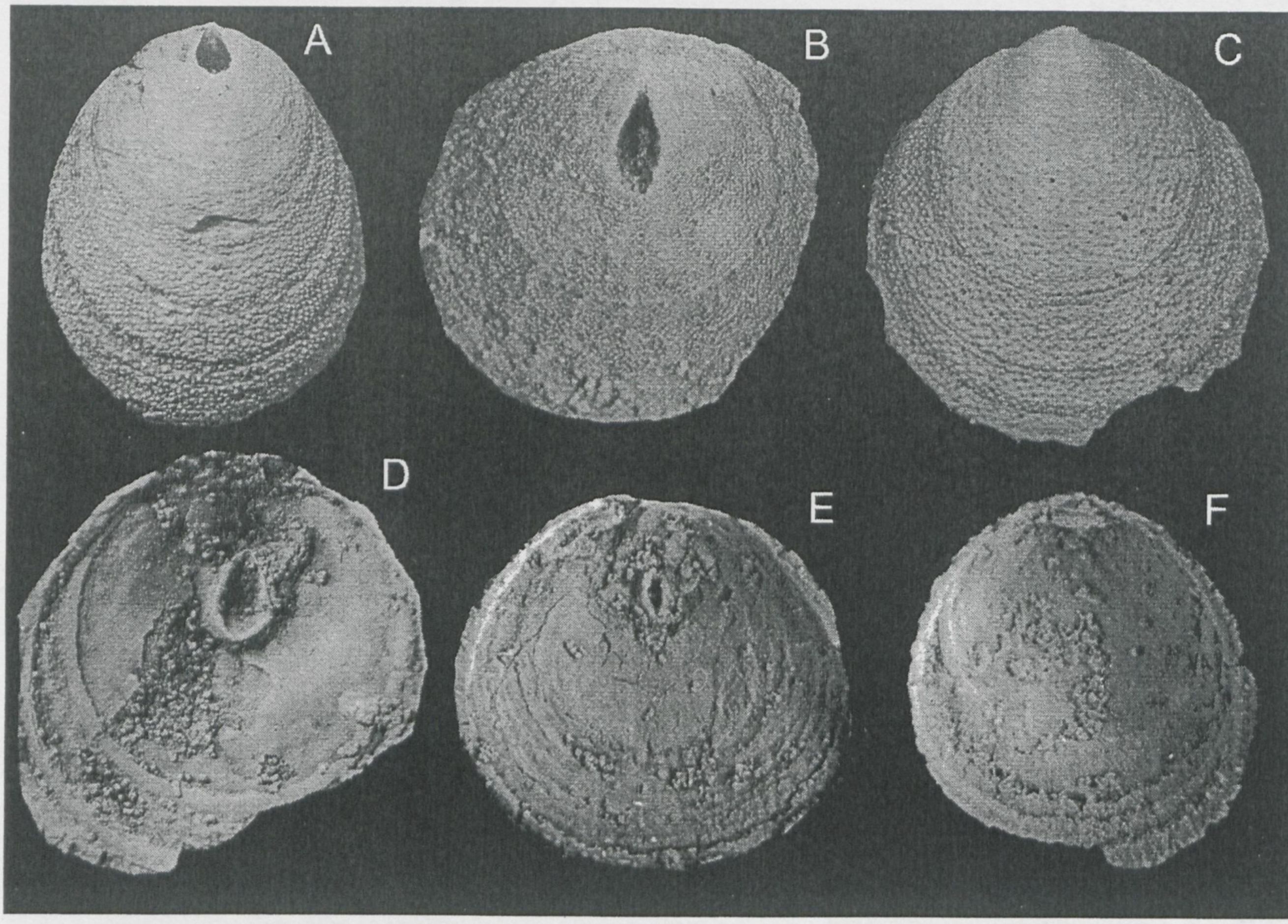

Fig. 73

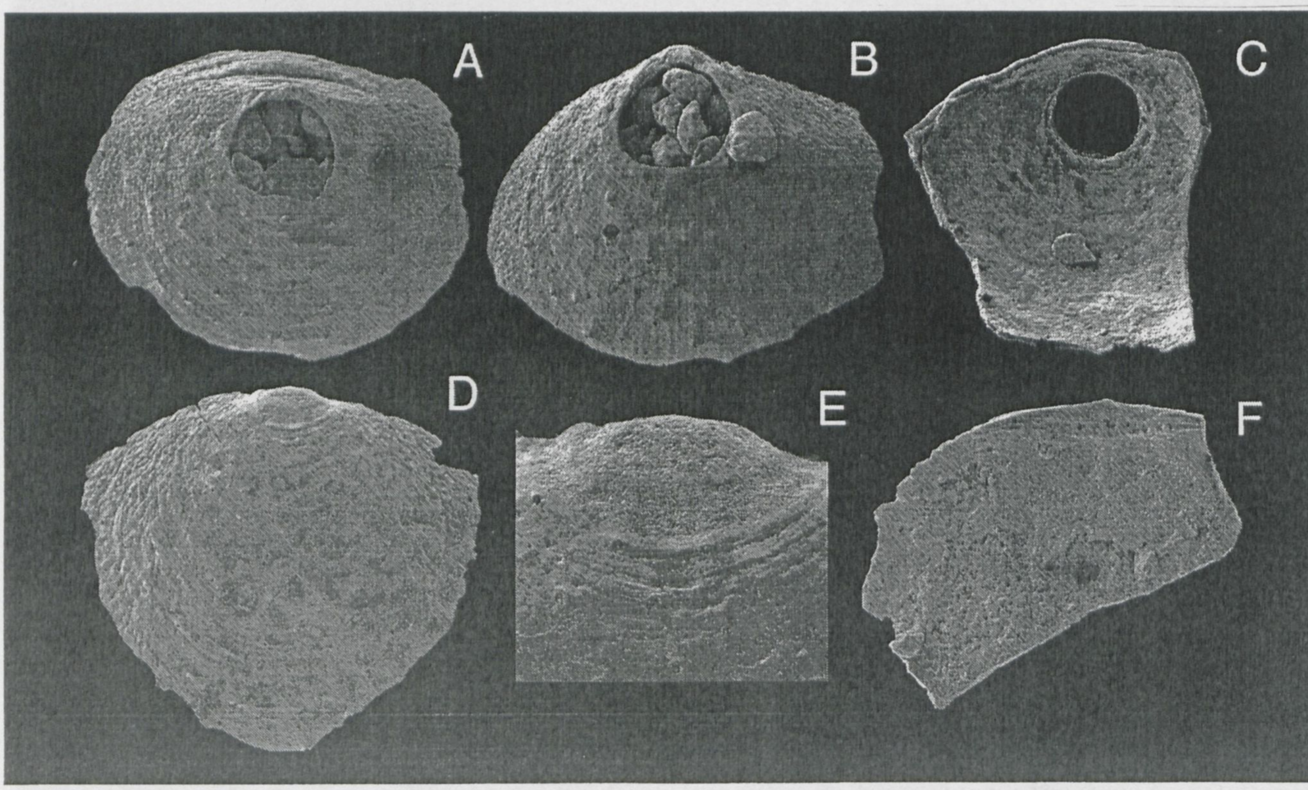

Fig. 74

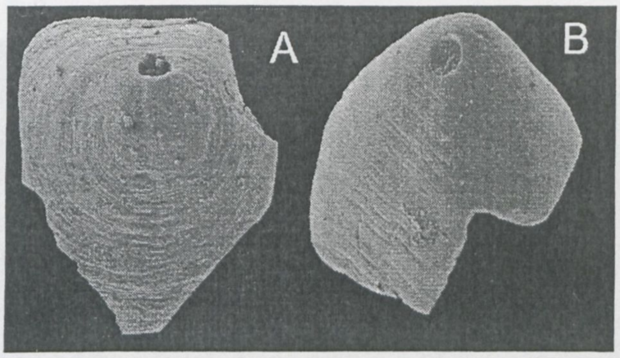

Fig. 75

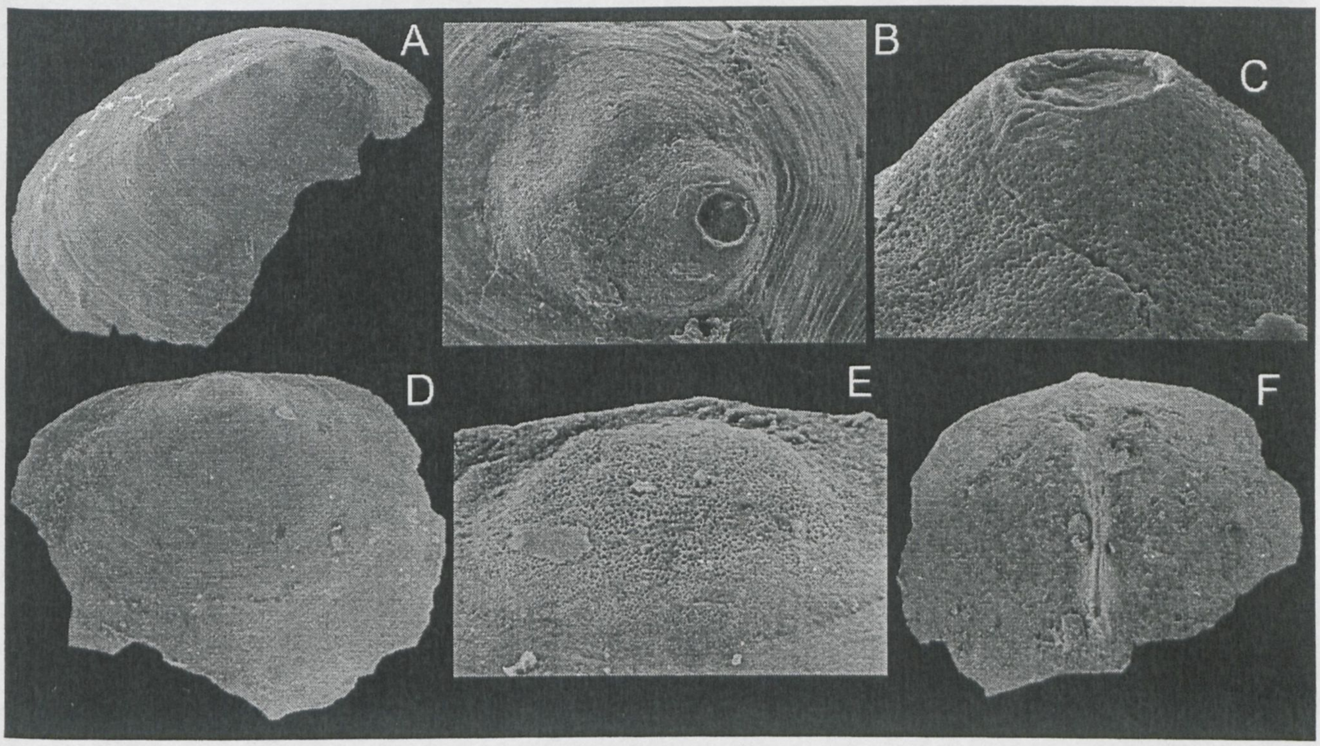

Fig. 76

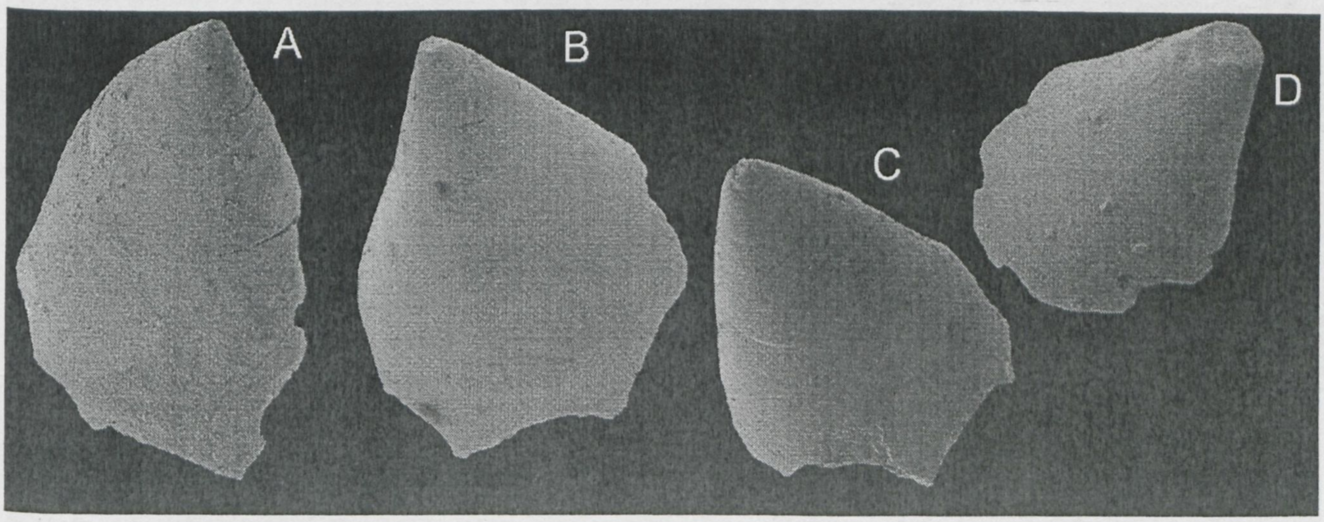

Fig. 77

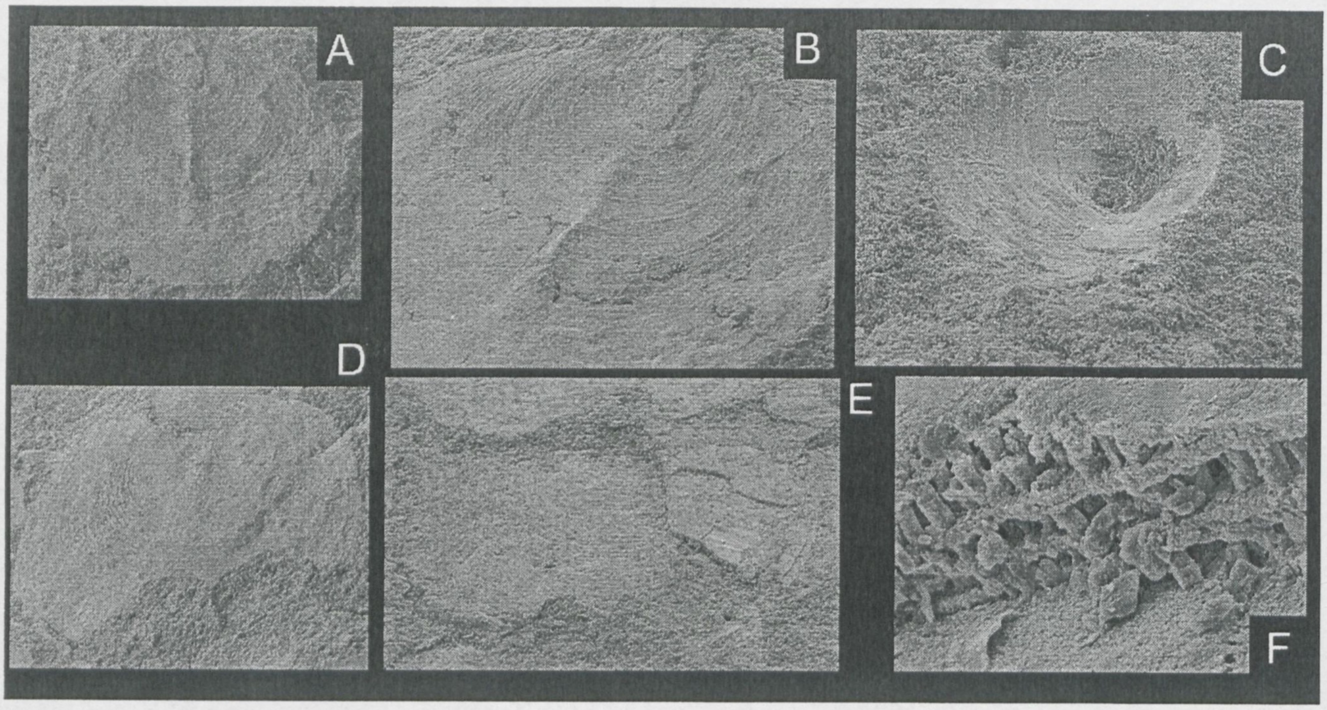

Fig. 78

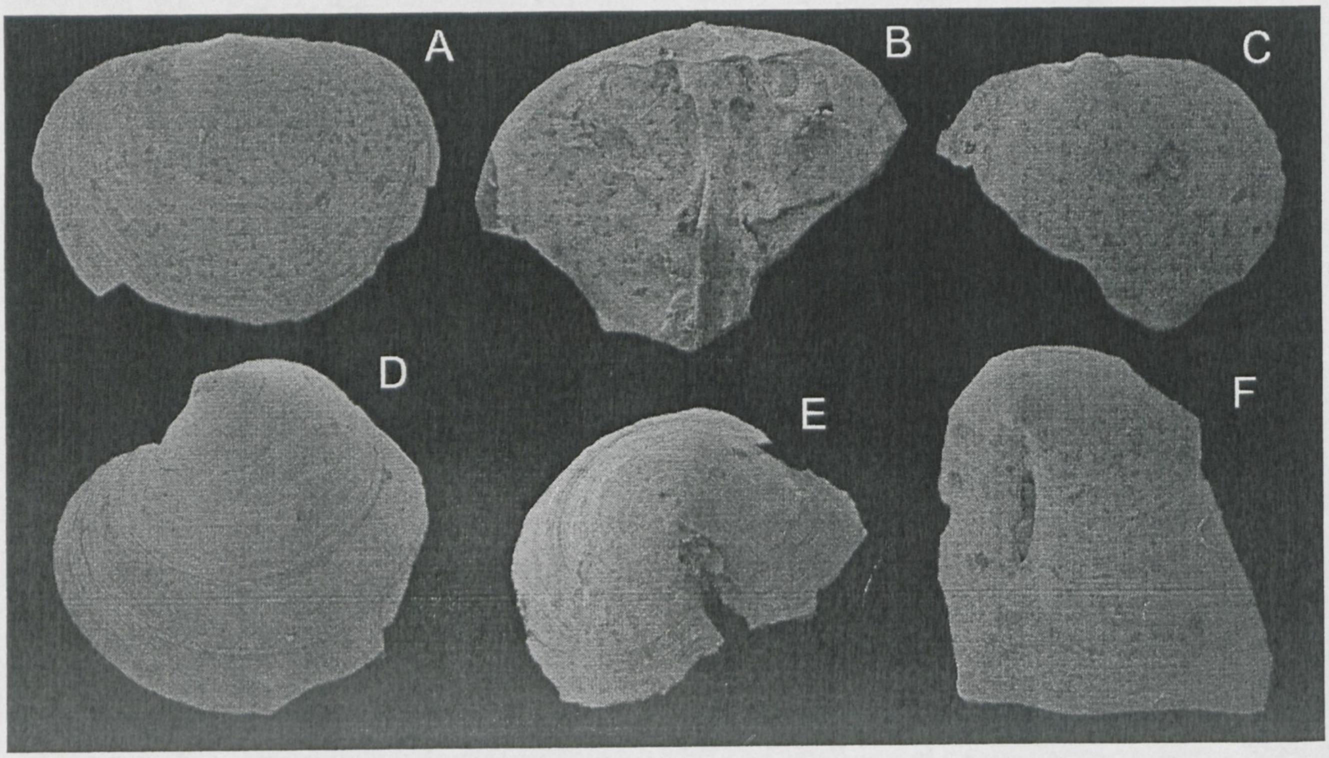

Fig. 79

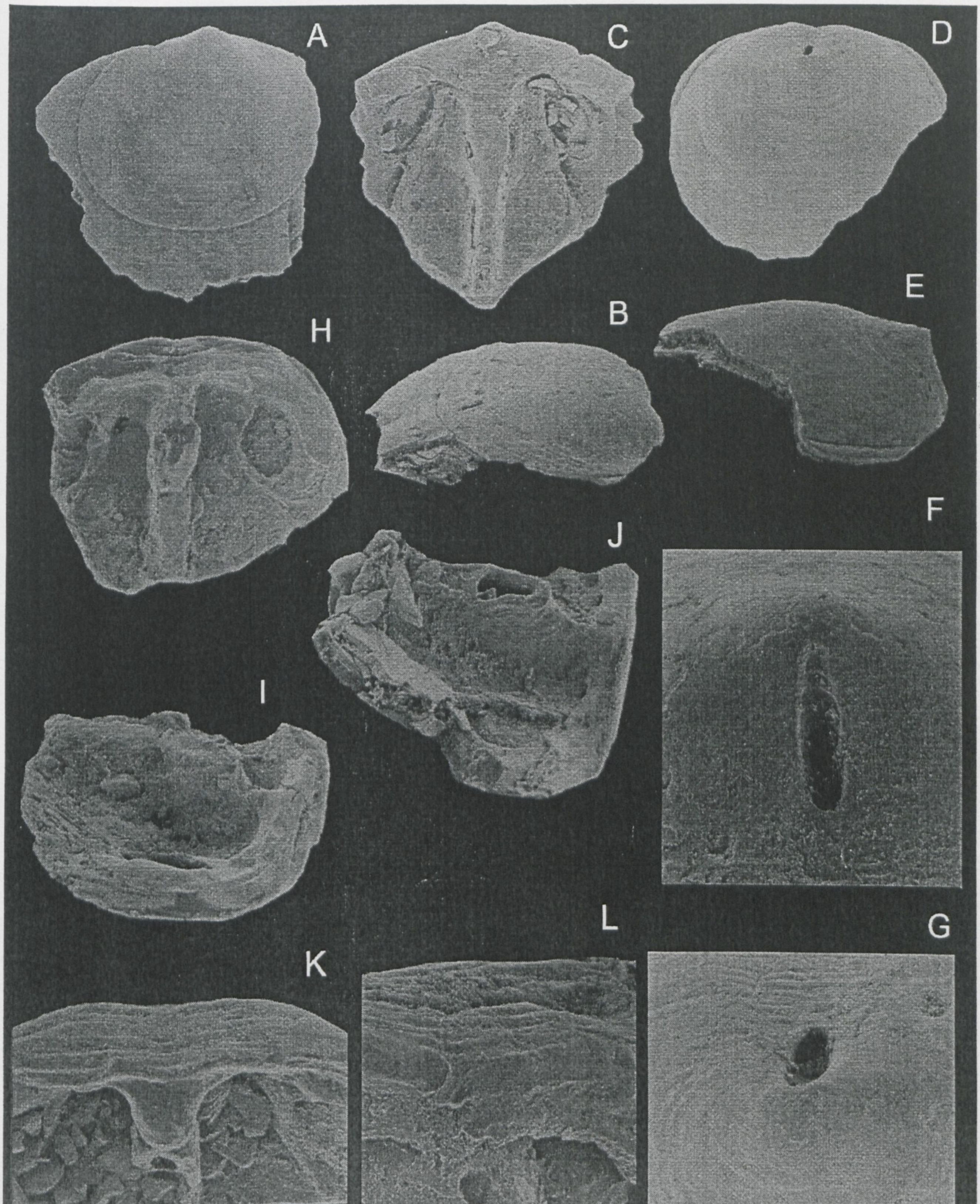

Fig. 80

199

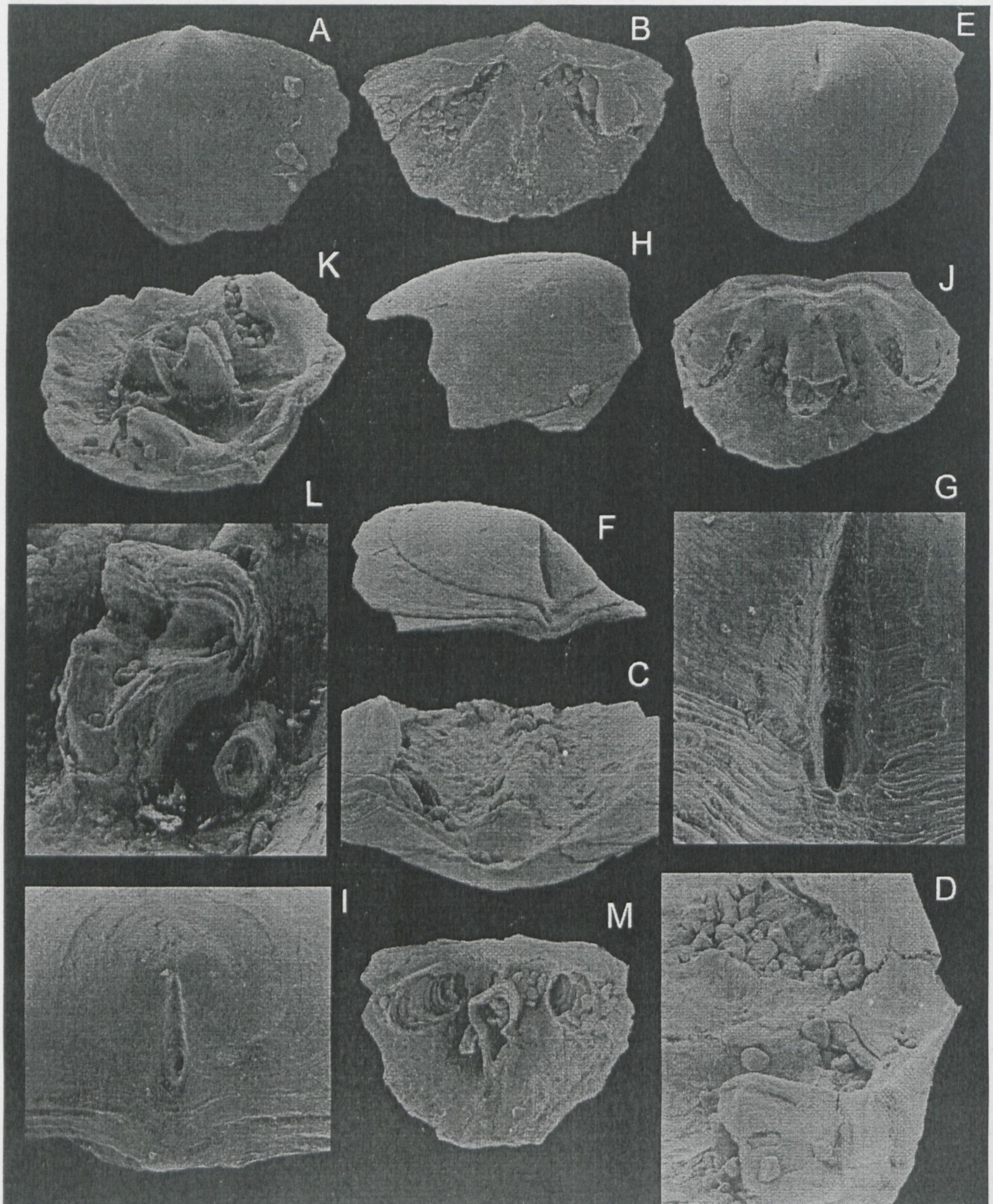

Fig. 81

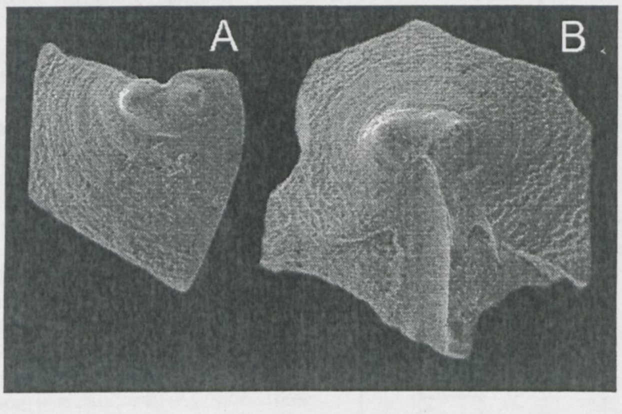

Fig. 82

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Lingulate brachiopods from the Cambrian–Ordovician boundary beds in Sweden

IVAR PUURA and LARS E. HOLMER

GFF

Puura, I. & Holmer, L.E., 1993 09 01: Lingulate brachiopods from the Cambrian–Ordovician boundary beds in Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, Vol. 115, Pt. 3, pp. 215–237. Stockholm. ISSN 0016-786X.

Lingulate brachiopods are described from the so-called 'Obolus' beds in the Siljan district, South Bothnian submarine district, and on the island of Öland, Sweden. The fauna includes *Ungula inornata, U. ingrica, Schmidtites celatus, Oepikites* sp., *Ceratreta tanneri* and *Keyserlingia reversa* that are well-known in the Upper Cambrian of the northern East Baltic (Estonia and Ingria); most examined sections also include species of probable late Tremadoc to early Arenig age. Lingulate and conodont-based correlation with the Ülgase and Saka sections in Estonia indicates that the Swedish 'Obolus' beds were formed during several phases of redeposition in the time interval from the Late Cambrian to early Arenig. ☐ *Brachiopoda, Lingulata,* Ungula inornata, U. ingrica, Schmidtites celatus, Oepikites *sp.*, Keyserlingia reversa, *Late Cambrian, Tremadoc, Arenig, Dalarna, South Bothnian submarine district, Öland, Sweden.*

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The presence of thin conglomerates and sandstones containing obolid brachiopods, the so-called 'Obolus' beds, at about the Cambrian–Ordovician boundary in Östergötland, the South Bothnian submarine district, the Siljan district, and on the island of Öland, has been known since the early half of the 19th Century. However, since that time, no work has been published on the lingulate fauna from these beds in Sweden, except for the recent review of *Ceratreta tanneri* by Holmer & Popov (1990). At the same time, the biostratigraphy of the Cambrian–Ordovician boundary beds in Estonia and Ingria (St. Petersburg region of Russia) has been investigated thoroughly and modernised (e.g., Kaljo et al. 1986 and Popov et al. 1989 for recent summaries).

The object of this paper is to revise and describe the brachiopod faunas of the 'Obolus' beds in Sweden, and to compare these with the correlative sequences in Estonia.

Methods. – The specimens were mostly isolated from the calcium carbonate cemented, quartzose rocks by means of etching with weak (10 %) acetic acid using standard techniques; specimens from soft sandstones were prepared mechanically with needles.

Repository. – The investigated collections are housed in the Geological Survey of Sweden, Uppsala (SGU) and in the Palaeontological Museum, Uppsala (PMU).

Brief historical review

Eichwald (1829) and Pander (1830) first demonstrated the presence of abundant lingulate brachiopods in the sandstones around the Cambrian–Ordovician boundary in northern Estonia and Ingria (St. Petersburg district), Russia. Since then, these sandstones have been referred to most commonly as the 'Obolus Sandstone', after the prevailing genus described by Eichwald (1829). In 1842, Eichwald (1843, p. 151) visited the environs of Omberg, Östergötland, as well as other parts of Sweden and Norway, in order to find the equivalents of Russian and Estonian 'Obolus' beds, but he did not succeed in doing so. Andersson (1896) and Moberg & Segerberg (1906) published reviews of the early studies on the 'Obolus conglomerate and sandstones' in Sweden.

Holm (1882, p. 66) observed the presence of a species of '*Obolus*' in the conglomerate at Horns udde, Öland, and suggested that this 'Obolus conglomerate' could be correlated with the 'Obolus' beds in Dalarna and Estonia. Mickwitz (1896,

p. 30) referred this species to *Obolus apollinis* Eichwald.

The comprehensive taxonomic study by Mickwitz (1896), describing the obolids from the 'Obolus sandstone' at Jägala-Joa, northern Estonia, applied a wide concept of the genus *Obolus*. Unfortunately, he followed the misinterpretations of earlier works in lumping together Eichwald's species *Obolus apollinis* and *Obolus ingricus* (see discussion in the systematic section below). This study by Mickwitz, and the reproduction of his descriptions by Walcott (1898, 1912), established an erroneous taxonomic interpretation that lasted for more than 70 years.

Following Mickwitz's interpretation, '*Obolus apollinis*' was described by Wiman (1905) from erratic boulders on the island of Fanton, Singö Fiord, Uppland and by Moberg & Segerberg (1906) from Klittberget, Siljan district.

Tanner (1911) found a phosphatic brachiopod, described by Metzger (1922) as *Acrotreta tanneri*, from the fissure filling at Långbergsöda-Öjen, on the island of Åland. Westergård (1940) discovered this species in the Upper Cambrian of the drill core at Borghamn quarry, Östergötland. The species was revised as *Ceratreta tanneri* by Martinsson (1968) and subsequently described from the Upper Cambrian at many localities in Sweden and the northern East Baltic by Holmer & Popov (1990).

Waern (1952) recorded fragmentary specimens of '*Obolus apollinis*' from what was regarded as the basal Ordovician conglomerate in the Böda Hamn core, northern Öland. Thorslund & Axberg (1979) reported '*Obolus*' from the 'Obolus' beds in the drill cores at Finngrundet (Östra Banken) and Västra Banken in the South Bothnian submarine district.

The confusion between two of Eichwald's species, *Obolus apollinis* and *Ungula ingrica*, was cleared up partly by Gorjansky (1969) and finally by Popov & Khazanovitch (*in* Popov et al. 1989).

Systematic palaeontology

Ungula Pander, 1830

Systematic position. – Class Lingulata Gorjansky & Popov, 1985; Order Lingulida Waagen, 1885; Superfamily Linguloidea Menke, 1828; Family

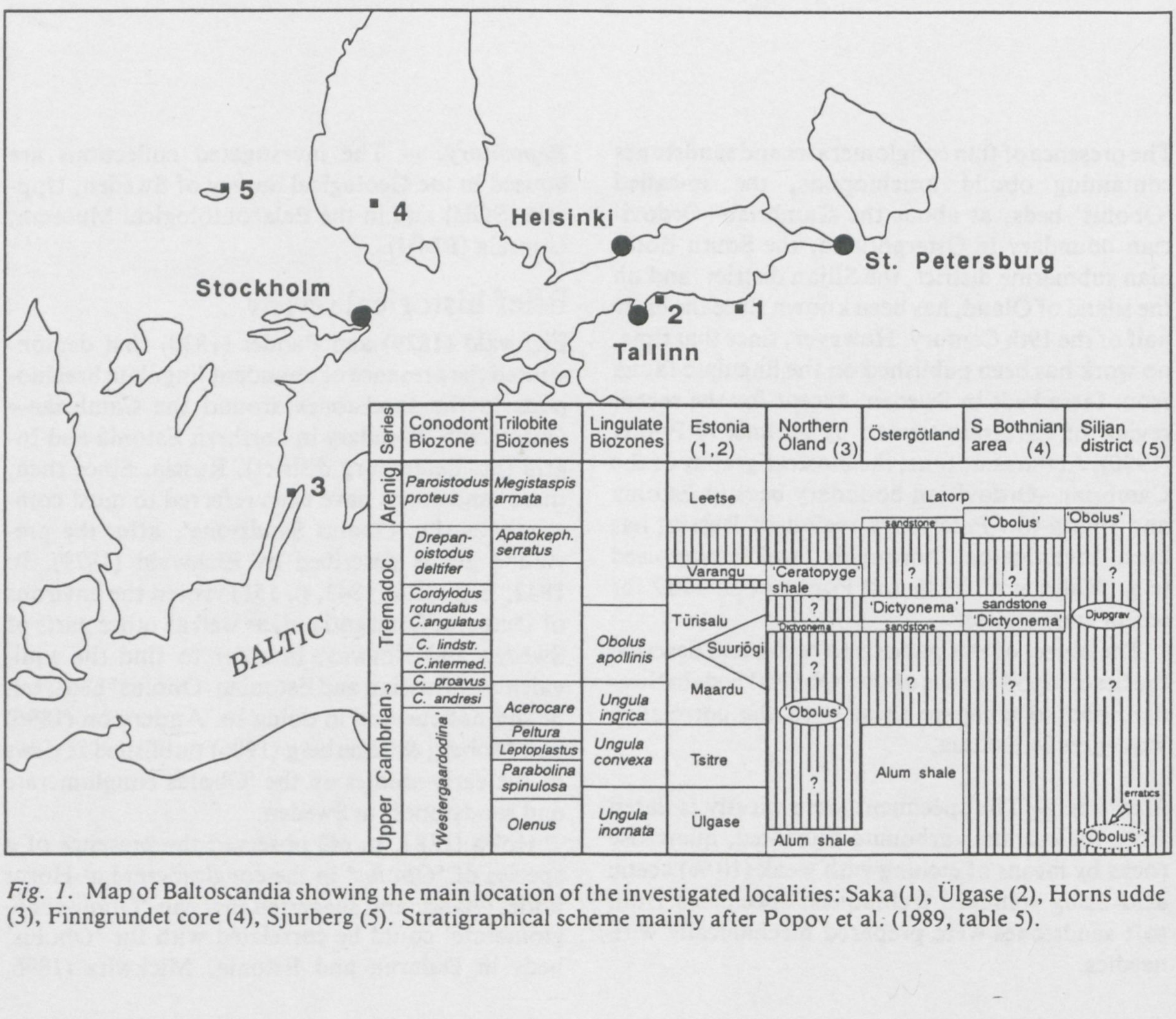


Fig. 1. Map of Baltoscandia showing the main location of the investigated localities: Saka (1), Ülgase (2), Horns udde (3), Finngrundet core (4), Sjurberg (5). Stratigraphical scheme mainly after Popov et al. (1989, table 5).

Obolidae King, 1846; Subfamily Obolinae King, 1846.

Type species. — By original designation; *Ungula convexa* Pander, 1830; Upper Cambrian Ladoga Formation, Ingria, Russia.

Diagnosis. — Shell dorsi-biconvex to almost flat, subcircular to suboval in outline; smooth or with fine concentric rugellae; ventral pseudointerarea with narrow, deep pedicle groove which may be closed in adult specimens; pseudointerareas of both valves with well-defined flexure lines; dorsal pseudointerarea with wide, slightly concave median groove, elevated above the valve floor; ventral visceral area elevated anteriorly, forming low platform with heart-shaped depression at about the centre; dorsal visceral area slightly thickened; ventral and dorsal *vascula lateralia* arcuate, peripherally placed; dorsal *vascula media* short, widely divergent.

Species assigned. — *Ungula convexa* Pander, 1830; *Obolus ingricus* Eichwald, 1829; *Obolus inornatus* Mickwitz, 1896.

Discussion. — *Ungula* Pander, 1830, was considered previously to be a junior synonym of *Obolus* Eichwald, 1829, but Popov & Khazanovitch (*in* Popov et al. 1989) have demonstrated the integrity of these two genera. *Obolus* is clearly distinguishable from *Ungula* by: 1) having a subcircular, thinner and flatter shell, 2) having thinner pseudointerareas in both valves, and a less well-developed pedicle groove; and 3) in lacking an elevated ventral visceral area with a heart-shaped depression.

Occurrence. — Upper Cambrian — ?Lower Ordovician (*Cordylodus proavus* Biozone).

Ungula ingrica (Eichwald, 1829)

Figs. 2A–F, 5I–K.

Synonymy. — □ *1829 *Obolus ingricus* n. sp. Eichwald, p. 274. □ 1896 *Obolus Apollinis* Eichwald – Mickwitz, p. 133, pl. 1:1–14. □ 1896 *Obolus Apollinis* var. *ingricus* n. var. Mickwitz, p. 137, pl. 1:15–28. □ 1896 *Obolus Apollinis* var. *maximus* n. var. Mickwitz, p. 140, pl. 2:1–6. □ 1898 *Obolus apollinis* Eichwald – Walcott, pl. 26:3–6. □ 1905 *Obolus Apollinis* Eichwald – Wiman, p. 62, pl. 3:1–11. □ 1906 *Obolus Apollinis* Eichwald – Moberg & Segerberg, p. 65, pl. 3:1–3. □ 1912 *Obolus apollinis* Eichwald – Walcott, p. 381, figs. 4, 15, pl. 7:1–8, 10–17; 14:6, 6a. □1912 *Obolus apollinis ingricus* (Eichwald) – Walcott, p. 384. □ 1912 *Obolus apollinis maximus* Mickwitz – Walcott, p. 384, pl. 7:9; 14:7, 7a. □ 1912 *Obolus apollinis quenstedti* (Mickwitz) – Walcott, p. 384, fig. 34a, b. □ 1969 *Obolus* (*Obolus*) *ingricus* Eichwald – Gorjansky, p. 22, pl. 1:12–20. □ 1969 *Obolus* (*Obolus*) *apollinis* (Eichwald) – Gorjansky, pl. 1:10–11. □ 1989 *Ungula ingrica* (Eichwald) – Popov & Khazanovitz (*in* Popov et al.), p. 119, pl. 7:12, 16, 20, 21.

Lectotype. — Selected by Popov & Khazanovitch (*in* Popov et al. 1989, p. 119). Specimen no. 1/778 (Department of Historical Geology, St. Petersburg State University). The specimen has been redeposited into the Lower Ordovician Tosna Formation, Luga river near Kingissepp (Yamburg), Ingria.

Material. — Illustrated: PMU B56, B58, B61, B608 – B610; SGU 8489 – 8491. In addition, numerous fragments.

Diagnosis. — Shell moderately equibiconvex, transversely suboval in outline; smooth; posterior half of shell strongly thickened; ventral pseudointerarea with narrow triangular pedicle groove; pseudointerareas of both valves with well-defined flexure lines; dorsal pseudointerarea with wide, slightly concave median groove, elevated above the valve floor; ventral visceral area elevated anteriorly forming a platform with a heart-shaped depression at about mid-valve; dorsal visceral area slightly thickened.

Discussion. — *Ungula ingrica* is the most variable species of the genus. Its range of morphological variation has been estimated on abundant and well-preserved material from Estonia. The Swedish material is less representative, but of satisfactory preservation, and it fits well into the range of morphological variation of the species. The diagnostic interior features include a well-defined heart-shaped depression as well as a characteristic, well-preserved pseudointerarea.

U. ingrica differs from *Ungula convexa* in having a less concave and more transverse shell, lower pseudointerareas in both valves, and a slightly wider pedicle groove.

As noted by Popov & Khazanovitch (*in* Popov et al. 1989, p. 120), *U. ingrica* has been confused almost invariably with *Obolus apollinis*. The original description of *O. apollinis* Eichwald (1829, p. 274; pl. 4:5) was based on a distinctive thin-shelled, oval form (Popov & Khazanovitch *in* Po-

207

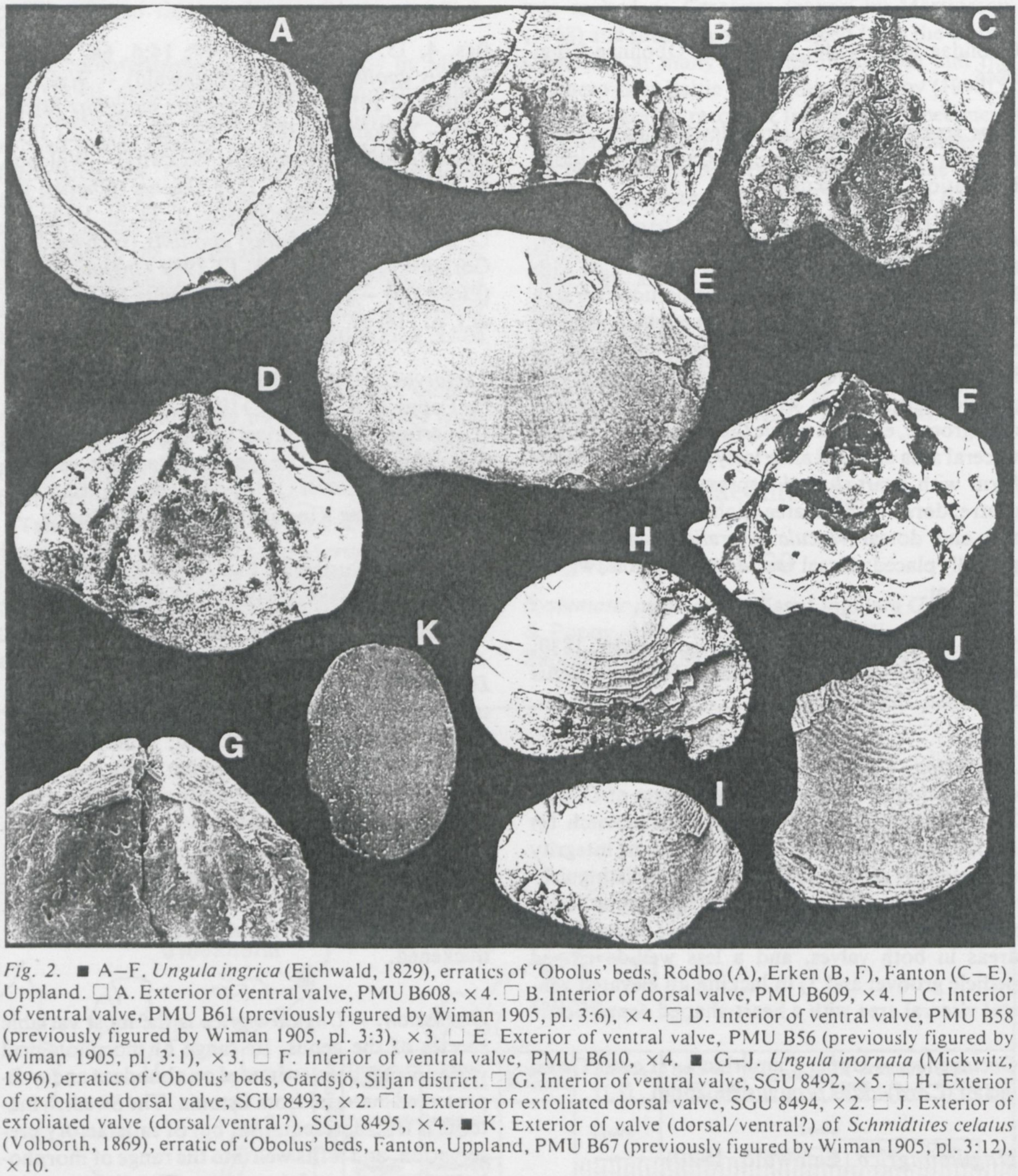


Fig. 2. ■ A–F. *Ungula ingrica* (Eichwald, 1829), erratics of 'Obolus' beds, Rödbo (A), Erken (B, F), Fanton (C–E), Uppland. □ A. Exterior of ventral valve, PMU B608, ×4. □ B. Interior of dorsal valve, PMU B609, ×4. □ C. Interior of ventral valve, PMU B61 (previously figured by Wiman 1905, pl. 3:6), ×4. □ D. Interior of ventral valve, PMU B58 (previously figured by Wiman 1905, pl. 3:3), ×3. □ E. Exterior of ventral valve, PMU B56 (previously figured by Wiman 1905, pl. 3:1), ×3. □ F. Interior of ventral valve, PMU B610, ×4. ■ G–J. *Ungula inornata* (Mickwitz, 1896), erratics of 'Obolus' beds, Gärdsjö, Siljan district. □ G. Interior of ventral valve, SGU 8492, ×5. □ H. Exterior of exfoliated dorsal valve, SGU 8493, ×2. □ I. Exterior of exfoliated dorsal valve, SGU 8494, ×2. □ J. Exterior of exfoliated valve (dorsal/ventral?), SGU 8495, ×4. ■ K. Exterior of valve (dorsal/ventral?) of *Schmidtites celatus* (Volborth, 1869), erratic of 'Obolus' beds, Fanton, Uppland, PMU B67 (previously figured by Wiman 1905, pl. 3:12), ×10.

pov et al. 1989, pl. 1:1–11, 8:1) occurring in great numbers at Luga river, Ingria. The confusion dates back to around 1840 (e.g. Verneuil 1845), and since then most textbooks and monographs have erroneously figured *U. ingrica* as *O. apollinis* (e.g. Mickwitz 1896; Walcott 1898, 1912). In his monograph on the genus *Obolus*, Mickwitz (1896) considered many obolids to be distinct varieties of *O. apollinis*. Recent examination of Mickwitz's only locality near Jägala-Joa (Jägala Falls, referred to as Jaggowall bei Jegelecht), 20 km east of Tallinn, Estonia, has confirmed that all these specimens represent *Ungula ingrica*.

Wiman (1905) and Moberg & Segerberg (1906) identified '*Obolus apollinis*' from several Swedish localities; re-examination of the figured specimens reveals that all of them belong to *Ungula ingrica* (see synonymy). True *Obolus apollinis* has seemingly never been found in Sweden.

Because of the fact that *U. ingrica* appears in the Upper Cambrian, well below the level of the *Cordylodus proavus* Biozone, its confusion with

Obolus apollinis (appearing at the base of the *C. proavus* Biozone) has lead to incorrect stratigraphic correlations of the level traditionally considered as the Cambrian-Ordovician boundary accross the East European Platform.

Occurrence. – In Estonia and Ingria, *U. ingrica* ranges from the Upper Cambrian and questionably into the lowermost Ordovician (redeposition?). In Sweden, all known specimens seem to be redeposited; the species was found in the 'Obolus' beds at Sjurberg and Horns udde as well as in erratic boulders from Uppland (Figs. 9–10).

Ungula inornata (Mickwitz, 1896)

Fig. 2G–J.

Synonymy. – □ *1896 *Obolus triangularis* n. sp. Mickwitz, p. 145, pl. 2: 7–9. □ 1896 *Obolus triangularis* var. *inornatus* n. var. Mickwitz, p. 148, pl. 2: 10–12. □ 1896 *Obolus panderi* n. sp. Mickwitz, p. 149, pl. 2: 13. □ 1906 *Obolus triangularis* Mickwitz – Moberg & Segerberg, p. 65. □ 1969 *Obolus* (*Obolus*) *triangularis* Mickwitz – Gorjansky, p. 24, pl. 1: 21, 22. □ 1989 *Ungula inornata* (Mickwitz) – Popov & Khazanovitch (*in* Popov et al.), p. 121, pl. 6:1–4,14, pl. 7:19,22– 24.

Lectotype. – Selected by Popov & Khazanovitch (*in* Popov et al. 1989, p. 121). Specimen no. 10843 (CNIGR Museum, St. Petersburg). The specimen was redeposited into the Upper Cambrian Maardu Member, Jägala river, near Jägala-Joa, Estonia. *'Obolus' triangularis* Mickwitz is a junior secondary homonym of *Ungula triangularis* Pander, 1830; Popov & Khazanovitch (in Popov et al., 1989) proposed the use of the replacement name *U. inornata* to resolve this homonymy, in recognition of the synonymy of *O. triangularis* Mickwitz, 1896 and *O. inornatus* Mickwitz, 1896.

Material. – Illustrated: SGU 8492–8495. In addition, an undetermined number of fragments.

Diagnosis. – Shell almost flat, slightly dorsibiconvex; transversely subtriangular in outline, with well-developed concentric rugellae becoming more pronounced anteriorly; ventral pseudointerarea with triangular pedicle groove; ventral visceral area slightly elevated anteriorly forming a platform with a heart-shaped depression at about the mid-valve.

Discussion. – *Ungula inornata* can be distinguished mainly by the presence of well-developed concentric rugellae on both valves and by the subtriangular outline. Moreover, the shell is considerably thinner posteriorly and thus the pseudointerareas of both valves are also less thickened, and the heart-shaped cavity is shallower.

Occurrence. – Upper Cambrian (Ülgase Formation) in Estonia. In Sweden, *U. inornata* occurs in the 'Obolus' beds at Sjurberg as well as from the erratic boulders at Gärdsjö; some questionable fragments occur in the 'Obolus' beds (interval 62.68–62.82 m) and the Latorp Limestone in the Finngrundet core (Figs. 9–10).

Schmidtites Schuchert & Levene, 1929

Type species. – By original designation; *Schmidtia celata* Volborth, 1869, p. 209; Upper Cambrian-lowermost Tremadoc Maardu Member, Toolse river, Estonia.

Diagnosis. – Ventri-biconvex and thick-shelled; elongate oval or subtriangular in outline; ventral pseudointerarea with deep, narrow pedicle groove; ventral propareas elevated, slightly concave with flexure lines; dorsal pseudointerareas with concave median plate and reduced, elevated propareas; visceral areas of both valves thickened; ventral heart-shaped depression shallow, but well-developed; dorsal visceral area with long median anterior projection, bisected by low median ridge; ventral *vascula lateralia* subparallel, marginally placed; dorsal *vascula media* short, widely divergent.

Species assigned. – Type species only.

Schmidtites celatus (Volborth, 1869)

Figs. 2K, 3A–D.

Synonymy. – □ *1869 *Schmidtia celata* n. sp. Volborth, p. 209, pl. 27:1–6. □ 1896 *Obolus* (*Schmidtia*) *celatus* (Volborth) – Mickwitz, p. 159, pl. 2:19–20. □ 1896 *Obolus celatus* var. *orbiculatus* n. var. Mickwitz, p. 163, pl. 2:21–22. □ 1896 *Obolus celatus* var. *praecisus* n. var. Mickwitz, p. 166, pl. 2: 37–38. □ 1896 *Obolus acuminatus* n. sp. Mickwitz, p. 179, pl. 2: 39, 40. □ 1896 *Obolus acuminatus* var. *alatus* n. var. Mickwitz, p. 183, pl. 2: 41, 42. □ 1896 *Obolus acuminatus* var. *humeratus* n. var. Mickwitz, p. 184, pl. 2: 43, 44. □ 1896 *Obolus acuminatus* var. *subtriangul-*

209

aris n. var. Mickwitz, p. 186, pl. 2: 45, 46. □ 1896 *Obolus crassus* n. sp. Mickwitz, p. 187, pl. 2: 47–49, 52–55. □ 1896 *Obolus crassus* var. *angulatus* n. var. Mickwitz, p. 193, pl. 2: 50, 51. □ 1898 *Obolus* (*Lingulella*) *celatus* – Walcott, pl. 26:1, 2. □ 1905 *Obolus obtusus* Mickwitz? – Wiman, p. 63, pl. 3:12. □ 1912 *Obolus* (*Schmidtia*) *celatus* (Volborth) – Walcott, p. 444, pl. 14:1, 1a–c. □ 1969 *Obolus* (*Schmidtites*) *celatus* (Volborth) – Gorjansky, p. 26, pl. 2:4, 8, 9 (*non* pl. 2:5–7, 10). □

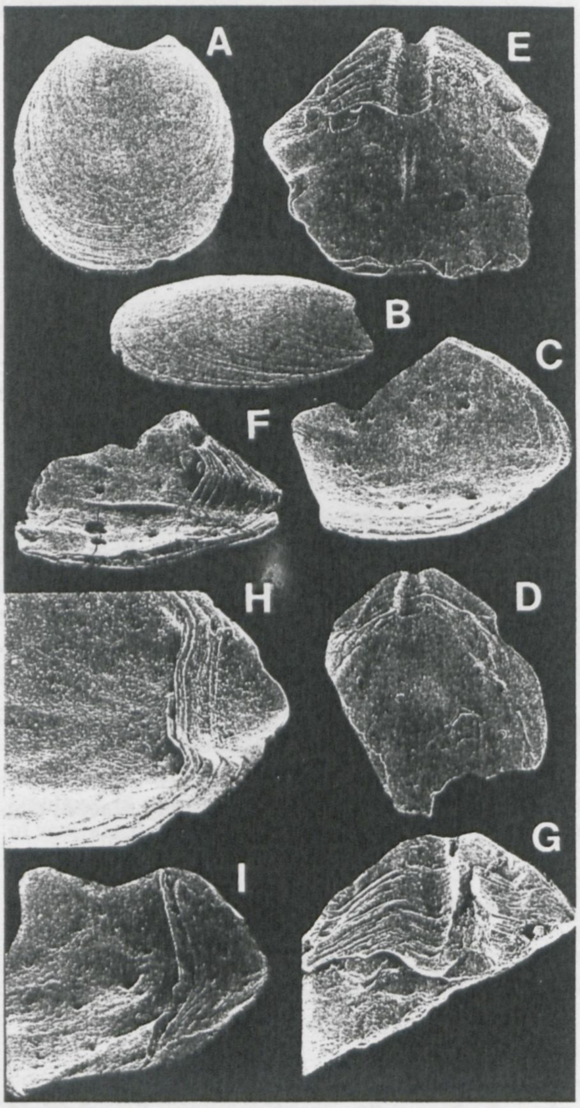


Fig. 3. ■ A–D. *Schmidtites celatus* (Volborth, 1869), 'Obolus' beds (62.68 – 62.82 m) in Finngrundet core, South Bothnian submarine district. □ A. Exterior of dorsal valve, PMU B601, ×10. □ B. Lateral view of A, ×10. □ C. Lateral view of dorsal interior, PMU B602, ×13. Interior of ventral valve, PMU B603, ×10. ■ E–I. *Oepikites* sp., 'Obolus' beds (62.68 – 62.82 m) in Finngrundet core, South Bothnian submarine district. □ E. Interior of ventral valve, PMU B604, ×9. □ F. Lateral view of E, ×9. □ G. Ventral pseudointerarea, PMU B605, ×10. □ H. Lateral view of dorsal interior, PMU B606, ×22. □ I. Lateral view of dorsal interior, PMU B607, ×12.

1989 *Schmidtites celatus* (Volborth) – Popov & Khazanovitch (*in* Popov et al.), p. 115, pl. 3:12–14; 4:5–14; 8:1.

Neotype. – Selected by Popov & Khazanovitch (*in* Popov et al. 1989, p. 115). Specimen no. 97/12348 (CNIGR Museum, St. Petersburg); Toolse river; Upper Cambrian, Maardu Member.

Material. – Illustrated: PMU B67, B601–B603. In addition, numerous fragments.

Diagnosis. – As for the genus.

Discussion. – The specimen figured by Wiman (1905) as *Obolus obtusus* is closer in external morphology to *S. celatus* and is here referred tentatively to the latter species (Fig. 2K).

Occurrence. – In Estonia and Ingria this species ranges from the Upper Cambrian to the lowermost Lower Ordovician. In Sweden, *S. celatus* occurs in the 'Obolus' beds in the Finngrundet core (intervals 62.97–63.18 m and 62.68–62.82 m) as well as in erratic boulders from Rödbo and Fanton in Uppland (Figs. 9–10).

Oepikites Khazanovitch & Popov, 1984

Type species. – By original designation; *Oepikites macilentus* Khazanovitch & Popov (*in* Khazanovitch et al. 1984, p. 40); Middle Cambrian Sablinka Formation, Sarya river, Ingria, Russia.

Diagnosis. – Shell inequivalved, elongate oval to subtriangular in outline; propareas of both valves high, with well-defined flexure lines; visceral area of both valves slightly thickened; dorsal visceral field with long anterior median projection, bisected by short median ridge; dorsal anterior lateral muscle scars placed close to anterior margin of anterior median projection; vascula lateralia of both valves submarginal, arcuate; dorsal *vascula media* short, divergent.

Species assigned. – *Obolus* (*Schmidtia*) *obtusus* Mickwitz, 1896; *Lingulella acuta* Pelman, 1978; *Lingulella kitatiensis* Aksarina, 1978; *Oepikites macilentus* Popov & Khazanovitch, 1984; *Oepikites triquetrus* Popov & Khazanovitch, 1984; *Oepikites fragilis* Popov & Khazanovitch, 1984; *Oepikites*? *elongatus* Popov & Khazanovitch, 1984.

Occurrence. – Middle – Upper Cambrian.

Oepikites sp.

Figs. 3E–I.

Material. – Illustrated: PMU B604–B607. In addition, numerous fragments.

Discussion. – Because of the fragmentary state of preservation, the specimens cannot be classified confidently; they probably belong to *Oepikites obtusus* or *O. triquetrus*.

Occurrence. – *Oepikites* sp. has been identified from the 'Obolus' beds in the Finngrundet core (interval 62.68–62.82 m), and questionably from erratic boulders at Fanton (Figs. 9–10).

Rowellella sp.

Fig. 4J–L.

Systematic position. – Subfamily Lingulellinae Schuchert, 1893; Genus *Rowellella* Wright, 1963.

Material. – Illustrated: SGU 8482–8483. In addition, numerous fragments.

Discussion. – All available specimens of *Rowellella* sp. are worn, and appear to have been redeposited; the fragmented material cannot be assigned to any described species. In fact, as noted by Holmer (1989, p. 76), *Rowellella* is almost invariably poorly preserved throughout the Ordovician of Baltoscandia. In the examined material, only the thickened anterior part of both valves is usually preserved (Fig. 4J–L). Most specimens seem to represent dorsal valves, and the closely spaced central and anterior lateral muscle scars are well-developed in some valves (Fig. 4L), but commonly it is difficult to tell the ventral and dorsal valves apart. The ornamentation is invariably with strongly developed rugae, sometimes superposed on lamellae (Fig. 4J–K). Convexity and ornamentation are strongly variable in most *Rowellella*. Poorly preserved fragments with a somewhat similar type of ornamentation have been illustrated by Bednarczyk (1986, pl. 1:1, 2, 4, 5) who described *R. parallela* (= *R. multilamellata* Bednarczyk, 1986) from lower Arenig limestones in the Białogóra core, northern Poland.

Occurrence. – Fragments of *Rowellella* sp. are common in the sample from the 'Obolus' beds in Sjurberg; they also occur in the overlying Latorp Limestone (Figs. 9–10). The earliest known records of the genus are from the Tremadoc of Poland (Biernat 1973), and it is also known from the upper Tremadoc Bjørkåsholmen ('Ceratopyge') Limestone and throughout the Lower Ordovician in Baltoscandia (Popov & Holmer, unpublished). It has never been found in the Upper Cambrian, and the specimens from the 'Obolus' beds are probably of late Tremadoc or early Arenig age.

Lamanskya splendens Moberg & Segerberg, 1906

Synonymy. – □ *1906 *Lamanskya splendens* n. gen. et n. sp. Moberg & Segerberg, p. 71, pl. 3, fig. 17.

Systematic position. – Family Elkaniidae Walcott & Schuchert, 1908; Genus *Lamanskya* Moberg & Segerberg, 1906.

Material. – Not illustrated; numerous fragments.

Discussion. – This species is redescribed by Holmer (*in press*); the fragmentary material can be recognized easily by its distinctive pitted microornamentation with elongate, lenticular pits, superposed on rugae, and by the strongly thickened posterior parts of the valves.

Occurrence. – *L. splendens* is known from the Lower Ordovician (upper Tremadoc – Arenig) of Baltoscandia (Holmer *in press*); it occurs in the Latorp Limestone of the Finngrundet core (interval 62.68–62.82 m); in the Sjurberg section it ranges from the 'Obolus' beds into the Latorp Limestone (Figs. 9–10).

Treptotreta? sp.

Fig. 5D–E.

Systematic position. – Order Acrotretida Kuhn, 1949; Superfamily Acrotretoidea Schuchert, 1893; Family Acrotretidae Schuchert, 1893; Subfamily Acrotretinae Schuchert, 1893; ?Genus *Treptotreta* Henderson & MacKinnon, 1981.

Material. – Illustrated: SGU 8486–8487. Total of two dorsal and one ventral valves.

211

Discussion. – The fragments of this form are similar to the type species, *Treptotreta jucunda* Henderson & MacKinnon (1981) from the Middle–Upper Cambrian of Australia and New Zealand. Both species have a well-developed dorsal pseudointerarea with a median groove, a high dorsal median septum and a cardinal buttress, as well as a conical ventral valve lacking an intertrough, but with a well-developed apical process filling the apex.

Occurrence. – This species is found only in the sample from the 'Obolus' beds at Horns udde (Fig. 9). The genus is not known from the Ordovician,

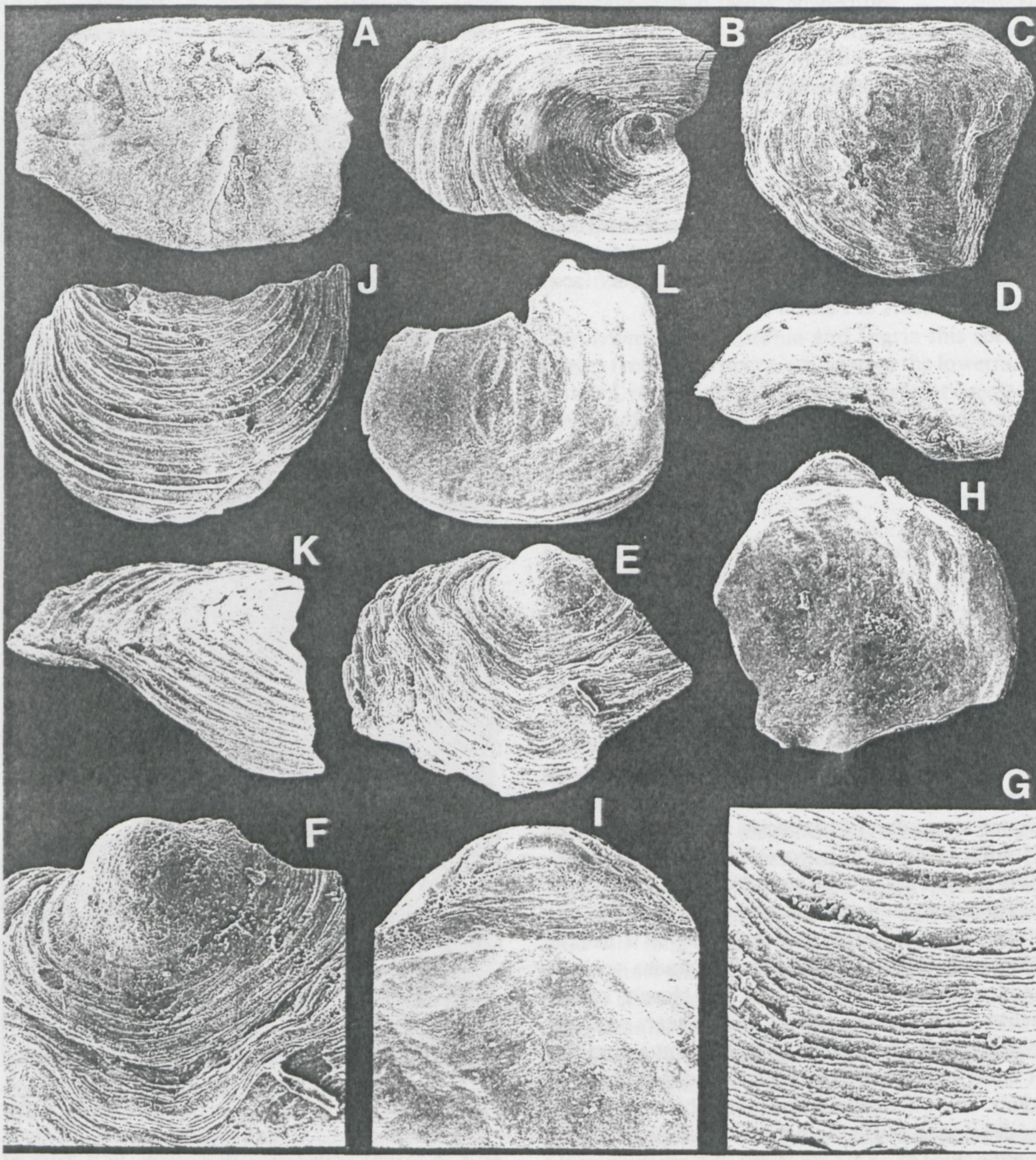


Fig. 4. ■ A–B. Torynelasmatinae gen. et sp., 'Obolus' beds at Sjurberg, Siljan district. □ A. Interior of dorsal valve, SGU 8477, ×30. □ B. Exterior of ventral valve, SGU 8478, ×40. ■ C–I. *Eoconulus*? spp., 'Obolus' beds at Sjurberg, Siljan district. □ C. Exterior of dorsal valve, SGU 8479, ×40. □ D. Lateral view of C, ×40. □ E. Exterior of dorsal valve, SGU 8480, ×50. □ F. Detail of larval shell of E, ×100. □ G. Detail of ornamentation of E, ×400. □ H. Interior of dorsal valve, SGU 8481, ×50. □ I. Detail of pseudointerarea of E, ×150. ■ J–L. *Rowellella* sp. 'Obolus' beds at Sjurberg, Siljan district. □ J. Exterior of valve (dorsal/ventral?), SGU 8482, ×37. □ K. Lateral view of J, ×37. □ L. Interior of dorsal valve, SGU 8483, ×23.

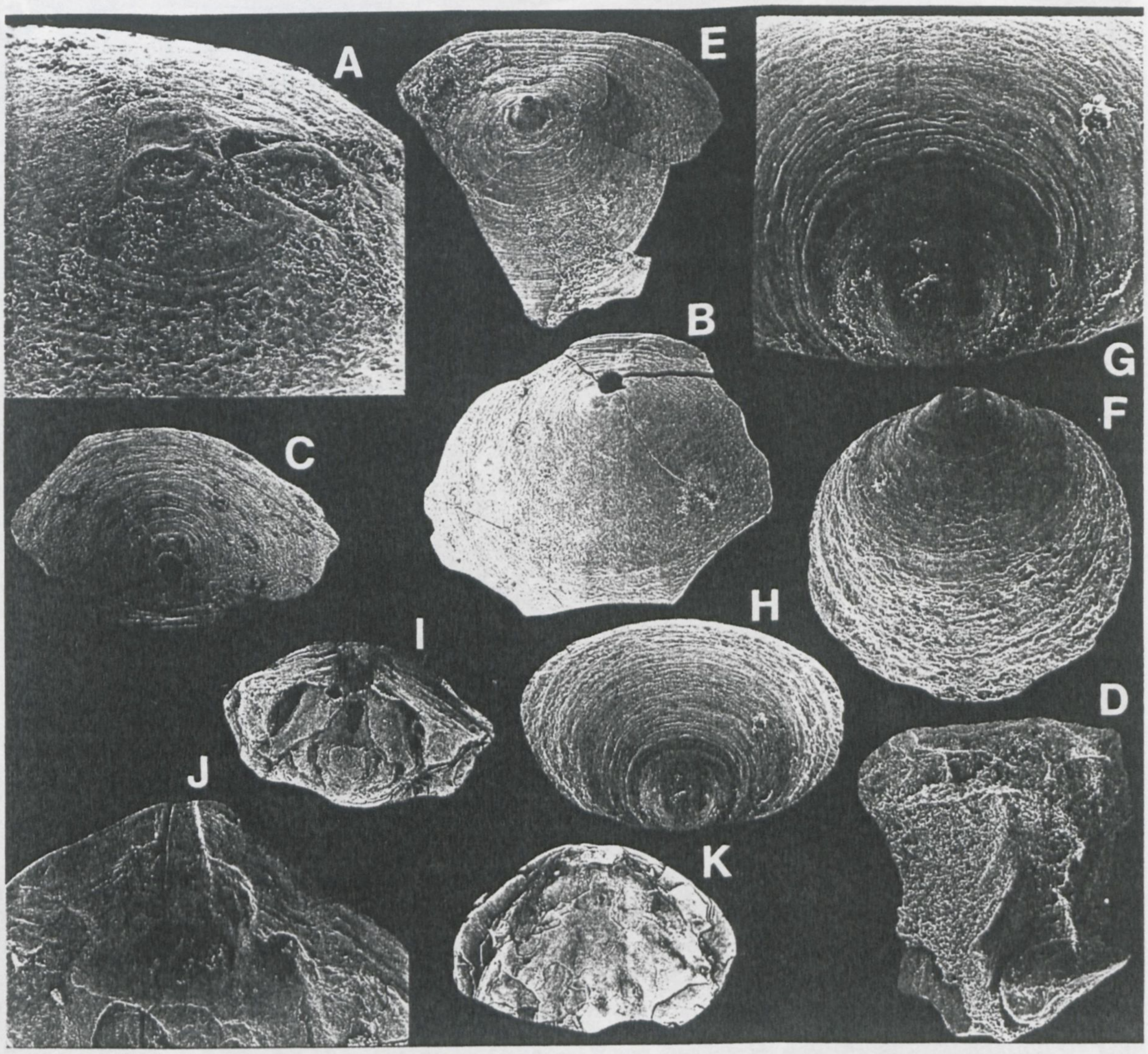


Fig. 5. 'Obolus' beds at Horns udde, northern Öland. ■ A–C. *Acrothele coriacea* Linnarsson, 1876. □ A. Lateral view of larval shell of ventral valve, SGU 8484, ×75. □ B. Exterior of ventral valve, SGU 8485, ×16. □ C. Posterior view of B, ×16. ■ D–E. *Treptotreta*? sp. □ D. Interior of dorsal valve, SGU 8486, ×38. □ E. Exterior of ventral valve, SGU 8487, ×25. ■ F–H. *Stilpnotreta*? sp., SGU 8488. □ F. Exterior of dorsal valve, ×70. □ G. Larval shell of F, ×156. □ H. Posterior view of F, ×70. ■ I–K. *Ungula ingrica* (Eichwald, 1829). □ I. Latex cast of ventral internal mould, SGU 8489, ×4. □ J. Pseudointerarea of ventral valve, SGU 8490, ×9. □ K. Interior of dorsal valve, SGU 8491, ×4.

and the fragments are probably redeposited, originally from beds of Middle-Late Cambrian age.

Quadrisonia? sp.

Fig. 7A–H.

Systematic position. – ?Genus *Quadrisonia* Rowell & Henderson, 1978.

Material. – Illustrated: PMU B585–B588. Total of 3 dorsal and 9 ventral valves.

Discussion. – This material is referred questionably to the genus becuse of the following similarities with the type species *Quadrisonia minor* Rowell & Henderson, 1978: the ventral pseudointerarea lacks an intertrough (Fig. 7E–G); the ventral interior is dominated by an elongate, ridge-like, subtriangular apical process with a well-developed pedicle tube (Fig. 7H); the dorsal pseudointerarea is short and has a wide median groove; the dorsal median septum is short with a cardinal buttress (Fig. 7D). It differs from the type species mainly in having a higher dorsal median septum, a better-developed cardinal buttress, as well as a higher

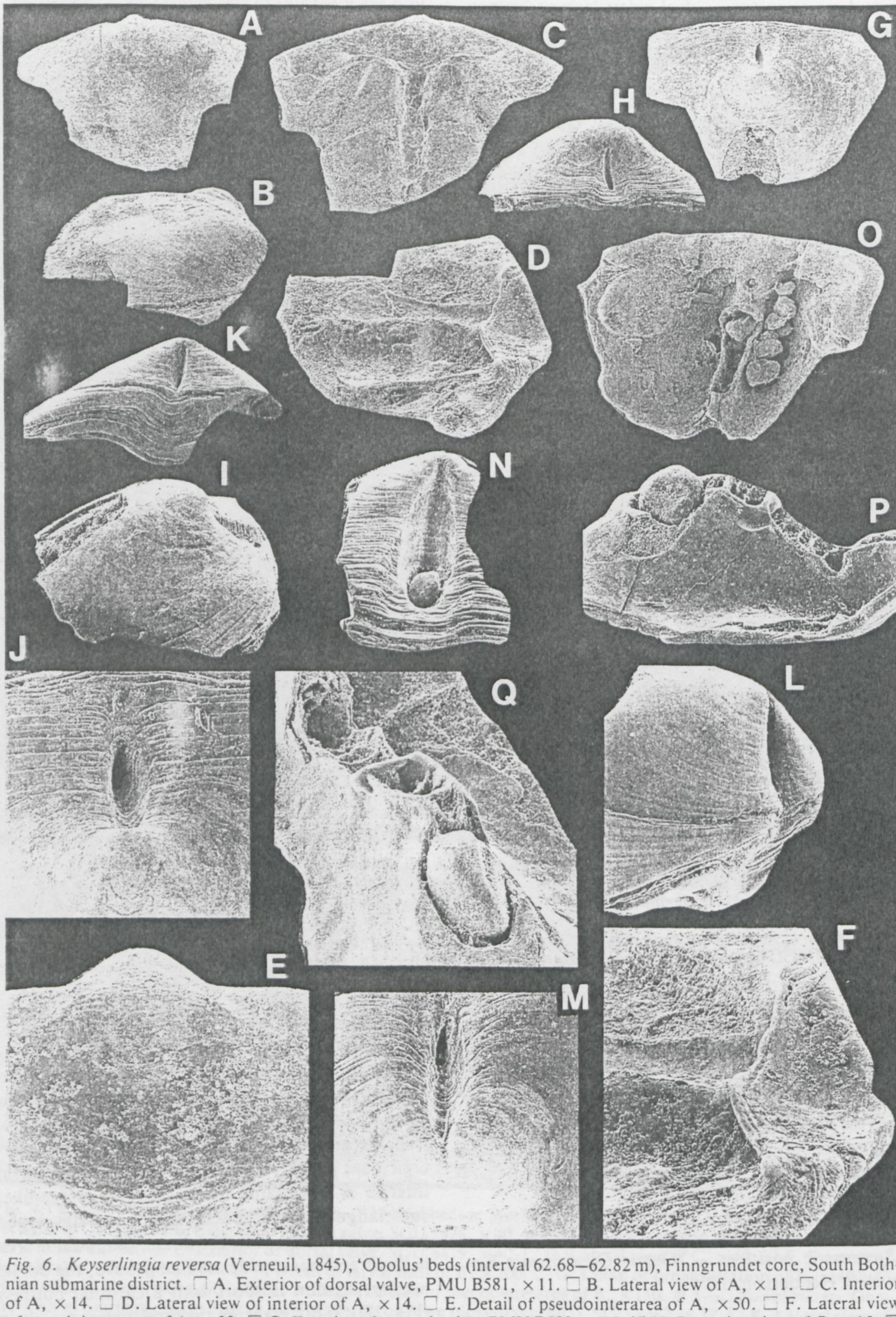


Fig. 6. Keyserlingia reversa (Verneuil, 1845), 'Obolus' beds (interval 62.68–62.82 m), Finngrundet core, South Bothnian submarine district. □ A. Exterior of dorsal valve, PMU B581, ×11. □ B. Lateral view of A, ×11. □ C. Interior of A, ×14. □ D. Lateral view of interior of A, ×14. □ E. Detail of pseudointerarea of A, ×50. □ F. Lateral view of pseudointerarea of A, ×32. □ G. Exterior of ventral valve, PMU B582, ×15. □ H. Posterior view of G, ×15. □ I. Lateral view of G, ×15. □ J. Detail of pedicle opening of G, ×50. □ K. Posterior view of ventral valve, PMU B583, ×18. □ L. Lateral view of K, ×30. □ M. Detail of pedicle opening of K, ×50. □ N. Posterior view of ventral valve, PMU B584, ×32. □ O. Interior of G, ×16. □ P. Lateral view of apical process of N, ×37. □ Q. Detail of apical process of N, ×60.

ventral apical process. The dorsal valve exterior of the Swedish species is closely comparable with that of *Stilpnotreta* sp. from the 'Obolus' beds at Horns udde, which also has a larval shell with two distinct nodes (Fig. 5F–H).

Occurrence. – *Quadrisonia* sp. occurs in the sample from the 'Obolus' beds in the Finngrundet core (interval 62.68–62.82 m), and some possible fragments occur in the directly overlying Latorp Limestone (Figs. 9–10). The genus is currently known from the Upper Cambrian to the Lower Ordovician (Popov & Holmer, unpublished); the worn specimens were probably redeposited.

Torynelasmatinae gen. et sp.

Fig. 4A–B.

Systematic position. – Subfamily Torynelasmatinae Rowell, 1965.

Material. – Illustrated: SGU 8477–8478. Total of one dorsal and one ventral valves.

Discussion. – The complete outline of the valves is unknown, but the shell seems to have been elongate oval, with a wide and straight posterior margin. The ventral pseudointerarea is flattened and almost undivided; the apical process is well-developed. The dorsal pseudointerarea is wide, short, and almost undivided, lacking a clearly defined median groove; the median septum appears to be ridge-like and low; the cardinal buttress is well-developed, and wide. The fragmentary material cannot be assigned confidently to any described torynelasmatine genus. The earliest representatives of the Torynelasmatinae generally lack a high dorsal median septum with surmounting platform that are typical of the younger Ordovician torynelasmatines (Holmer, unpublished).

Occurrence. – This species is found in the 'Obolus' beds at Sjurberg, and in the overlying Latorp Limestone (Figs. 9–10). The oldest torynelasmatines are known from the Tremadoc in Baltoscandia (Holmer, unpublished).

Stilpnotreta? sp.

Fig. 5F–H.

Systematic position. – Subfamily Linnarssoniinae Rowell, 1965; ?Genus *Stilpnotreta* Henderson & MacKinnon, 1981.

Material. – Illustrated: SGU 8488. Total of 3 dorsal and 8 ventral valves.

Discussion. – This taxon is similar to the type species, *Stilpnotreta magna* Henderson & MacKinnon (1981), from the Middle–Upper Cambrian of Australia and New Zealand, in having the following five characters: (1) a subequally biconvex shell, with a short posterior margin, (2) a vestigial ventral pseudointerarea and an orthocline dorsal pseudointerarea, with a broad median groove, (3) a well-developed ventral apical process filling the entire apex, (4) a low dorsal median ridge, and (5) a dorsal larval shell with two distinct nodes (Fig. 5F–H). A closely similar (and possibly synonymous), undescribed species of *Stilpnotreta*? is also present in the Middle to Upper Cambrian of Östergötland and Västergötland (Holmer, unpublished).

Occurrence. – This species has been found only in the 'Obolus' beds at Horns udde (Figs. 9–10). The genus is not known from the Ordovician; the valves are probably redeposited, originally of mid or late Cambrian age.

Keyserlingia Pander, 1861

Systematic position. – Family Ceratretidae Rowell, 1965

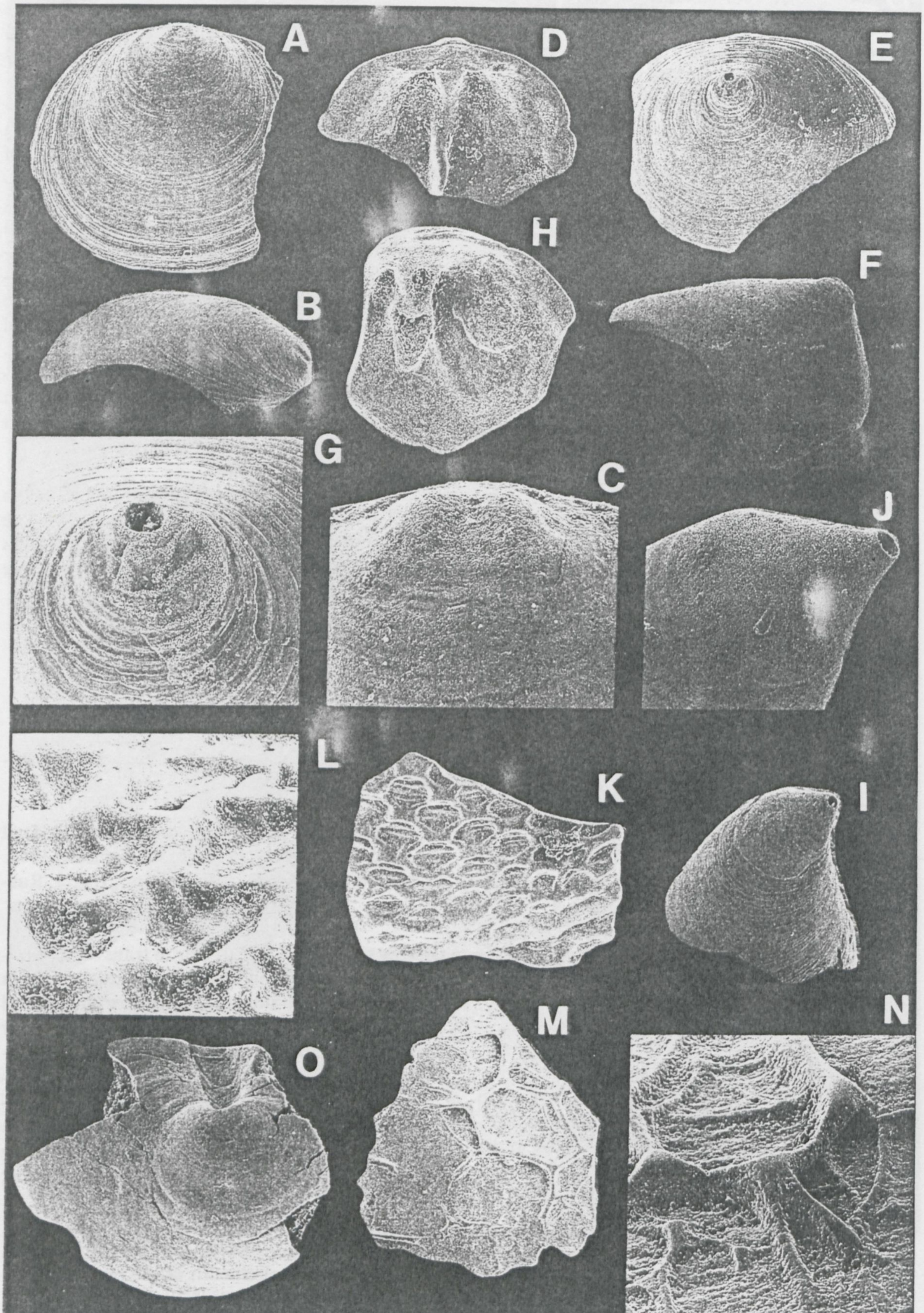
Type species. – Subsequent designation by Dall (1877, p. 75); *Orbicula reversa* de Verneuil, 1845. Upper Cambrian Ladoga Formation, Ingria, Russia.

Diagnosis. – Shell subcircular to transversely suboval; ventral valve low conical, with thickened rim of lamellose shell along posterior margin; ventral pseudointerarea procline to catacline, divided by broad intertrough; pedicle foramen elongate lenticular, placed partly outside of the larval shell; ventral apical process forming high, thickened septum, perforated posteriorly by internal pedicle tube; cardinal muscle fields of both valves forming strongly elevated, sometimes undercut platforms; dorsal median septum low, triangular.

Species assigned. – *Orbicula reversa* de Verneuil, 1845; *O. buchii* de Verneuil, 1845.

Discussion. – *Keyserlingia* has been a poorly understood genus, and for many years *K. buchii* was assumed mistakenly to be the type species (see Ro-

215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well 1963, 1965; Gorjansky 1969; Popov et al. 1989 for details). As noted by Popov et al. (1989, p. 131), *Clistotrema* Rowell, 1963 is a junior synonym. *Keyserlingia* appears to be endemic to Baltoscandia.

Keyserlingia reversa (de Verneuil, 1845)

Fig. 6.

Synonymy. — □ *1845 *Orbicula reversa* sp. n. de Verneuil, p. 289, pl. 19: 2a–c. □ 1989 *Keyserlingia reversa* (de Verneuil) — Popov & Khazanovitch (*in* Popov et al.), p. 132: pl. 4:3, pl. 10: 18, pl. 12: 1–6.

Neotype. — Selected by Popov & Khazanovitch (*in* Popov et al. 1989, p. 133). Specimen no. 234/12348 (CNIGR Museum, St. Petersburg). Quarry at Kirchshoff hill, 750 m south of Kavelahti village, Ingria. Upper part of the Upper Cambrian Ladoga Formation (*Ungula convexa* Biozone).

Material. — Illustrated: PMU B581 — B584. Total of 6 dorsal and 8 ventral valves.

Description. — See Popov & Khazanovitch (*in* Popov et al. 1989, p. 132).

Discussion. — The detailed morphology of *K. reversa* was virtually unknown until the revision by Popov & Khazanovitch (*in* Popov et al. 1989). By contrast, the only other species of the genus, *K. buchii* (de Verneuil, 1845), is fairly well-known (e.g., Walcott 1912, p. 628, pl. 81:4; Rowell 1965, p. H278, fig. 171:4); it is only somewhat younger than the type species and ranges from the Upper Cambrian (*Ungula ingrica* Biozone) to the Tremadoc (*Obolus apollinis*/*Helmersenia ladogensis* Biozone) in the northern East Baltic. The Swedish specimens are referrable to the type species, and differ from *K. buchii* mainly in the following five characters: (1) the shape is more subcircular than transversely suboval, (2) the apical process forms an elongate, narrow ridge (Fig. 6O–Q), rather than a high, wide, triangular, spoon-like projection as in *K. buchii* (see, e.g., Walcott 1912, pl. 81:4a, b), (3) the cardinal muscle scars in both valves are less elevated (Fig. 6C, D, O) and do not form undercut platforms like in *K. buchii* (Popov & Khazanovitch *in* Popov et al. 1989, pl. 11: 1), (4) the pedicle opening is generally less elongate (Fig. 6G, J), and (5) the dorsal pseudointerarea is proportionally narrower and longer (Fig. 6C) than in *K. buchii* (Walcott 1912, pl. 81:4e; Popov & Khazanovitch *in* Popov et al. 1989, pl. 1:1, 2).

Occurrence. — *K. reversa* was known previously only from Ingria, where it is restricted to the upper part of the Ladoga Formation (*Ungula convexa* Biozone). In Sweden it occurs in the 'Obolus' beds in the Finngrundet core (interval 62.67–62.82 m), and some doubtful fragments range into the Latorp Limestone (Figs. 9–10); the worn specimens were probably redeposited, and might be of Late Cambrian to Tremadoc age.

Keyserlingia sp.

Fig. 7O.

Material. — Illustrated: PMU B592. One ventral valve.

Discussion. — The valve is too poorly preserved for any closer comparative analysis.

Occurrence. — It was found in an erratic boulder of 'Obolus' beds from Slätö (Fig. 10).

Ceratreta tanneri (Metzger, 1922)

Synonymy. — □ *1922 *Acrotreta tanneri* n. sp. Metzger, p. 4, fig. 1A–I. □ 1990 *Ceratreta tanneri* (Metzger) — Holmer & Popov, p. 251, Figs. 3–6 [full synonymy].

Systematic position. — Genus *Ceratreta* Bell, 1941.

Material. — Not illustrated. Numerous fragments.

Discussion. — The morphology and stratigraphic distribution of this species were discussed by Holmer & Popov (1990).

Fig. 7. 'Obolus' beds (interval 62.68–62.82 m) in Finngrundet core, South Bothnian submarine district (A–N); Erratic boulder from Slätö (O). ■ A–H. *Quadrisonia*? sp. □ A. Exterior of dorsal valve, PMU B585, ×42. □ B. Lateral view of A, ×42. □ C. Larval shell of A, ×200. □ D. Interior of dorsal valve, PMU B586, ×42. □ E. Exterior of ventral valve, PMU B587, ×34. □ F. Lateral view of E, ×34. □ G. Larval shell of E, ×125. □ H. Interior of ventral valve, PMU B588, ×34. ■ I–J. *Pomeraniotreta* sp. □ I. Lateral view of ventral exterior, PMU B589, ×73. □ J. Lateral view of larval shell of ventral valve, PMU B590, ×170. ■ K. Paterinida gen. et sp., fragment of valve exterior, PMU B591, ×27. □ L. Detail of K, ×100. ■ M. *Marcusodictyon priscum*?, encrusting on an obolid fragmentary valve, PMU B600, ×31. □ N. Detail of M, ×90. ■ O. *Keyserlingia* sp., exterior of ventral valve, PMU B592, ×37.

217

Occurrence. — As noted by Holmer & Popov (1990), *C. tanneri* is found in the Upper Cambrian Ülgase and Ladoga formations in Estonia and Ingria as well as in the Upper Cambrian alum shales in Östergötland and in fissure fillings on the island of Åland; in Dalarna, erratic boulders of 'Obolus' sandstone at Gärdsjö also contains poorly preserved fragments of the species along with *Ungula inornata* (Fig. 10).

Pomeraniotreta Bednarczyk, 1986

Systematic position. — Subfamily Ephippelasmatinae Rowell, 1962.

Type (and only) species. — By original designation; *Pomeraniotreta biernati* Bednarczyk, 1986, p. 414; lowermost Arenig; Białogóra core, Łeba, northern Poland.

Diagnosis. — Ventral valve highly conical; deltoid pseudointerarea catacline to slightly apsacline with intertrough; apical process occluding the apex; external pedicle tube long; dorsal valve of varying convexity; dorsal pseudointerarea long and narrow, lacking well-developed median groove, but with concave anterior margin; dorsal median septum lacking, but sometimes with very low ridge; larval shell almost circular, with strongly raised rim around.

Discussion. — Bednarczyk (1986) referred the genus to the torynelasmatines but, as discussed by Holmer (1989, p. 112), it is clearly an ephippelasmatine.

Pomeraniotreta sp.

Fig. 7I—J.

Material. — Illustrated: PMU B589, B590. Total of two ventral valves.

Discussion. — The highly conical ventral valve has a long external pedicle tube and a well-developed apical process (Fig. 7I—J), and is closely similar to that of the type species.

Occurrence. — The type species is known from the Tremadoc and lower Arenig of Poland, Sweden, and Norway; *Pomeraniotreta* sp. was found in the 'Obolus' beds in the Finngrundet core (interval 62.68—62.82 m) and some questionable fragments occur in the directly overlying Latorp Limestone (Figs. 9—10; the worn specimens were probably redeposited, and might be of Tremadoc — early Arenig age.

Acrothele coriacea Linnarsson, 1876

Fig. 5A—C.

Synonymy. — □ 1876 *Acrothele coriacea* n.sp. Linnarsson, p. 21, pl. 4:44—48. □ 1912 *Acrothele coriacea* Linnarsson — Walcott, p. 642, pl. 56:1 [synonymy].

Systematic position. — Family Acrothelidae Walcott & Schuchert, 1908; Subfamily Acrothelinae Walcott & Schuchert, 1908; Genus *Acrothele* Linnarsson, 1876.

Material. — Illustrated: SGU 8484 — 8485. Total of 2 dorsal and 9 ventral valves.

Description. — See Walcott (1912, p. 642).

Discussion. — The Middle Cambrian type species, *A. coriacea* has not been revised and re-illustrated recently, and its detailed internal and external morphology are still poorly known. The fragmentary and strongly worn material (Fig. 5A—C) available for this study does not alleviate this situation.

Occurrence. — In Sweden, *A. coriacea* is presently known only from the Middle Cambrian; in the sections examined for this paper, it was found only in the sample from the 'Obolus' beds at Horns udde (Figs. 9—10); the fragmented valves were obviously redeposited.

Orbithele sp.

Systematic position. — Genus *Orbithele* Sdzuy, 1955.

Material. — Not illustrated. Total of one dorsal valve and several fragments.

Discussion. — Fragments of *Orbithele* can be distinguished from those of other acrothelid genera by the spinose edge of growth lamellae, and the well-developed interior pedicle tube.

Occurrence. — The genus is presently known only from the Lower Ordovician (Tremadoc-Arenig); it was obtained in the 'Obolus' beds at Sjurberg, and from the Latorp Limestone in the Finngrundet core (Fig. 9).

Eoconulus? spp.

Fig. 4C–I.

Systematic position. – Family Eoconulidae Rowell, 1965; ?Genus *Eoconulus* Cooper, 1956.

Material. – Illustrated: SGU 8479 – 8481. Total of 10 dorsal valves.

Discussion. – As noted by Holmer (1989, p. 147) the taxonomy of *Eoconulus* is very complex, due to the common lack of a preserved ventral valve and the strongly variable morphological characters of the dorsal valve. The dorsal valves found in the present study might represent more than one species. One dorsal valve has a well-developed, undivided psudointerarea (Fig. 4E–I). The pseudointerea is lacking from all other described species of the genus.

Occurrence. – The genus is known from throughout the Ordovician; *Eoconulus*? spp. was obtained in the 'Obolus' beds and the overlying Latorp Limestone at Sjurberg, as well as in the Latorp Limestone of Finngrundet core (Figs. 9–10).

Eosiphonotreta? sp.

Systematic position. – Order Siphonotretida Kuhn, 1949; Superfamily Siphonotretoidea Kutorga, 1848; Family Siphonotretidae Kutorga, 1848; ?Genus *Eosiphonotreta* Havlíček, 1982.

Material. – Not illustrated; numerous fragments.

Discussion. – These fragments assigned to *Eosiphonotreta*? sp. mostly consist of isolated interior pedicle tubes and the thickened dorsal and ventral

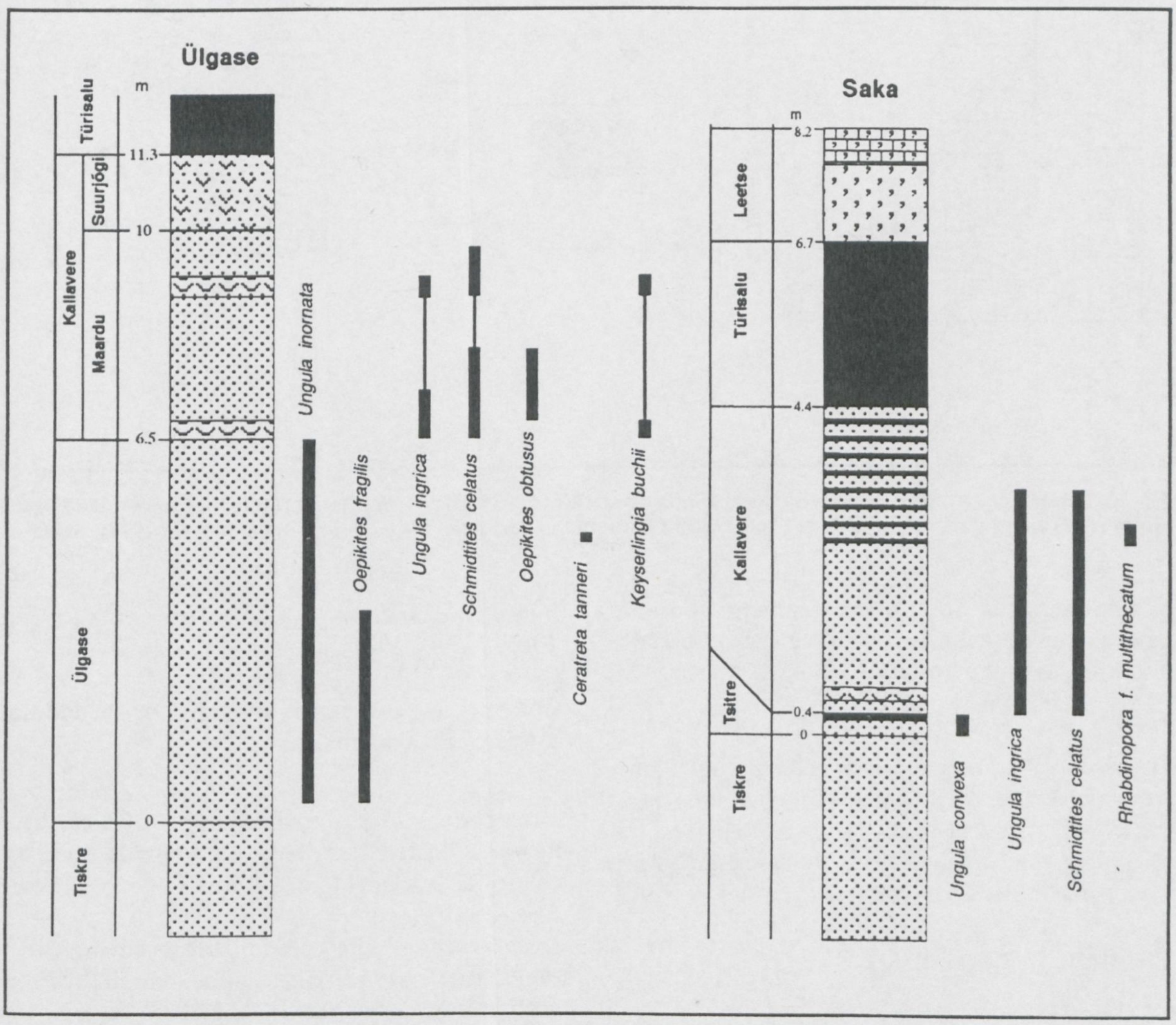

Fig. 8. Faunal logs from the Ülgase and Saka sections, northern Estonia. For legend see Fig. 9.

219

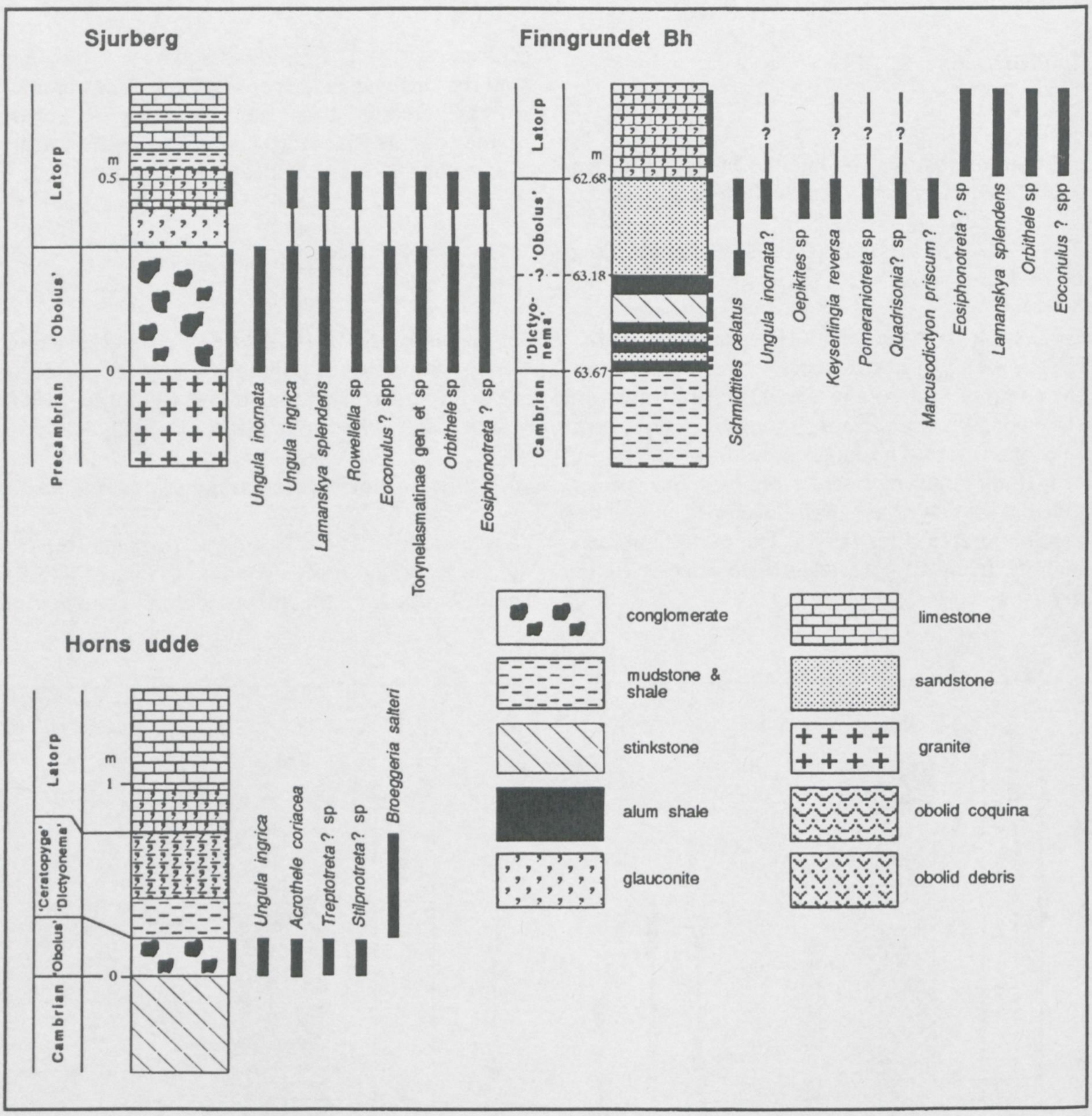

Fig. 9. Faunal logs from sections at Sjurberg, Siljan district (after Tjernvik 1956), Horns udde, northern Öland (after Holm 1882) and the Finngrundet core, South Bothnian submarine district (after Thorslund & Axberg 1979), Sweden.

pseudointerareas. Some of the fragments appear to have had an apsacline to catacline ventral pseudointerarea, as in the Lower Ordovician type species, *E. verrucosa* (Eichwald, 1840).

Occurrence. — The genus is at present known only from the Lower Ordovician (Tremadoc-Arenig); the fragments occur in the '*Obolus*' beds and Latorp Limestone at Sjurberg, as well as in the Latorp Limestone in the Finngrundet core (Figs. 9—10).

Paterinida gen. et sp.

Fig. 7K—L.

Systematic position. — Order Paterinida Rowell, 1965.

Material. — Illustrated: PMU B591; in addition numerous fragments.

Discussion. — The pitted ornament of these fragments indicates that they are paterinids, but they cannot be assigned to any genus.

Occurrence. — The paterinid fragments occur in the 'Obolus' beds at Horns udde, and in the Finngrundet core (interval 62.67—62.82 m; Figs. 9—10).

Problematicum

Genus *Marcusodictyon* Bassler, 1952.

Systematic position. – Phylum, Class, Order, Family unknown.

Type species. – By original designation; *Heteronema priscum* Bassler, 1911.

Diagnosis. – See Taylor (1984, p. 177).

Species assigned. – *Heteronema priscum* Bassler, 1911, *Marcusodictyon expectans* Mergl, 1984, ?*Gochtia rete* Eisenack, 1968.

Discusson. – *Marcusodictyon* consists of a network of phosphatic ridges occurring mainly on the surface of lingulate brachiopod valves; it was originally described as a ctenostome bryozoan by Bassler (1911, 1952, 1953). However, the studies of Taylor (1984) indicate that *M. priscum* is not a bryozoan, but a problematicum that might possibly be related to the ascidians. It is to be noted that the obolid specimens with *M. priscum* from Jägala-Joa figured by Taylor (1984) as *Obolus appollinis* Eichwald, actually represent *S. celatus*.

Mergl (1984) described *Marcusodictyon expectans*, occurring on pebbles from the Lower Ordovician of Bohemia. Popov et al. (1989, p. 150, pl. 13: 3) described *Marcusodictyon* sp. encrusting on the hyolithelminth *Torellella putilovensis* from the Upper Cambrian of Ingria, Russia.

Gochtia rete was described by Eisenack (1968) from erratic boulders in Germany of the Upper Silurian *Beyrichia* limestone; the morphology of this species closely comparable to that of the *M. priscum*, and Taylor (1984) considered the genus *Gochtia* Eisenack, 1968 to be a junior synonym of *Marcusodictyon*.

Occurrence. – Upper Cambrian – ?Silurian.

Marcusodictyon priscum? (Bassler, 1911)

Fig. 7M–N.

Synonymy. – □ 1896 Bryozoen (?) – Mickwitz, pl. 3:38. □ 1911 *Heteronema priscum* n.sp. Bassler, p. 57, text-fig. 6a–d. □ 1953 *Marcusodictyon priscum* (Bassler) – Bassler, p. G35, figs. 8:7a–b.

Samples / Taxa documented	Finngrundet Bh			Sjurberg		Horns udde	Erratics				
	'Obolus'		Latorp	'Obolus'	Latorp	'Obolus'	Gärdsjö	Rödbo	Erken	Fanton	Slätö
	62.97-63.18 m	62.68-62.82 m									
Ungula ingrica				++	+	++		++	++	++	++
Ungula inornata		?	?	-			++				
Schmidtites celatus	+	++						-		-	
Oepikites sp		++								?	
Rowellella sp				++	++						
Lamanskya splendens			-	+	+						
Treptotreta ? sp						+					
Torynelasmatinae gen et sp				+	+						
Quadrisonia ? sp		+	?								
Stilpnotreta ? sp						++					
Eoconulus ? spp			+	+	+						
Pomeraniotreta sp		-	?								
Keyserlingia reversa		++	?								?
Ceratreta tanneri							+				
Acrothele coriacea						+					
Orbithele sp			+	-	-						
Eosiphonotreta ? sp			-	-	-						
Paterinida gen et sp		+				+					
Marcusodictyon priscum ?		-									
Cordylodus rotundatus	+	+									+
Cordylodus prion		+						+			
Cordylodus sp								+			+
Cordylodus angulatus		+									+
Paroistodus numarcatus	+	+									+
Paltodus subaequalis											+
Drepanoistodus deltifer		+									

Fig. 10. Distribution of lingulates, conodonts and problematica in the examined samples. The approximate estimated relative abundance is given: + +, abundant; +, present; –, rare; ?, questionable occurrence.

☐ 1984 *Marcusodictyon priscum* (Bassler) – Taylor, p. 178, figs. 1, 2, 3. ☐ 1989 *Marcusodictyon priscum* (Bassler) – Popov & Khazanovitch (*in* Popov et al.), p. 149, pl. 3:12–14.

Lectotype. – Selected by Taylor (1984, p. 178). Specimen no. 57180 (U.S. National Museum of Natural History, Washington D.C.); Kallavere Formation, Jägala river, near Jägala Falls, northern Estonia.

Material. – Illustrated: PMU B600. Total of 1 specimen.

Discussion. – One unidentifiable obolid fragment from the Finngrundet core has a polygonal network of low phosphatic ridges (Fig. 7M–N) covering the exterior surface; it is more or less identical to the phosphatic, epibiontic problematicum *Marcusodictyon priscum* (Bassler, 1911). This species was first figured by Mickwitz (1896).

Previously, *M. priscum* was known only from northern Estonia where it occurs almost exclusively on *Schmidtites celatus* (Heinsalu et al., 1987; Popov et al. 1989).

Occurrence. – *Marcusodictyon priscum*? was found in the 'Obolus' beds in the Finngrundet core (interval 62.68–62.82 m; Figs. 9–10); in northern Estonia the species occurs in the Upper Cambrian Tsitre Formation and Upper Cambrian–lowermost Tremadoc Maardu Member.

Cambrian–Ordovician lingulate biostratigraphy in Sweden and Estonia

For consistence and clarity throughout this paper we take the Cambrian–Ordovician boundary to be at the horizon employed traditionally on the East European platform, defined by the first appearance of *Cordylodus proavus*. However, there is as yet no formally established stratotype for the Cambrian–Ordovician boundary (e.g. Norford 1991; Landing 1993). The lower boundary of the *Cordylodus lindstromi* Biozone appears to be roughly correlative with the base of the Tremadoc Series in Wales (e.g. Fortey et al. 1991), and the base of the 'Dictyonema Shale' (and top of the *Acerocare* Biozone) in Sweden and Norway also seems to be located at about this level (Bruton et al. 1988). In Estonia, the first appearance of *Rhabdinopora* has been reported from within the *Cordylodus proavus* Biozone (Kaljo et al. 1988), but according to more recent interpretations this level might be within the *C. lindstromi* Biozone (Norford 1991, p. 31).

Because our biostratigraphic interpretations of the Swedish sections are based entirely on comparisons with sequences in the northern East Baltic, two Estonian sections are described briefly as 'reference sections'.

Estonia

Recent studies of more than twenty sections through the Cambrian- Ordovician sequences in the Baltic-Ladoga 'clint' [= cliff] area (in the sense of Popov et al. 1989) of the East Baltic have resulted in a detailed biostratigraphy based on conodonts, acritarchs and lingulates (e.g. Kaljo et al. 1986,1988; Popov et al. 1989; Mens et al. 1989). Most of the sections are incomplete, with one or more conodont biozones missing. The Ülgase and Saka sections are here selected as reference sections for the northern East Baltic (Fig. 8). We are adopting the lingulate biozones based on the recent taxonomic revision by Popov & Khazanovitch (*in* Popov et al. 1989). As noted above, the updated taxonomy of the obolids has implications for the biostratigraphic zonation, as some of the present zonal species have been confused previously with each other.

Ungula inornata is found in the Upper Cambrian Ülgase Formation of Estonia, where it is associated with the acrotretids *Angulotreta postapicalis* and *Ceratreta tanneri*. Redeposited, worn valves of *Ungula inornata* occur in coquinas at the base of the Kallavere Formation.

Ungula convexa occurs mainly in the Ladoga Formation in Ingria, but there are some rare finds also from northern Estonia, such as the Saka outcrop, where it occurs in the Tsitre Formation. *Schmidtites celatus* also appears together with *U. convexa*, but it is more common in the *U. ingrica* Biozone.

Ungula ingrica commonly occurs in association with *Schmidtites celatus, Oepikites obtusus*, and *Keyserlingia buchii*. Assemblages from coarse-grained sandstones are dominated by thick-shelled *U. ingrica*, whilst *S. celatus* is most common in fine-grained sandstones.

Obolus apollinis seldom has any accompanying brachiopods, but sometimes it occurs together with *Helmersenia ladogensis*, and most commonly in fine-grained sandstones. Stratigraphically, both species appear just above the first appearance of *Cordylodus proavus*. They are distributed in the Tosna Formation, Ingria (see Popov et al. 1989, for a list of localities). In Estonia, recent finds of *Obolus apollinis* from drill cores in the Rakvere area and on the island of Hiiumaa suggest that the facies yielding this species extends from Ingria to North Estonia and Hiiumaa (Mens et al. in press).

Locality 1. Saka section (Figs. 1, 8); this coastal section, situated 2 km west of the village of Saka, was exposed in 1984 as a result of the construction of a waste water pipe; it forms an unbroken section from the Lower Cambrian Tiskre Formation to the Lower Ordovician Kunda Stage. The detailed lithostratigraphic subdivision of the Kallavere Formation at this locality has been the subject of some debate (e.g. Kaljo et al. 1986; Popov et al. 1989; Heinsalu et al. 1991) but, for the purpose of the present study, we use this formation without further subdivision. Lithostratigraphically it corresponds to the Maardu and Suurjôgi members in the Ulgase section (locality 2).

The greyish-green and light-grey, fine-grained sandstones and siltstones of the Tiskre Formation are exposed at the base of the section. The overlying Tsitre Formation, reaching 0.4 m in thickness, consists of light grey siltstones and fine-grained sandstones, interbedded in the upper part with lensoid, dark brown shales. *Ungula convexa* has been found both at the base and at the top of the formation. The paraconodonts *Westergaardodina* cf. *bicuspidata*, *Prooneotodus* cf. *gallatini* and *Furnishina* sp. indicate a Late Cambrian age (Heinsalu et al. 1991).

The Tsitre Formation is evidently younger than the Ulgase Formation at Ulgase (see below) and older than the Kallavere Formation; it is made up of sandstone lenses, which, according to the acritarch zonation have slightly varying ages (I. Paalits, pers. comm., 1991). Some of these lenses (e.g. in core M-77, Holmer & Popov 1990) yield a brachiopod fauna including *Ungula ingrica*, *Schmidtites celatus*, *Oepikites obtusus* and *Oepikites triquetrus*, similar to that of the overlying Kallavere Formation.

The lower 1.8 m of the Kallavere Formation is represented by two cycles, starting with brachiopod coquinas and coarse- to medium-grained, light grey sandstones and terminating with fine-grained sandstones. *Ungula ingrica* and *Schmidtites celatus* occur in the coquinas at the base of the formation and 0.5 m above it. This interval corresponds to the *Cordylodus proavus* and the *C. lindstromi* conodont biozones.

The upper 2.2 m is composed of siltstones interbedded with thin layers of black kerogenous shale, which become more common in the topmost 40 cm. At the base of this interval, the conodonts *Iapetognathus* sp., *Eoconodontus notchpeakensis* and *Cordylodus intermedius* and the graptolite *Rhabdinopora flabelliformis* appear. The uppermost 1.2 m of the interval is referred to the *Cordylodus rotundatus/C. angulatus Biozone* (Heinsalu et al. 1991).

The overlying 2.3 m thick kerogenous shales of the Türisalu Formation ('Dictyonema Shale') yield the zonal species *Drepanoistodus deltifer pristinus* accompanied by *C. angulatus*, *C. rotundatus*, *Iapetognathus* sp., *Oneotodus altus* and *Acontiodus viirae*.

The shales of the Türisalu Formation are covered by glauconite sandstones (1 m) and glauconitic limestones (0.5 m) of the Leetse Formation, above which are exposed limestones of the Volkhov and Kunda Stages.

Locality 2. Ulgase section (Figs. 1, 8); two outcrops of Cambrian–Ordovician boundary beds are situated near the ruins of the 'Eesti Vosvoriit' factory, close to Kallavere, 10 km east of Tallinn. One outcrop is the stratotype of the Ulgase Formation and the second is exposed about 200 m eastwards. The brachiopods and conodonts have been recently studied in the upper part of the second outcrop, which is the neostratotype of the Maardu Member (Heinsalu et al., 1987).

As the two sections can be tied together by tracing the discontinuity surface and the coquina bed at the base of the Maardu Member, we can present a composite sequence using data from both outcrops (Fig. 8).

The Ülgase Formation is 6.5 m thick, represented by light-grey sandstones and siltstones. In its uppermost part it has yielded *Ungula inornata* and *Oepikites fragilis* and the hyolithelminth *Torellella* sp. A single valve of *Ceratreta tanneri* has been reported from 1.5 m below the top of the formation (Holmer & Popov 1990). These species, which occur together commonly with *Angulotreta postapicalis*, are characteristic of the Ülgase Formation. *Ungula inornata* and associated species occur in several outcrops along the so-called 'Baltic clint' (continuous cliff from Paldiski, northern Estonia to St. Petersburg – a distance of about 600 km), e.g. Tônismägi (Kaljo et al. 1988), Mäekalda (Mens et al. 1989), Iru, Valkla, Hundikuristik, Turjekelder and boring cores M-77 and R-1653 (Holmer & Popov 1990). The overlying Kallavere Formation is exposed in full thickness in an outcrop 200 m east.

The sequence of the Maardu Member can be interpreted as two transgressive sedimentary cycles, commencing with a brachiopod coquina and coarse-grained sandstones and terminating with fine-grained sandstones (see also Heinsalu et al. 1987, fig. 1). The distribution of brachiopods is related to grain size; as at Saka, the thick-shelled *Ungula ingrica* and the acrotretid *Keyserlingia buchii* are present in both coquinas, whilst *Schmidtites celatus* and *Oepikites obtusus* prevail in fine-grained sediments. Most species, however, range from the basal coquina level (*Westergaardodina* Biozone) to the upper coquina level and upwards (*Cordylodus proavus* or *C. intermedius* biozones). The problematical epibiont, *Marcusodictyon priscum* (Bassler) occurs here on the valves of *Schmidtites celatus*.

The overlying Suurjôgi Member is 1.3 m thick and consists of brownish-grey cross-bedded fine to medium grained sandstones, corresponding to the *Cordylodus rotundatus/C. angulatus* Biozone. It contains mostly redeposited unidentifiable debris of brachiopod valves and only rarely identifiable fragments of *Ungula ingrica* and *Schmidtites celatus* can be found.

The sandstones of the Kallavere Formation are overlain by black kerogenous shales of the Türisalu Formation, the 'Dictyonema Shale'.

Sweden

Island of Öland. – The Upper Cambrian sequence on Öland thins out towards the north and disappears in the northernmost part of the island, where numerous conglomerates occur at several levels between the Middle Cambrian and the Lower Ordovician (Martinsson 1974). The 'Obolus conglomerate' is developed only in northern Öland, where it occurs directly above the Cambrian sequence; '*Obolus*' has been reported from the conglomerate at several localities (e.g. Westergård 1922; 1947, p. 9), and at the coastal section at Djupvik (north of Borgholm) it is associated with '*Dictyonema flabelliforme*' according to Westergård (1947, p. 9).

223

Locality 3. Horns udde (Figs. 1, 9); the basal part (including the 'Obolus conglomerate') of this coastal section on northern Öland is most commonly covered by beach gravel (as noted by Westergård 1947, p. 9), and we could observe here only small exposures of 'Obolus conglomerate' yielding poorly preserved lingulate fragments. Samples used in the present study were collected by G. Holm in 1889.

There are some minor differences between the sections given by, e.g., Holm (1882) and Hadding (1927), in that Holm (1882, pl. 12) found the 'Obolus conglomerate' directly above a stinkstone bed, whilst Hadding (1927, fig. 24) noted a glauconitic bed between the stinkstone and the conglomerate; there appears to be some lateral variation along the section (see also van Wamel 1974 for an account of the stratigraphy at Horns udde).

Holm (1882, p. 72) reported the trilobites *Paradoxides tessini* [= *P. paradoxissimus*], *Olenus gibbosus*, *Agnostus pisiformis*, and *A. laevigatus* [= *Lejopyge laevigata*] from the 'Obolus conglomerate' at this locality. As would be expected, we also found a fauna of redeposited lingulates varying in age from mid to late Cambrian; the assemblage includes *Acrothele coriacea*, *Stilpnotreta*? sp., *Treptotreta*? sp, and *Ungula ingrica* (referred to as '*Obolus*' by Holm 1882, and as '*Obolus apollinis*' by numerous subsequent authors). None of the recorded lingulate species are known to occur in the Tremadoc and it is possible that the latest stage of redeposition at Horns udde took place during the Late Cambrian, rather than during the Tremadoc as proposed by Westergård (1947).

The overlying 'Dictyonema/Ceratopyge shale' contains only *Broeggeria salteri* (Fig. 9).

South Bothnian submarine district. — During 1970–1972, two cores were drilled in the Bothnian Sea, at Finngrundet (Östra Banken) and Västra Banken. The interval with 'Obolus sandstone' from both cores was described by Thorslund & Axberg (1979).

Locality 4. Finngrundet core (Figs. 1, 9); only the Finngrundet core was investigated for the present paper, for which two of the samples (intervals 62.97 – 63.18 m and 62.68 – 62.82 m) yielded lingulates. The sandstones within the 'Dictyonema Shale' were barren.

Only *Schmidtites celatus* and the conodonts *Cordylodus rotundatus* and *Paroistodus numarcuatus* were found in the lower sample (interval 62.97–63.18 m; Figs. 9–10), possibly indicating that the last stage in redeposition could have taken place during the late Tremadoc/ early Arenig.

The overlying sample (interval 62.68–62.82 m) yielded a much richer assemblage of redeposited Upper Cambrian lingulates including *Keyserlingia reversa*, *Schmidtites celatus*, *Oepikites* sp., and questionable *Ungula inornata*. *Pomeraniotreta* sp. is possibly of late Tremadoc – early Arenig age, and numerous conodonts indicate the *Drepanoistodus deltifer* Biozone as the latest stage in the redeposition.

The lowermost sample from the overlying Latorp Limestone also includes some redeposited *Ungula inornata*? and *Keyserlingia reversa*?

Uppland. — In Uppland the 'Obolus' beds are known only from ice-transported erratic boulders; the source rock of these boulders is most likely in the submarine sequence north of Gävle and the Åland Sea (e.g. Söderberg 1993, figs. 2, 3). The discussed boulders are in old collections in the Palaeontological Museum, Uppsala and the Geological Survey of Sweden (SGU), Uppsala.

The lingulates in numerous erratic boulders (housed in the Palaeontological Museum; collected by C. Wiman) from the island of Fanton in Singö Fiord (see Wiman 1905, for locality data) were described by Wiman (1905, p. 59, pl. 3:1–12). Redeposited and worn specimens of *Ungula ingrica*, *Schmidtites celatus*, and *Oepikites*? sp. (Figs. 2C–E, K, 10) are present. An equivalent assemblage has not been found in the Finngrundet/Västra Banken cores.

One erratic boulder (number 121, housed in SGU and collected by A.H. Westergård in 1929) from the area around Lake Erken yielded only numerous worn redeposited specimens of *Ungula ingrica* (Figs. 2B, F, 10); the boulder consists of a calcareous poorly sorted sandstone, but the possibility of further investigations by etching in weak acids has not yet been attempted.

From the small village of Rödbo, north of Uppsala (see Wiman 1905), one large erratic boulder (number 16, stored in the Palaeontological Museum, collected by C. Wiman) contains numerous worn, redeposited specimens of *Ungula ingrica*, and one valve of *Schmidtites celatus* (Figs. 2A, 10). The conodonts *Cordylodus prion* and *C.* sp. were also recorded (Fig. 10), indicating that the last stage of redeposition in this case could have taken place sometime during the Tremadoc (*C. lindstromi – C. rotundatus/C. angulatus* biozones).

One erratic boulder from Slätö (housed in SGU, Uppsala, collected by N.O. Holst in 1883) contains numerous redeposited specimens of *Ungula ingrica* and one questionable valve of *Keyserlingia reversa* (Figs. 7O, 10). The associated conodont assemblage (Fig. 10) indicates that the last stage of redeposition took place sometime during the early Arenig.

Siljan district. — In this region, the 'Obolus' beds, where present, rest directly on the Precambrian basement. Holmer & Popov (1990, p. 259) summarized the state of knowledge concerning this interval in the district (see also Jaanusson 1982; Wickman & Nyström 1985).

The specimens of '*Obolus apollinis*' illustrated by Moberg & Segerberg (1906, pl. 3:1, 2) from Klittberget are *Ungula ingrica*, but this locality was not investigated further for our study.

At the Djupgrav section, the conglomeratic Djupgrav Formation has been dated as early Tremadoc by the occurrence of *Rhabdinopora socialis* (as *Dictyonema sociale*; Thorslund & Jaanusson

1960; Jaanusson 1982; identification confirmed by D. Kaljo, pers. comm., 1992) in a shale unit close to the top of the formation; no obolids have been found in the conglomerate at this locality.

Holmer & Popov (1990, p. 259) noted the co-occurrence of *Ceratreta tanneri* and *Ungula inornata* (Figs. 2G–J, 10) in erratic boulders of a soft sandstone at Gärdsjö.

Locality 5. Sjurberg (Figs. 1, 9); this railway section outside Rättvik (Fig. 1) was described by Tjernvik (1956) who took the occurrence of '*Obolus apollinis*' as an indicator of an early Tremadoc age. However, this conglomerate evidently contains redeposited material from various sources, and yields several lingulate species ranging in age from the Late Cambrian (e.g. *Ungula ingrica* and *U. inornata*) to the Arenig (e.g. *Lamanskya splendens* and *Rowellella* sp.; Figs. 9–10). Thus, the latest stage of redeposition of the 'Obolus' beds occurred not earlier than the Arenig (Fig. 1).

Östergötland. – In this district, the hiatus at the Cambrian–Ordovician boundary is of much smaller magnitude than in any of the districts discussed above; in most sections only the Upper Cambrian *Acerocare* Biozone is missing (Fig. 1). At many localities (see Holmer & Popov 1990 for a review) the overlying 'Dictyonema Shale' includes several sandstone units. Holmer & Popov (1990) reported *Ceratreta tanneri* from the Upper Cambrian at four localities, but the sandstones in the 'Dictyonema shale' have so far not yielded any lingulates. The report of '*Obolus*' by Linnarsson & Tullberg (1882) from the sandstones has not been confirmed by our investigations.

As noted by Holmer & Popov (1990), the latest development of sandstones in Östergötland was during the Arenig (Fig. 1).

Summary and conclusions

In the past, sandstones containing '*Obolus apollinis*' were interpreted mostly as being of earliest Ordovician age, that is, younger than the base of *C. proavus* Biozone (see also discussion above). Our data now suggest that the 'Obolus' beds in Sweden were formed during several consecutive phases of Late Cambrian–Early Ordovician transgressions (see also Hadding 1927). In many cases, the Swedish 'Obolus' beds represent repeatedly reworked material yielding fossils from source rocks of a considerable age range. The refinement of the biostratigraphical zonation, based on lingulate brachiopods from the reference sections in Estonia and Ingria, allows us to estimate the age range of the source rock in these cases.

This revision of the lingulate brachiopods from the Swedish 'Obolus' beds shows that many of the faunas are common with those of the sandstone sequence in the Cambrian–Ordovician boundary beds of northern Estonia. *Ungula inornata* and *Ceratreta tanneri* indicate a Late Cambrian age, correlative with the Ülgase Formation in Estonia. However, *Obolus apollinis* and *Helmersenia ladogensis*, both appearing at the base of the *C. proavus* Biozone in Ingria and Estonia, have not been found in Sweden. The 'Obolus' beds in Sweden also contain lingulates known from the Middle–Late Cambrian or Arenig in other Scandinavian sections.

At Horns udde the 'Obolus conglomerate', containing *Ungula ingrica*, can tentatively be dated as Late Cambrian, and in Dalarna, erratic boulders from Gärdsjö, containing *Ungula inornata* and *Ceratreta tanneri*, also indicate the presence of Upper Cambrian source rocks in the vicinity. A find of *Rhabdinopora socialis* from the Djupgrav section (Thorslund & Jaanusson 1960) indicates that sediments were also deposited during the Tremadoc. The 'Obolus' beds in the Sjurberg section, yielding *Ungula ingrica* and associated species, contain also elements of an early Arenig fauna.

In the South Bothnian area and in land, erratic boulders contain *Keyserlingia reversa*, *Ungula ingrica*, and conodonts ranging from *Westergaardodina* to *Cordylodus rotundatus*/*C. angulatus* biozones. In some cases, conodonts of the *Drepanoistodus deltifer* Biozone are also present. The interval of the 'Obolus beds' in the Finngrundet core yields *Schmidtites celatus*, *Keyserlingia reversa* and conodonts of the *Cordylodus rotundatus*/*C. angultus* and *Drepanoistodus deltifer* biozones, and the latest stages of their formation can be dated as earliest Arenig.

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225

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227

III

228

III

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UPPER CAMBRIAN BIOSTRATIGRAPHY OF ESTONIA

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Abstract. In Estonia the Upper Cambrian is represented by siliciclastic rocks, mainly quartzose sand- and siltstones containing thin interlayers of greenish-grey clays in the lower and dark kerogenous argillites in the upper part of the section. The Upper Cambrian of Estonia is subdivided into four formations: Petseri, Ülgase, Tsitre, and Kallavere.

The biostratigraphic subdivision is based on three fossil groups—acritarchs, conodonts, and lingulates. Five acritarch-, four conodont-, and at least three lingulate-based biostratigraphic units are distinguished, which may be used in the Upper Cambrian stratigraphic scale of Estonia. Subdivision of the lower part of the section is more reliable on acritarchs and that of the upper part, on conodonts.

Using the succession of acritarchs and conodonts the Petseri and Ülgase formations are approximately correlated with the *Olenus* Zone and the latter also with the *Parabolina spinulosa* Zone (lower part). The Tsitre Formation (lower part) corresponds to the *P. spinulosa* (upper part) and *Leptoplastus* zones, its uppermost part to the *Peltura scarabaeoides* Zone and the lower part of the Kallavere Formation can be referred to *Acerocare* Zone.

Key words: acritarchs, conodonts, lingulates, Upper Cambrian, Estonia.

INTRODUCTION

In the framework of biostratigraphic studies of the Cambrian—Ordovician boundary beds in Estonia and neighbouring areas, a number of key sections have been described in detail during the past 10 years with the documentation of the distribution of acritarchs, conodonts, and lingulate brachiopods. Conodont zonation has also contributed to detailed biostratigraphic correlation of the Upper Cambrian deposits exposed in the outcrops along the Baltic—Ladoga clint (Kaljo et al., 1986; Попов et al., 1989). Alongside conodonts, lingulate brachiopods have proved to be useful for basinwide correlations, particularly between Estonian and Swedish sections (Puura & Holmer, 1993). Acritarchs, which occur only in thin argillaceous interbeds of the sandstone sequence, serve as a basis for a detailed biostratigraphic subdivision of sections and for correlation with distant sequences worldwide (Волкова, 1990; Paalits, 1992a, 1992b).

Only part of the results of this research has been published, mostly as detailed descriptions of separate key sections (e. g. Хейнсалу et al., 1987, 1991; Kaljo et al., 1988; Mens et al., 1989).

231

The purpose of the present paper is to document the co-occurrence of acritarchs, conodonts, and lingulates in Estonian Upper Cambrian sections and to discuss the relationships of their biounits. A tentative correlation of acritarch, conodont, and lingulate biounits with Scandinavian trilobite zones is presented.

GEOLOGICAL SETTING

In the present paper the Upper Cambrian is considered in its traditional extent for the East European Platform, i. e. from the base of the *Agnostus pisiformis* Zone to the top of the *Acerocare* Zone. As trilobites are lacking in Estonia and *Cordylodus proavus* is documented in the Nærsnes section, Norway, together with trilobites of the *Acerocare* Zone (Bruton et al., 1988), we have included also the *C. proavus* Zone level into our discussion.

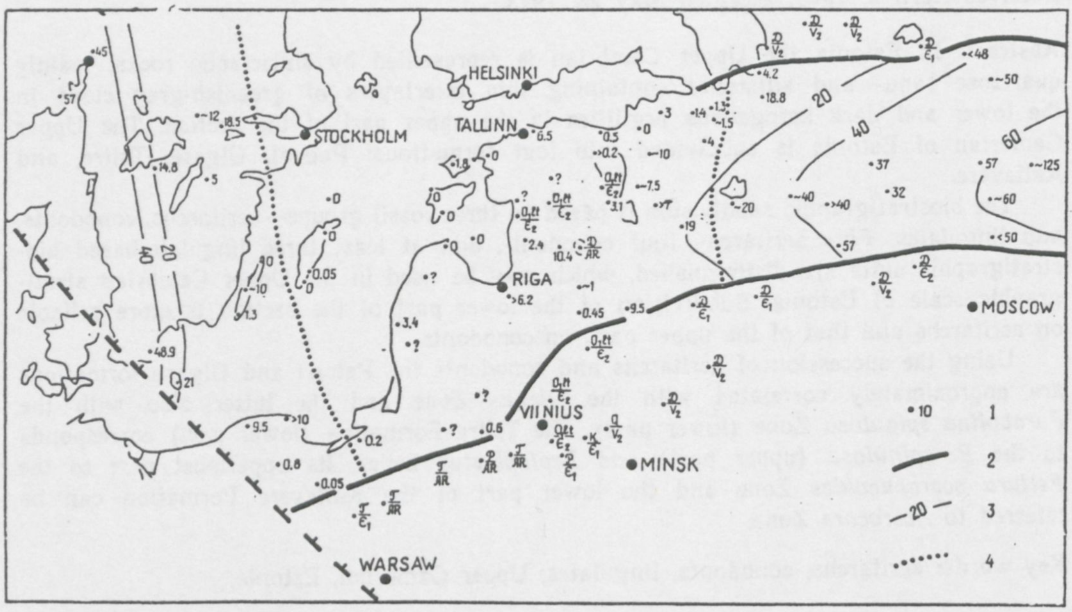


Fig. 1. The distribution, thickness, and facies of the Upper Cambrian in the north-western part of the East European Platform.

1 — thickness of the corresponding deposits (up to the base of the *Cordylodus* succession); the question mark shows an undetermined Cambrian or Ordovician age of deposits; *2* — recent erosional boundary of the Upper Cambrian; *3* — isopachytes; *4* — boundary of a facies belt.

The Upper Cambrian rocks, which have been preserved from post-Cambrian erosion, are widely distributed in the north-western part of the East European Platform ranging as a sublatitudinal zone from the Oslo graben to the Moscow syneclise (Fig. 1). They are exposed along the Baltic—Ladoga clint area and in the river valleys intersecting it, occurring in the form of isolated patches also in the Oslo graben, South and Central Sweden, and are often allochthonously lying near the north-western margin of the Platform. In the rest of the territory, the Upper Cambrian rocks are lying at a depth from a few metres (e.g. northern Estonia and southern Scandinavia) to two thousand metres (central part of the Moscow syneclise).

From the west to the east, the following lateral lithofacies sequences can be observed. In the west, approximately up to the Prabuty—Öland—Närke line, alum shales are prevailing. Eastwards, there occurs a facies of sand- and siltstones, with rare thin interlayers of so-called Dictyonema shale, clay and sandstones with lenses of lingulate brachiopod valves and debris. East of the Ladoga—Porhov line, the Upper Cambrian is represented by siltstones and clays, more rarely by sandstones, while organic-rich rocks are absent (Fig. 1).

The sections of these three areas, tentatively distinguished as western, transitional, and eastern facies belts, differ not only in lithology and thickness, but also in stratigraphic completeness (see Mens et al., 1990) and paleontological evidences.

The Upper Cambrian biostratigraphy of the western facies belt is mainly based on trilobites and their zonation serves as a standard for platform correlation and a basis for interregional correlation (Westergård, 1922). From these sections of the transitional belts no trilobites have been found whereas the sections of the eastern facies belt have yielded only a few specimens. In the transitional belts the Upper Cambrian biostratigraphy is based on the other groups occurring in abundance, namely, acritarchs, conodonts, and lingulate brachiopods.

The Upper Cambrian sequence of Estonia is exposed in numerous outcrops and boring cores (Fig. 2). This has allowed of detailed investigation of the corresponding deposits.

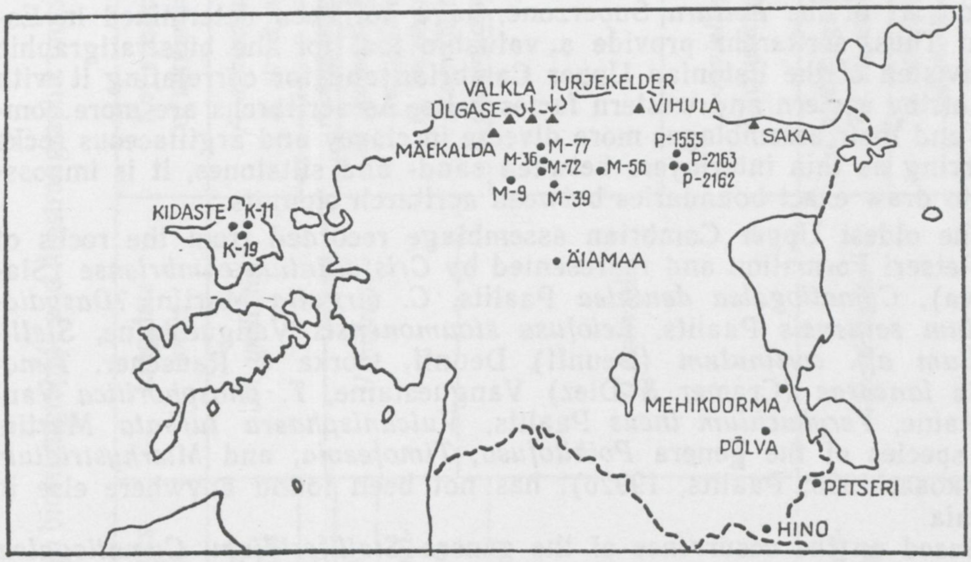


Fig. 2. Location of the main outcrops (triangles) and borings (solid circles) mentioned in the text.

In Estonia the strata considered as the Upper Cambrian are siliciclastic, dominated by silt- and sandstones less than 20 m in thickness (Fig. 1). Argillaceous rocks are limited, forming greenish-grey clayey interlayers within light-coloured coarse-grained deposits while in the uppermost part of the section they are often represented by their kerogen-bearing variety, the Dictyonema shales.

The Upper Cambrian succession is very condensed and interrupted by several minor as well as major hiatuses. The presence of gaps is supported by petrographic evidences and by the absence of one or some biounits in the section.

The Upper Cambrian lies mainly on Lower Cambrian silt- and sandstones and only locally on Middle Cambrian rocks. It is overlain by Tremadocian siliciclastics, in places by younger Ordovician limestones.

According to the stratigraphic subdivision, the Upper Cambrian

233

includes the Petseri, Ülgase, and Tsitre formations and a part of the Kallavere Formation. The Petseri Formation, known only in the subsurface, is distributed in south-eastern Estonia (see Волкова et al., 1981). The other three formations occur more widely in northern Estonia (Kaljo et al., 1986; Mens et al., 1990; etc.).

Acritarchs have been studied from the Tõnismägi, Mäekalda, Suhkrumägi, Ülgase, Valkla, Turjekelder, Vihula, and Saka outcrops and from the boring cores M-9, M-36, M-46, M-56, M-72, M-77, P-2162, Hino, Mehikoorma, Petseri, and Põlva (Fig. 2).

The taxonomic diversity and stratigraphic as well as relatively wide lateral distribution of acritarchs have enabled to establish the guide assemblages within the Upper Cambrian succession of the East European Platform including six acritarch assemblages (BK 1, BK 2, BK 3, BK 4A, BK 4Б, BK 5) by Volkova (Волкова, 1990). Three similar assemblages (BK 3, BK 4Б, BK 5) have been established in the Estonian Upper Cambrian while the assemblage BK 2 can be divided into two independent parts with key species ?*Dasydiacrodium setuensis* and *Leiofusa stoumonensis* for the lower and *Impluviculus multiangularis*—?*Veryhachium dumontii* for the upper one. The assemblages BK 1 and BK 4A, corresponding respectively to the *A. pisiformis* Zone and to the lower part of the *Peltura* Superzone, have not been determined in Estonia. Thus, acritarchs provide a valuable tool for the biostratigraphic subdivision of the Estonian Upper Cambrian and for correlating it with that of the eastern and western facies belts. As acritarchs are more common and their assemblages more diverse in clayey and argillaceous rocks occurring as thin interlayers between sand- and siltstones, it is impossible to draw exact boundaries between acritarch biounits.

The oldest Upper Cambrian assemblage recorded from the rocks of the Petseri Formation and represented by *Cristallinium cambriense* (Slavikova), *Cymatiogalea dentalea* Paalits, *C. virgulta* Martin, ?*Dasydiacrodium setuensis* Paalits, *Leiofusa stoumonensis* Vanguestaine, *Stelliferidium aff. certinulum* (Deunff) Deunff, Gorka & Rauscher, *Timofeevia lancarae* (Cramer & Diez) Vanguestaine, *T. phosphoritica* Vanguestaine, *Veryhachium incus* Paalits, *Vulcanisphaera turbata* Martin, and species of the genera *Poikilofusa*, *Timofeevia*, and *Micrhystridium* (Волкова, 1990; Paalits, 1992b), has not been found anywhere else in Estonia.

Based on the occurrence of the genera *Stelliferidium*, *Cymatiogalea*, *Leiofusa*, and *Veryhachium*, which appeared in the *Olenus* time (Potter, 1974; Downie, 1984), and the absence of the *Impluviculus* species, the deposits yielding this acritarch assemblage are considered as a stratigraphic equivalent of the lower and/or middle parts of the *Olenus* Zone.

The next acritarch assemblage is similar to the one described, but differs in the presence of the representatives of the genus *Impluviculus* and in the lack or restricted distribution of typical Middle Cambrian species (Волкова, 1982). In all the studied sections this assemblage occurs in the Ülgase Formation. As the appearance of the genus *Impluviculus* has been correlated with the uppermost part of the *Olenus* Zone (Downie, 1984) and with the lowermost part of the *P. spinulosa* Zone (Martin & Dean, 1988), we regard the Ülgase Formation tentatively as a stratigraphic equivalent of the uppermost *Olenus* and the lowermost *Parabolina* zones (Table).

The third Upper Cambrian assemblage, containing *Trunculumarinum revinium* (Vang.) Loeblich et Tappan, *Dasydiacrodium caudatum* Vanguestaine, *D. obsenum* Martin, *Leiofusa stoumonensis* Vanguestaine, *Veryhachium dumontii* Vanguestaine, *Cymatiogalea wironia* Paalits, *C.*

Table

Suggested correlation of the Upper Cambrian biostratigraphic and litostratigraphic units of Estonia and their relationship with trilobite zones

	Trilobite zones	Conodont zones & subzones		Lingulate zones	Key species of acritarchs	Lithostratigraphic units: N and NW Estonia	Lithostratigraphic units: SE Estonia
O	*Boeckaspis hirsuta*	*C. lindstromi* *C. intermedius*		*O. apollinis*	*A. echinatum* *A. striatum*	Kallavere Fm. (part)	Kallavere Fm. (part)
–? €	*Acerocare*	*C. proavus* / *C. andresi*		*U. ingrica*	*A. angustum* / *D palmatilobum* *I. angulata* *O. rossicum* *E. armillata* *V. cervinacornua*	Kallavere Fm. (part) / Tsitre Fm.	Kallavere Fm. (part)
	Peltura scarabaeoides	*Westergaardodina*	*Proconodontus*	*U. ingrica* / *U. convexa*	*D palmatilobum* *I. angulata* *O. rossicum* *E. armillata* *V. cervinacornua*	Tsitre Fm.	
	Peltura minor	*Westergaardodina*	?	*U. convexa*	?	Tsitre Fm.	
	Protopeltura praecursor	*Westergaardodina*	?	*U. convexa*	?	Tsitre Fm.	
	Leptoplastus	*Westergaardodina*	?	*U. convexa*	*T. revinium* *D. caudatum*	Tsitre Fm.	
	Parabolina spinulosa	*Westergaardodina*	? / *W. bicuspidata*	*U. convexa* / *U. inornata*	*T. revinium* *D. caudatum* / *I. multiangularis* ?*V. dumontii*	Tsitre Fm. / Ülgase Fm.	
	Olenus	*Westergaardodina*	*W. bicus-pidata*	*U. inornata*	*I. multiangularis* ?*V. dumontii* / ?*D. setuensis* *L. staumonensis*	Ülgase Fm.	Petseri Fm.
	Agnostus pisiformis	*Westergaardodina*	*W. bicus-pidata*	*U. inornata*	?*D. setuensis* *L. staumonensis*		Petseri Fm.

235

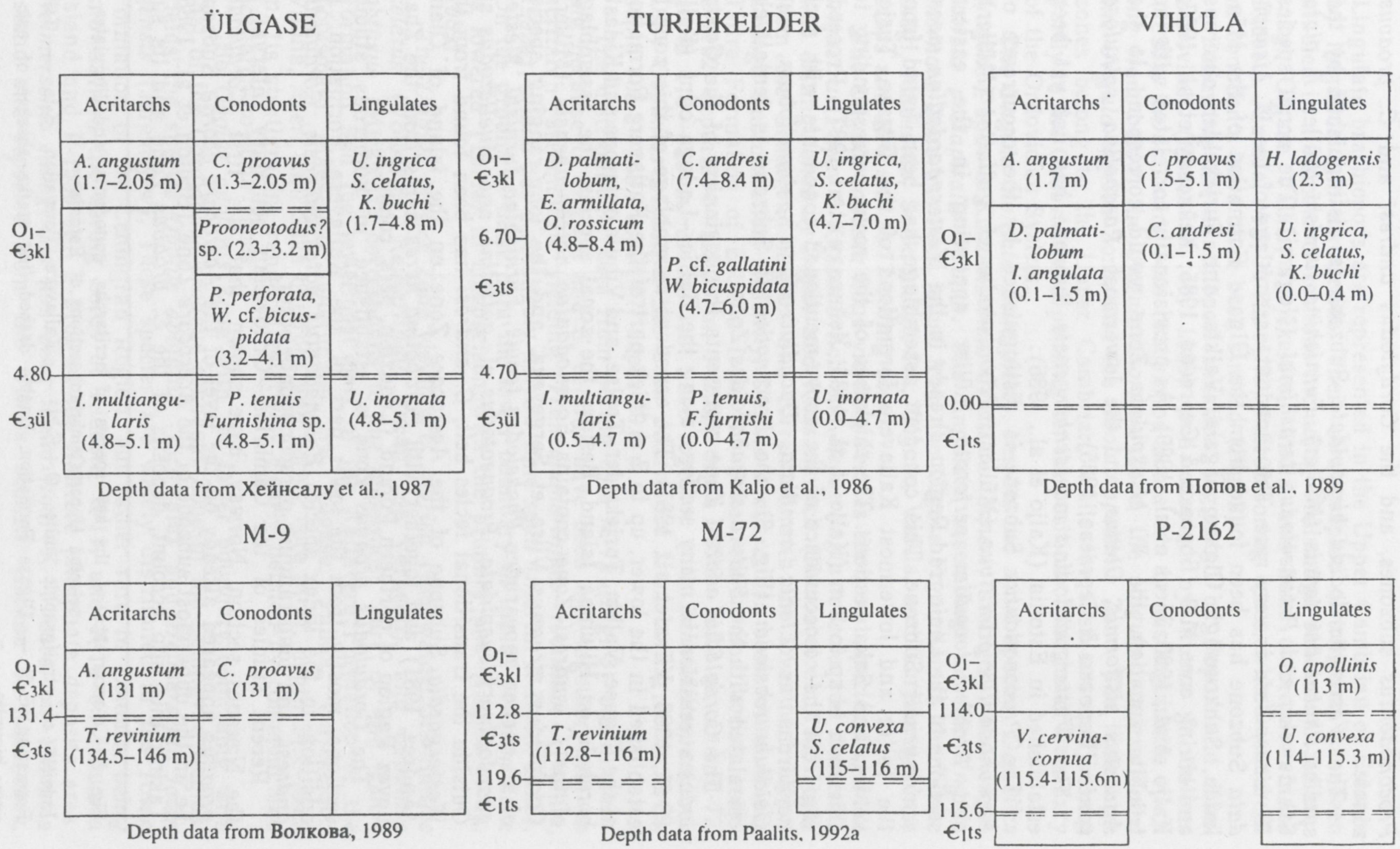
dentalea Paalits, *C.* aff. *virgulta* Martin, *C.* sp. sp., *Goniosphaeridium* aff. *tuberatum* (Downie) Wolf, *G.* aff. *dentatum* (Timofeev) Rauscher, *G.* sp. sp., *Stelliferidium cortinulum* (Deunff) Deunff, Gorka & Rauscher, *S.* aff. *pseudoornatum* Pittau, *Timofeevia phosphoritica* Vanguestaine, *T. estonica* Volkova, *Vulcanisphaera turbata* Martin, *V.* sp., *Actinodissus* sp., *Cristallinium* sp., corresponds to the microflora A_4, i.e. *T. revinium—D. caudatum* assemblage *sensu* Martin & Dean (1988) and to assemblage BK-3 *sensu* Volkova (Волкова, 1990). In northern Estonia, this assemblage occurs in the lowermost part of the Tsitre Formation found only in boring cores M-9, depth 134.5—140.6 m; M-46, depth 38.7—40.5 m; M-72, depth 112.8—119.6 m (Paalits, 1992a.; Волкова, 1990). The tentative correlation of this assemblage with the trilobite zones is based on *Trunculumarinum revinium* and *Dasydiacrodium caudatum* known as the species with a limited stratigraphic range from the uppermost *P. spinulosa* Zone through the whole *Leptoplastus* Zone (Table).

The next acritarch assemblage, showing high taxonomic diversity and variation in different sections, contains a significant amount of diacroids and maybe endemic forms. On the East European Platform this assemblage was first described from the upper part of the Ladoga Formation, St. Petersburg area (Волкова & Голуб, 1985), and is referred to as BK-4Б (Волкова, 1990). It is characterized by the prevalence of *Acanthodiacrodium timofeevii* Volkova et Golub, *Ladogiella rotundiformis* Volkova et Golub, *Calyziella izhoriensis* Volkova et Golub, *Izhoria angulata* Volkova et Golub, *Nellia longiscula* Volkova et Golub, *Schizodiacrodium fibrosum* Volkova et Golub, *Dasydiacrodium palmatilobum* Timofeev, *Elenia armillata* (Vand.) Volkova, in some samples by *Ooidium timofeevii* Loeblich and *O. rossicum* Timofeev. In Estonia this acritarch assemblage is found from the upper part of the Tsitre Formation of the Valkla, Turjekelder, and Saka outcrops and from the boring cores P-2162, depth 115.4—115.6 m, and M-56, depth 138.6—147.4 m, together with the conodonts of the *Proconodontus* Subzone. These acritarchs have also been found in the *Cordylodus andresi* Zone of the Vihula section (Волкова, 1990). A relatively similar assemblage together with the trilobites of the *Peltura scarabaeoides* Zone has been determined from the Degerhamn section of southern Öland (di Milia et al., 1989).

The youngest Upper Cambrian acritarch assemblage which, as the above one, contains a large number of diacroids (Волкова, 1989, 1990), can be distinguished by the appearance of *Acanthodiacrodium angustum* (Downie) Combaz and *Dicrodiacrodium ramusculosum* (Combaz) Volkova. It is found together with conodonts of the *C. proavus* Zone from the lower part of the Kallavere Formation of the Tõnismägi, Mäekalda, Suhkrumägi, and Vihula outcrops and from the boring core M-9, depth 131.1 m.

Conodonts have been studied from a number of outcrops and boring cores embracing the Cambrian—Ordovician boundary beds. Late Cambrian conodonts have been found in the Mäekalda, Suhkrumägi, Ülgase, Valkla, Turjekelder, Vihula, Toolse, and Saka outcrops and from the Kidaste and M-9 boreholes (Fig. 2). The number of specimens is small, representing mostly the genera *Phakelodus*, *Furnishina*, *Prooneotodus*, and *Westergaardodina*. Eoconodonts (*Proconodontus*, *Eoconodontus*, and *Cordylodus*) have been found only in the uppermost Upper Cambrian.

Here we accept the conodont zonation proposed by Viira and Sergeyeva for the correlation of the Cambrian—Ordovician boundary beds along the Baltic—Ladoga clint area (see Боровко & Сергеева, 1985; Kaljo et al., 1986). According to this zonation, the Upper Cambrian sequence is subdivided as follows, starting from below: the


ÜLGASE
Acritarchs
Conodonts
Lingulates
A. angustum (1.7–2.05 m)
C. proavus (1.3–2.05 m)
U. ingrica S. celatus, K. buchi (1.7–4.8 m)
O1–€3kl
Prooneotodus? sp. (2.3–3.2 m)
P. perforata, W. cf. bicuspidata (3.2–4.1 m)
4.80
€3ül
I. multiangularis (4.8–5.1 m)
P. tenuis Furnishina sp. (4.8–5.1 m)
U. inornata (4.8–5.1 m)
Depth data from Хейнсалу et al., 1987
TURJEKELDER
Acritarchs
Conodonts
Lingulates
O1–€3kl
6.70
€3ts
4.70
€3ül
D. palmatilobum, E. armillata, O. rossicum (4.8–8.4 m)
C. andresi (7.4–8.4 m)
U. ingrica, S. celatus, K. buchi (4.7–7.0 m)
P. cf. gallatini W. bicuspidata (4.7–6.0 m)
I. multiangularis (0.5–4.7 m)
P. tenuis, F. furnishi (0.0–4.7 m)
U. inornata (0.0–4.7 m)
Depth data from Kaljo et al., 1986
VIHULA
Acritarchs
Conodonts
Lingulates
A. angustum (1.7 m)
C proavus (1.5–5.1 m)
H. ladogensis (2.3 m)
O1–€3kl
D. palmatilobum I. angulata (0.1–1.5 m)
C. andresi (0.1–1.5 m)
U. ingrica, S. celatus, K. buchi (0.0–0.4 m)
0.00
€1ts
Depth data from Попов et al., 1989
M-9
Acritarchs
Conodonts
Lingulates
O1–€3kl
A. angustum (131 m)
C. proavus (131 m)
131.4
€3ts
T. revinium (134.5–146 m)
Depth data from Волкова, 1989
M-72
Acritarchs
Conodonts
Lingulates
O1–€3kl
112.8
€3ts
119.6
€1ts
T. revinium (112.8–116 m)
U. convexa S. celatus (115–116 m)
Depth data from Paalits, 1992a
P-2162
Acritarchs
Conodonts
Lingulates
O1–€3kl
114.0
€3ts
115.6
€1ts
O. apollinis (113 m)
V. cervinacornua (115.4-115.6m)
U. convexa (114–115.3 m)

Westergaardodina Zone with *W. bicuspidata*, *W. moessenbergensis*, and *Proconodontus* subzones, and the *Cordylodus andresi* and *C. proavus* zones.

The *Westergaardodina bicuspidata* Subzone is distinguished by the species *Phakelodus tenuis* (Müller), *Furnishina furnishi* Müller, *F. alata* Szaniawski, and *Prooneotodus terashimai* (Nogami). The zonal species *W. bicuspidata* is very rare. The conodont assemblage of the *W. bicuspidata* Subzone has been found from the Ülgase Formation of the Mäekalda, Suhkrumägi, Ülgase, Jägala, Valkla, and Turjekelder outcrops and boring core M-9 (Боровко & Сергеева, 1985; Хейнсалу et al., 1987; Kaljo et al., 1986; Mens et al., 1989). As provisionally correlated with the trilobite zonation, the *W. bicuspidata* Zone would correspond to the *Agnostus pisiformis*, *Olenus*, and the lowermost *Parabolina spinulosa* zones (Боровко & Сергеева, 1985).

The *Westergaardodina moessenbergensis* Subzone has not yet been established in Estonia (Kaljo et al., 1986).

The *Proconodontus* Subzone is distinguished by the occurrence of *Proconodontus primitivus* (Müller), *Prooneotodus* cf. *gallatini* (Müller), and *Problematoconites perforata* Müller appearing in the eastern sections of the Leningrad Region already in the *Westergaardodina moessenbergensis* Subzone. This conodont assemblage has been found from the Tsitre and lowermost Kallavere formations of the Ülgase, Turjekelder, and Saka sections. The thickness of the rocks corresponding to this zone is up to 2 m (Kaljo et al., 1986; Хейнсалу et al.,1987). Proceeding from the co-occurrence of the above-mentioned conodonts with such acritarchs as *Elenia armillata*, *Dacydiacrodium palmatilobum*, and *Ooidium rossicum* (Fig. 3), the *Proconodontus* Subzone is tentatively correlated with the *Peltura scarabaeoides* Zone.

The *Cordylodus andresi* Zone represents the beginning of the *Cordylodus* succession in many sections along the Baltic—Ladoga clint (Kaljo et al., 1986; Viira et al., 1987). The conodont assemblage of this zone is established in the lower, up to 2 m thick part of the Kallavere Formation of the Ülgase, Valkla, Turjekelder, Toolse, and Vihula outcrops and Kidaste borehole on Hiiumaa Island. Besides the zonal species, the assemblage of the *C. andresi* Zone contains *Eoconodontus notchpeakensis* (Miller), *Cordylodus viruanus* Viira et Sergeyeva, and the long-ranging species of an earlier appearance *Phakelodus tenuis*, *Furnishina furnishi*, *Westergaardodina bicuspidata*, *Prooneotodus* cf. *gallatini*, and *Muellerodus* sp. Outside the transitional facies belt, *C. andresi* has been found from the *Westergardia* Subzone of the *Acerocare* Zone on the island of Öland (Andres, 1981) and together with *Parabolina heres heres* from the Zharnovez Region of northern Poland (Lendzion, pers. comm.).

The *Cordylodus proavus* Zone is established in numerous studied sections, mostly from the lower part of the Kallavere Formation. In addition to the index species *Eoconodontus notchpeakensis*, *Cordylodus andresi*, and long-ranging paraconodonts occur.

Recent studies of the Cambrian—Ordovician boundary interval in the Nærsnes section, Norway, have shown that the first *Cordylodus proavus* appeared already on the level of the *Acerocare ecorne* Subzone, i.e. in the uppermost subzone of the *Acerocare* Zone (Bruton et al., 1988). Taking this into account, deposits of the *C. proavus* Zone and its sup-

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Fig. 3. Co-occurrence of the key species of acritarchs, conodonts, and lingulates in selected Upper Cambrian sections of Estonia.

Indexes of stratigraphic units: O_1—$Є_3$kl — Kallavere Formation, $Є_3$ts — Tsitre Formation, $Є_3$ül — Ülgase Formation. Double dashed line marks absence of one or some biounits.

posed stratigraphic equivalents are included within the Upper Cambrian (Table).

Lingulate brachiopods are represented in the Upper Cambrian of Estonia by lingulids and acrotretids. Their stratigraphic distribution has been studied in a number of sections including Tõnismägi, Mäekalda, Suhkrumägi, Ülgase, Valkla, Turjekelder, Vihula, and Saka outcrops and the Kidaste, Äiamaa, M-9, M-72, M-77, P-2162 boring cores, where acritarchs or conodonts have often been studied (Fig. 2).

Following the brachiopod zonation suggested by Popov and Khazanovitch (Попов et al., 1989) and adopted by Puura & Holmer (1993), the following four brachiopod zones can be distinguished, starting from below: the *Ungula inornata* Zone, the *Ungula convexa* Zone, the *Ungula ingrica* Zone, and the *Obolus apollinis* Zone. The first three zones belong to the Upper Cambrian, while the last one can belong partly to the Ordovician, depending on the position of the lower boundary of the Ordovician System.

The *Ungula inornata* Zone yields, besides the zonal species, *Oepikites fragilis* Popov & Khazanovitch, *Ceratreta tanneri* (Metzger), and *Angulotreta postapicalis* Palmer. The lingulata assemblage of the *Ungula inornata* Zone has been found from the Ülgase Formation in the Tõnismägi, Mäekalda, Suhkrumägi, Iru, Ülgase, Valkla, and Turjekelder outcrops and M-9 and M-77 boring cores.

The *Ungula convexa* Zone yielding besides the zonal species *Oepikites triquetrus* Popov & Khazanovitch and *Keyserlingia reversa* (de Verneuil) was distinguished by Popov and Khazanovitch (Попов et al., 1989) only from the Leningrad Region and correlated with the lowermost Upper Ladoga Subformation. Recently, *Ungula convexa* has been found in the Tsitre Formation of Estonia from the Saka section and boring cores P-2162, depth 114—115.36 m; P-2163, depth 108.8—111.3 m; and M-72, depth 115—116 m, in the last case together with *Schmidtites celatus*. Only *Oepikites triquetrus* has been determined from boring cores M-39, depth 165.2—168.7 m; M-77, depth 29.2 m.

The distributional data from boring core M-72 (Fig. 3) are interesting because *U. ingrica* and *S. celatus* have been met together with an acritarch assemblage yielding *Trunculumarinium revinium* (Paalits, 1992a), which has a relatively narrow time span (Martin & Dean, 1988). On the ground of these data the lower boundary of the *U. convexa* Zone is lowered (Table) in comparison with the primary one (Попов et al., 1989).

The *Ungula ingrica* Zone yielding *U. ingrica* (Eichwald), *Schmidtites celatus* (Volborth), *Keyserlingia buchii* (de Verneuil), and *Oepikites obtusus* (Mickwitz) corresponds to the uppermost part of the Tsitre Formation and the lowermost part of the Kallavere Formation of the Tõnismägi, Mäekalda, Suhkrumägi, Iru, Ülgase, Valkla, Turjekelder, Vihula, Aseri, and Saka outcrops and boring core M-77, depth 24.2—34.3 m. Its stratigraphic range is relatively clearly defined by conodont and acritarch co-occurrences.

The *Obolus apollinis* Zone with the lower boundary coinciding with that of the *Cordylodus proavus* conodont Zone in the Leningrad Region, yields the species *Obolus apollinis* (Eichwald) and *Helmersenia ladogensis* (Jeremejew). These species are widely distributed in the Tosno Formation of the Leningrad Region, but rather rare in Estonia, being known from the boring cores of Kidaste, K-11, and K-19 on Hiiumaa Island and P-1555 and P-2162 of the Rakvere phosphate deposits area. *Helmersenia ladogensis* has been found from K-11 core on Hiiumaa Island and reported from the Vihula section (Попов & Хазанович,

241

1989). Very often the finds of *O. apollinis* and/or *H. ladogensis* are related to the occurrences of *Cordylodus proavus* and *Acanthodiacrodium angustum.*

DISCUSSION AND CONCLUSIONS

The studied three groups of fossils—acritarchs, conodonts, and lingulate brachiopods—complement one another in respect of biostratigraphic correlation. Therefore, the documentation of their co-occurrences in a series of Estonian Upper Cambrian sections (Fig. 3) gives useful information both for short- and long-distance biostratigraphic correlation.

The oldest Upper Cambrian lithostratigraphic unit of Estonia, the Petseri Formation, is at present characterized only by acritarchs including *Leiofusa stoumonensis* Vanguestaine and *?Dasydiacrodium setuensis* Paalits (Table), which show early late Cambrian age.

The next lithostratigraphic unit, the Ülgase Formation, contains representatives of all the groups studied. Of the highest correlative value are *Impluviculus multiangularis*, *Westergaardina bicuspidata*, and *Ungula inornata*, indicating the deposition of the corresponding sediments during the first half of the late Cambrian.

The lower part of the Tsitre Formation is characterized by an association of lingulates and acritarchs, the acritarch *Trunculumarinum revinium* having a short stratigraphic range. Conodonts have not been found as yet from this part of the sequence, which is revealed only in a few boring cores. The upper part of the Tsitre Formation, however, yields acritarchs, conodonts, and lingulates, including also conodonts of the *Proconodontus* Subzone (Fig. 3, Turjekelder Section).

The upper stratigraphic boundary of the acritarch assemblage containing *Dasydiacrodium palmatilobum*, *Ishoria angulata*, etc. coincides with that of the *Cordylodus andresi* Zone.

The most debatable is the position of the boundary between the *Ungula ingrica* and *Obolus apollinis* zones in relation to the lower boundary of the *Cordylodus proavus* Zone. The acritarch assemblage with *Acanthodiacrodium angustum* appears at the base of the *Cordylodus proavus* Zone. In northern Estonian sequences *C. proavus* and *A. angustum* co-occur with *Ungula ingrica. O. apollinis*, which is distributed in a sublatitudinal belt extending from the Leningrad Region to the Rakvere phosphate deposit area and Hiiumaa Island, is always known to appear above the base of the *C. proavus* Zone. Defining the boundary between *U. ingrica* and *O. apollinis* zones by the first appearance of *O. apollinis*, we leave the question of its detailed correlation with the lower boundary of the *C. proavus* Zone open. Our provisional correlation provided in the Table shows the lower boundary of the *O. apollinis* Zone slightly below the top of the *Acerocare* Zone.

The tentative correlation of the Estonian Upper Cambrian biounits with Scandinavian trilobite zones is mostly based on acritarch correlation and only within the *Acerocare* Zone on conodonts. However, the direct correlation is possible only partly because of the lack of data on the distribution of acritarchs of the *Agnostus pisiformis*, *Leptoplastus*, *Protopeltura praecursor*, *Peltura minor*, and *Acerocare* zones in Scandinavia.

In all probability, stratigraphic analogues of the *Olenus*, *Parabolina spinulosa*, and *Peltura scarabaeoides* zones can be distinguished in Estonia. The *Cordylodus andresi* and *C. proavus* zones, respectively, correspond to the *Westergardia* and *A. ecorne* subzones of the *Acerocare* Zone.

The sandy lower part of the Petseri Formation has not yielded fossils. As the overlying clays in the middle part of this formation contain acritarchs of the *Olenus* Zone, the correlation of those barren sandstones with the *Agnostus pisiformis* Zone has been suggested (Mens et al., 1990).

The acritarch assemblage with *Trunculumarinum revinium* and *Dasydiacrodium caudatum* from the lower part of the Tsitre Formation, in addition to the upper part of the *P. spinulosa* Zone, is tentatively correlated with the *Leptoplastus* Zone.

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243

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ÜLEMKAMBRIUMI BIOSTRATIGRAAFIA EESTIS

Kaisa MENS, Viive VIIRA, Ivo PAALITS, Ivar PUURA

Ülemkambriumi läbilõigete kivimilise koostise ja ehituse järgi kuulub Eesti fatsiaalsesse üleminekuvööndisse.
Ülemkambriumi biostratigraafiliseks liigestamiseks analüüsiti akritarhide, konodontide ja lingulaatide levikut mitmetes paljandites ning puursüdamikes. Saadud andmete põhjal on esitatud Eesti ülemkambriumi biotsonaalne liigestus, bioüksuste omavahelised suhted, samuti ka korrelatsioon trilobiitide tsoonidega.

БИОСТРАТИГРАФИЯ ВЕРХНЕГО КЕМБРИЯ ЭСТОНИИ

Кайса МЕНС, Вийве ВИЙРА, Иво ПААЛИТС, Ивар ПУУРА

На основе анализа вертикального распределения акритарх, конодонтов и лингулат выделены сообщества этих фоссилий и по ним расчленен разрез верхнего кембрия Эстонии на биостратиграфические подразделения. По результатам сравнения родового и видового составов этих сообществ с соответствующими материалами из разрезов, охарактеризованных трилобитами, выделенные биостратиграфические подразделения сопоставлены с трилобитовой зональной шкалой платформы (таблица).

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ÜLEMKAMBRIUMI BIOSTRATIGRAAFIA EESTIS

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Ülemkambriumi [illegible] kriteeriumide [illegible] ja [illegible] Eesti [illegible].

Ülemkambriumi biostratigraafilis [illegible] akritarhide, konodontide ja lingulaatide [illegible] põhjal [illegible]. [illegible] Eesti [illegible] biostratigraafiline [illegible], [illegible] korrelatsioon [illegible].

БИОСТРАТИГРАФИЯ ВЕРХНЕГО КЕМБРИЯ ЭСТОНИИ

Кайса МЕНС, Вийве ВИЙРА, Иво ПААЛИТС, Ивар ПУУРА

На основе анализа вертикального распределения акритарх, конодонтов и лингулид выделены сообщества этих фоссилий и по ним [illegible] схемы расчленения верхнего кембрия Эстонии на биостратиграфические подразделения. По результатам сравнения видового состава [illegible] с соответствующими материалами из [illegible] биостратиграфических [illegible] с [illegible] зональной [illegible] формы [illegible].

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CAMBRIAN—ORDOVICIAN BOUNDARY BEDS IN THE PAKRI CAPE SECTION, NW ESTONIA

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Abstract. For obtaining new information on the biostratigraphy and mineralogy of the Pakerort Stage in its type area, the Cambrian—Ordovician sequence in the Pakri Cape section (previously known as Pakerort) located 1 km southeast of the promontory of the Pakri Peninsula, NW Estonia, is described.

The varigrained quartzose sandstones of the Kallavere Formation, representing a disputable part of the Cambrian—Ordovician boundary interval in Estonia, lie discontinuously on the sand- and siltstones of the Lower Cambrian Tiskre Formation. Lithological subdivisions of the Kallavere Formation, the Maardu and Suurjõgi members, differ in the structure and grain size, but show close mineral composition. The biostratigraphical age can be established only for the lower part of the Maardu Member which belongs to the *Cordylodus proavus* conodont Zone; the *C. andresi* Zone is apparently missing. Younger conodont zones cannot be established with confidence owing to scarcity and poor preservation of conodont elements. The overlying Türisalu Formation yields *Rhabdinopora flabelliformis* and *R.* cf. *desmograptoides*.

Key words: Upper Cambrian, Lower Ordovician, Kallavere Formation, Pakerort Stage, conodonts, brachiopods, mineralogy, Pakri Peninsula, Estonia.

INTRODUCTION

The westernmost exposures of the Cambrian—Ordovician boundary beds in Estonia are located on the Pakri Peninsula. Raymond (1916) outlined the modern stratigraphy of these beds by defining the Packerort Formation comprising *Obolus* Sandstone and *Dictyonema* Shale, with the type section near the lighthouse, close to the promontory of the Pakri Peninsula. Further, with the introduction of regional stages in the East Baltic stratigraphy, the Pakerort Stage having about the same stratigraphical extent, was introduced (Мюрисепп, 1958, 1960). While the debate on the Ordovician lower boundary is continuing, the base of the *Cordylodus andresi* conodont Zone is referred to as the tentative base of the Pakerort Stage (Männil, 1990).

Current research outside the type area has resulted in the biostratigraphical zonation of the Cambrian—Ordovician boundary beds in Estonia and adjacent areas (Kaljo et al., 1986, 1988; Попов & Хазанович, 1989; Mens et al., 1993; Puura & Holmer, 1993) and in detailed mineralogical

247

studies of selected sections (Хейнсалу et al., 1987; Mens et al., 1989). These data provide a valuable basis for interpreting the Cambrian—Ordovician stratigraphy on the Pakri Peninsula, the type area of the Pakerort Stage. Inaccessible for more than 30 years, this area has been available for geological studies since August, 1993, after the withdrawal of the Soviet troops from the navy base at Paldiski.

The present paper describes a coastal section on the Pakri Peninsula which was sampled in September, 1993. The mineralogy of very fine sand and clay fraction was examined by K. Mens and T. Kurvits, respectively, the grain size and distribution of skeletal fragments by H. Heinsalu, and the conodonts by K. Jegonjan and V. Viira. I. Puura studied the lingulate brachiopods and compiled the biostratigraphical review.

DESCRIPTION OF THE SECTION

The section studied is located in the northeastern klint wall approximately 1 km southeast of the promontory (Fig. 1). In the surroundings, the total thickness of the exposed Cambrian—Ordovician bedrock sequence, ranging from the sandstones of the Lower Cambrian Tiskre Formation to the carbonate rocks of the Middle Ordovician Uhaku Stage, is from 20 to 24 m. The Cambrian—Ordovician boundary beds are represented by the 4 m thick Kallavere Formation (*Obolus* Sandstone; Fig. 1) which is overlain by the Türisalu Formation (*Dictyonema* Shale). The description is given from base to top.

Lower Cambrian
Tiskre Formation ($Є_1$ts)

Light grey sandy siltstones with interbeds of shaly siltstones and clays. The topmost 0.1—0.2 m are strongly pyritized and now brownish-yellow due to oxidation of some of pyrite to jarosite. Ripple marks are common in the upper part of the Tiskre Formation. Its upper surface is uneven and deeply pitted, rarely smooth. The contact between the Tiskre and Kallavere formations is sharp and marked by the appearance of kerogenous shale and phosphatic shell fragments of lingulate brachiopods. Exposed thickness up to 4 m.

Upper Cambrian—Lower Ordovician

Pakerort Stage
Kallavere Formation
Maardu Member ($Є_3$—O_1klM)

Bed 1. Dark brown kerogenous shale with very thin quartzose fine- and very fine-grained sandstone interbeds at the base. Upwards the sandy interbeds become thicker and more frequent (sample 3). Occasionally there occur boulders derived from the underlying Tiskre Formation. Thin lenses of basal conglomerate are exposed about 200—300 m eastward (description in Nemliher & Puura, 1996). The lenses contain shell fragments of lingulate brachiopods, mostly from the genus *Ungula*. Thickness 0.1—0.25 m.

Bed 2. Yellowish-grey quartzose fine- and very fine-grained sandstone, with horizontal and wavy irregular dark kerogenous shale interbeds up to some cm in thickness. The ratio of sandstone and shale layers is 2:1 (samples 4—6). The sandstone contains only scarce phosphatic skeletal fragments of lingulate brachiopods. Thickness 0.5—0.65 m.

Bed 3. Greyish-yellow quartzose fine- and very fine-grained sandstone, weakly cemented, partly cross-bedded, with rare thin dark shale interbeds (sample 7). Thickness 0.35 m.

Bed 4. Greyish-yellow fine- and very fine-grained quartzose sandstone, gradually coarsening upwards. The sandstone is sometimes weakly cross-bedded and contains few 1—2 cm thick shale interbeds (samples 8—11). Thickness 1.20 m.

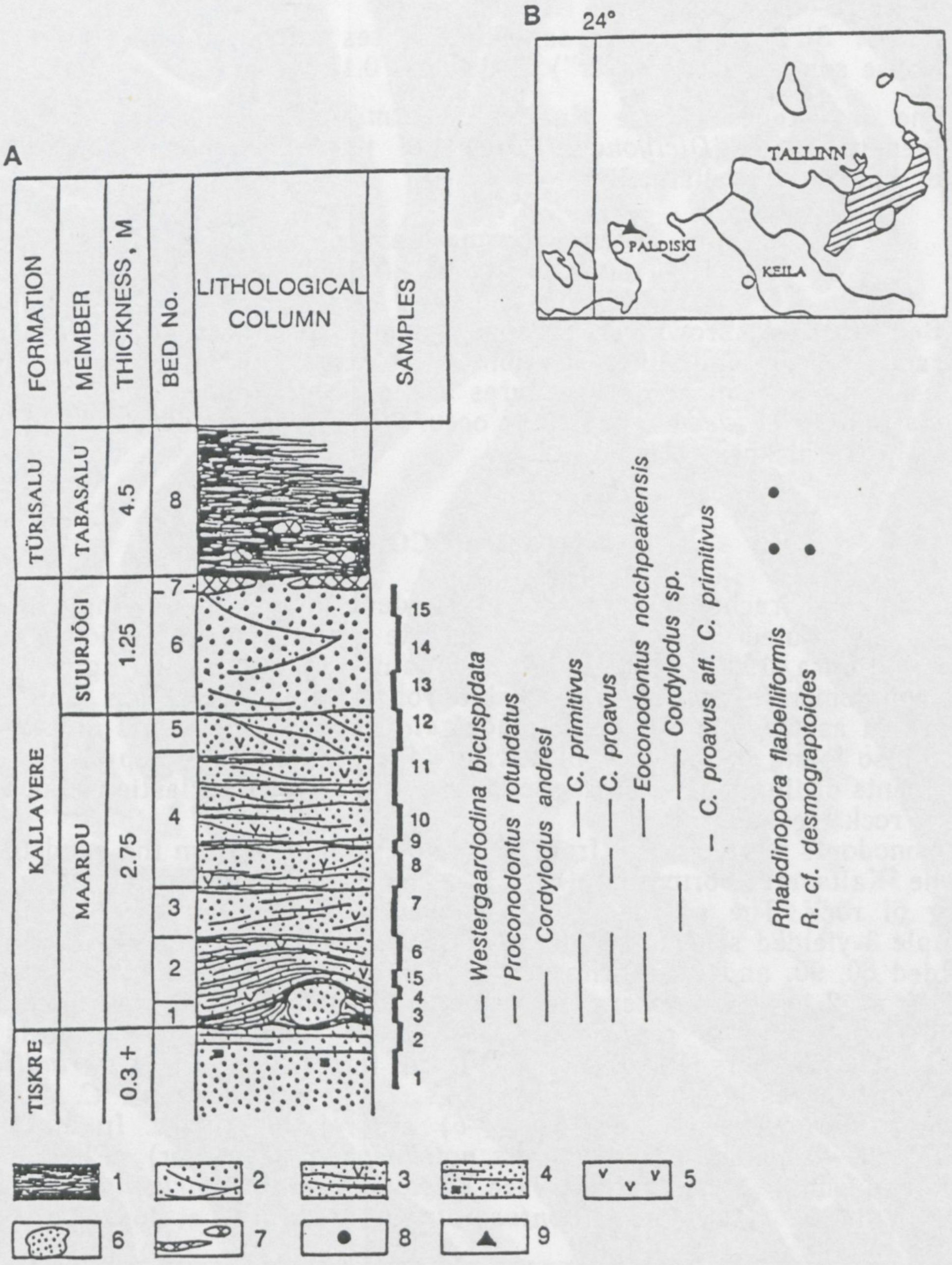


Fig. 1. Cambrian—Ordovician boundary beds in the Pakri Cape section: conodont and graptolite distribution (*A*) and location scheme (*B*). Legend: *1*, kerogenous shale; *2*, cross-bedded quartzose sandstone; *3*, quartzose sandstone intercalated with kerogenous shale; *4*, quartzose siltstone with clay interbeds; *5*, lingulate brachiopod debris; *6*, sandstone boulders; *7*, pyrite concretions and lenses; *8*, graptolite occurrences; *9*, location of the studied section.

Bed 5. Brownish-yellow quartzose fine-grained sandstone, occasionally cross-bedded (sample 12). In general appearance this bed is transitional between the Maardu and Suurjõgi members. Thickness 0.35 m.

Suurjõgi Member (O_1klS)

Bed 6. Yellowish-brown medium- to fine-grained cross-bedded sandstone with very rare tiny shell fragments of lingulate brachiopods (samples 13—15). Thickness 1.10 m.

Bed 7. Strongly pyritized sandstone lenses in medium- to fine-grained quartzose sand ("pyrite layer"). Thickness 0.15 m.

The sandstones of the Kallavere Formation are overlain by dark kerogenous shale (*Dictyonema* Shale) of the Türisalu Formation. The upper boundary is distinct.

Türisalu Formation (O_1tr)
Tabasalu Member (O_1trT)

Bed 8. Dark brown kerogenous shale. The lowermost 0.5 m are characterized by indistinct horizontal bedding. Higher up bedding is almost missing; conchoidal fractures are present. *Rhabdinopora flabelliformis* and *R.* cf. *desmograptoides* occur in the shale (identifications by D. Kaljo). Thickness 4 m.

FOSSIL RECORD

Lingulate brachiopods are most abundant in the basal conglomerate lenses distributed in a wide area outside the described section (Nemliher & Puura, 1996). Among the abundant lingulate shell fragments in the conglomerate matrix, rare valves of better preservation could be identified as *Ungula convexa* and *Ungula ingrica.* Fragments of *Ungula* were also found in some pebbles within the conglomerate. Upwards shell fragments of lingulate brachiopods make up part of the clastic component of the rock (see below).

Conodonts were studied from 13 samples (3—15) from the sandstones of the Kallavere Formation (Fig. 1), each sample amounting to about 2 kg of rock. The number of specimens is highest in lower samples: sample 3 yielded several hundreds of specimens, and samples 4, 5, and 6 yielded 60, 90, and 25 specimens, respectively. Upper samples contained only from 2 to 16 specimens per sample. In samples 3—6, the prevailing genus *Cordylodus* is represented by a large number of specimens of *C. proavus* Müller (Pl. I, fig. *9*; Pl. II, figs. *1—3*) and *C. primitivus* Bagnoli, Barnes et Stevens (Pl. I, figs. *7, 8*). Specimens of *C. andresi* Viira et Sergeyeva (Pl. I, figs. *1—6*) are relatively rare. In addition, samples 3—6 yielded *Eoconodontus notchpeakensis* (Miller) (Pl. II, figs. *4, 5*) and sample 3 yielded very rare *Westergaardodina bicuspidata* Müller (Pl. II, fig. *9*) and *Proconodontus rotundatus* (Druce et Jones) (Pl. II,

PLATE I

Figs. *1—6. Cordylodus andresi* Viira et Sergeyeva. *1—5,* rounded specimens Cn 1509—Cn 1513, sample 3, ×184, ×160, ×152, ×168, ×192. *6,* compressed specimen Cn 1514, sample 6, ×184.

Figs. *7, 8. Cordylodus primitivus* Bagnoli, Barnes et Stevens. Rounded specimens Cn 1515, Cn 1516. *7,* sample 6, ×192. *8,* sample 3, ×120.

Fig. *9. Cordylodus proavus* Müller. Compressed specimen Cn 1520, sample 5, ×120.

PLATE 1

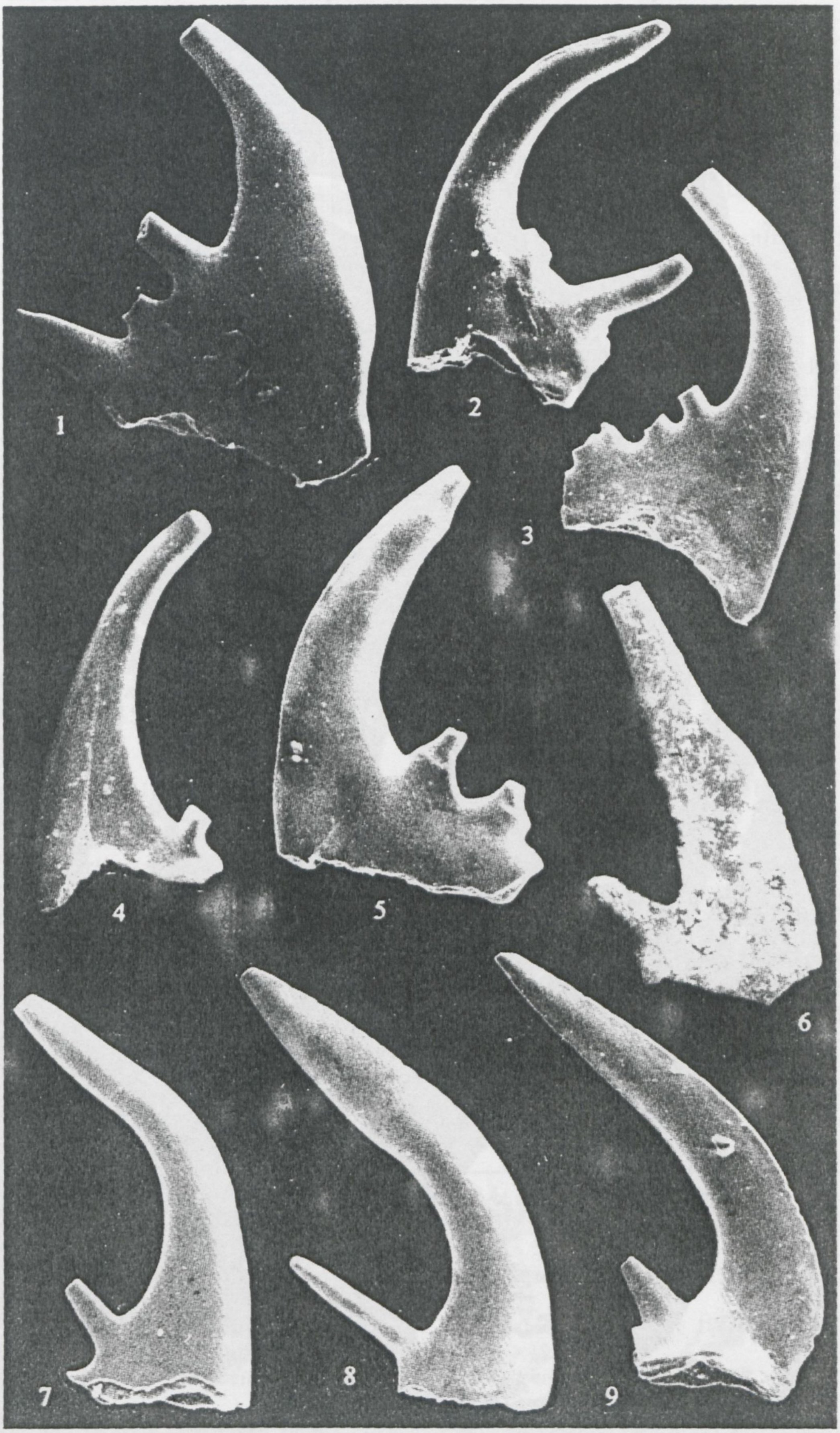
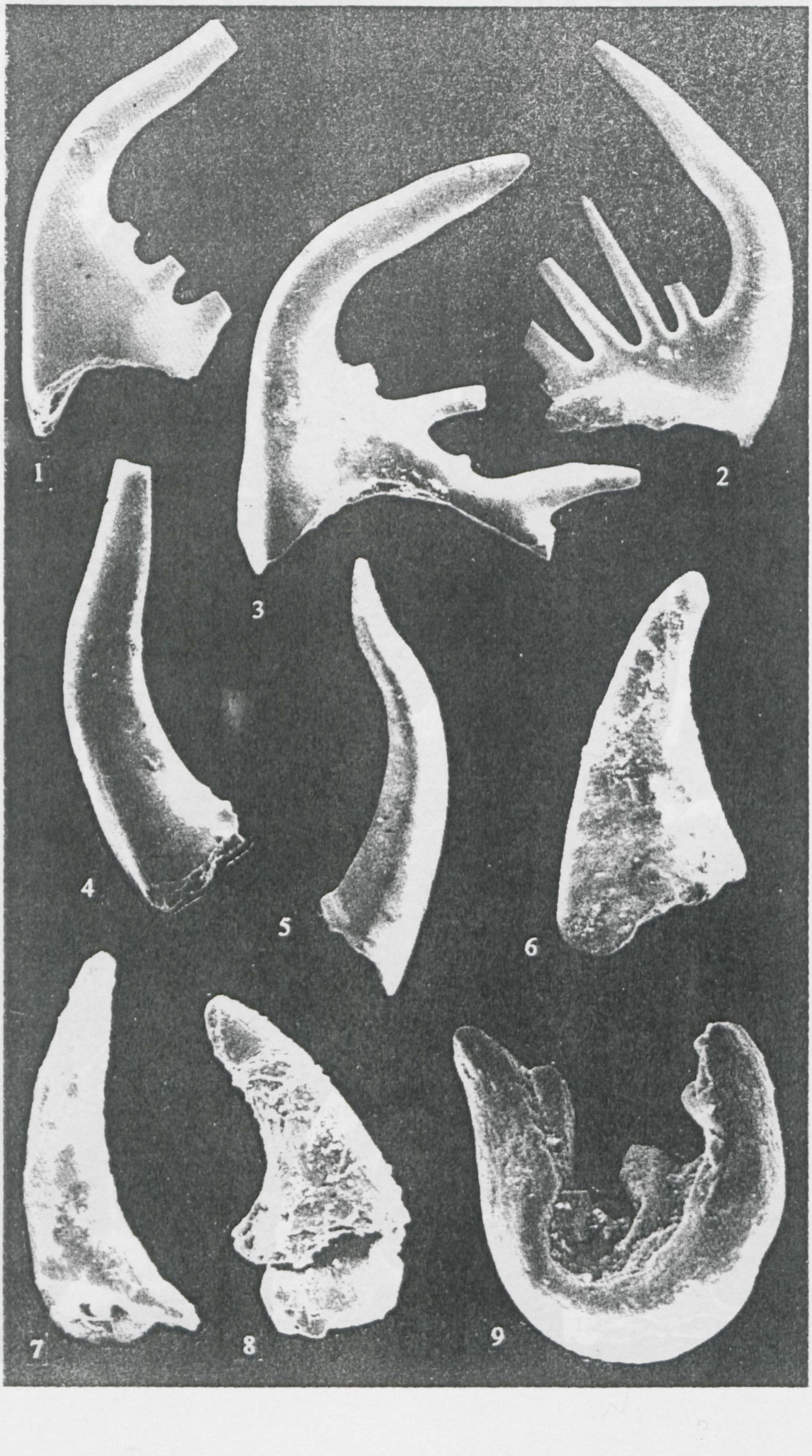


PLATE 2



figs. *6—8*). The conodonts from samples 3—6 are of yellowish-brown colour. In these samples, especially in sample 3, some specimens of *Cordylodus* show a series of growth lines subparallel to the basal margin, some other specimens have a cusp with the anterior bending of the uppermost part (somewhat similar to the posterior keel). These features are characteristic of very early euconodonts. Recently it was established that *C. primitivus* is a junior synonym of *C. andresi* Viira et Sergeyeva (Ross et al., 1993; Szaniawski & Bengtson, 1993). Still, in the Pakri Cape section these two species can be distinguished by the presence of white matter in the uppermost part of the cusp (*C. primitivus*) or its absence (*C. andresi*).

Samples 7—11 yielded poorly preserved conodonts, mostly white and semi-opaque broken specimens of *Cordylodus*; *C. proavus* (samples 8, 9, 10), *C. primitivus*, *P. rotundatus* (sample 10), and *E. notchpeakensis* (sample 10) were identified. Sample 12 from the Maardu Member and samples 13—15 from the Suurjõgi Member did not yield conodonts.

In this section the sandstone part with conodonts (samples 3—11) corresponds to the *C. proavus* Zone. It should be noted that among more than ten sections studied in northern Estonia, the Pakri Cape section is the only one where the Suurjõgi Member does not yield conodonts (Kaljo et al., 1986, 1988; Mens et al., 1989). Usually, the Suurjõgi Member has yielded the conodonts of the *C. angulatus* Zone or the *C. lindstromi* and *C. angulatus* zones (Kaljo et al., 1986, 1988), and occasionally even those of the *C. proavus* Zone.

One specimen of *Hadimopanella* sp. was found from the heavy mineral fraction of sample 4. The sclerites of *Hadimopanella*, previously known in Estonia from the Upper Cambrian Tsitre Formation of the Turjekelder section (Märss, 1988) and recently recognized as fragments of scleritome of palaeoscolecid worms (Hinz et al., 1990) have been reported from the Cambrian and Ordovician rocks all over the World (recent review in Müller & Hinz-Schallreuter, 1993).

GRAIN SIZE AND DISTRIBUTION OF SKELETAL FRAGMENTS

A distinct change in grain size of the clastic component is one of the main criteria for the subdivision of the Kallavere Formation into the Maardu and Suurjõgi members in northern Estonia (Хейнсалу, 1987). As this change can be clearly observed in the studied section, the same subdivisions can be distinguished on the Pakri Peninsula (Table 1).

The Maardu Member is mostly represented by very fine-grained (0.05—0.1 mm) and fine-grained (0.1—0.25 mm) sand, which together make up 75—98% of the whole clastic material with the predominance of the former. About 94—96% of the rock of the Suurjõgi Member are fine- to medium-grained (0.25—0.5 mm) sand dominated by fine sand.

Although the grain size of the clastic component increases gradually through the upper part of the Maardu Member (Table 1, samples 11—12), the boundary between the two members is distinct.

PLATE II

Figs. *1—3*. *Cordylodus proavus* Müller. Rounded specimens Cn 1517—Cn 1519, sample 5, ×96, ×136, ×120.

Figs. *4*, *5*. *Eoconodontus notchpeakensis* (Miller). Specimens Cn 1521, Cn 1522, sample 3, ×120.

Figs. *6—8*. *Proconodontus rotundatus* (Druce et Jones). Specimens Cn 1523—Cn 1525. *6*, *7*, sample 3. *8*, sample 10. *6*, *8*, ×192; *7*, ×144.

Fig. *9*. *Westergaardodina bicuspidata* Müller. Specimen Cn 1526, sample 3, ×296.

Table 1

Grain-size distribution of terrigenous and bioclastic components

Samples	Grain-size fractions (mm) of the terrigenous / bioclastic material, %					
	1.0—0.5	0.5—0.25	0.25—0.1	0.1—0.05	0.05—0.01	<0.01*
Suurjõgi Member						
Pa-93-15	0.18 / —	22.28 / —	74.05 / —	2.63 / —	0.26 / —	0.60
Pa-93-14	0.26 / —	20.02 / —	75.96 / —	1.73 / —	0.49 / —	1.54
Pa-93-13	0.36 / —	20.62 / —	73.34 / —	3.23 / —	0.96 / —	1.49
Maardu Member						
Pa-93-12	— / —	0.04 / —	83.25 / —	14.74 / —	1.32 / —	0.65
Pa-93-11	— / —	0.019 / 0.002	58.66 / 0.35	36.62 / 0.86	2.94 / 0.12	0.43
Pa-93-10	— / —	0.03 / —	39.89 / 0.10	47.71 / —	11.75 / 0.12	0.40
Pa-93-9	— / —	0.01 / —	36.3 / 0.1	54.06 / 0.16	8.75 / 0.05	0.57
Pa-93-8	— / —	0.009 / 0.001	33.38 / 0.1	55.87 / 0.17	9.72 / 0.06	0.69
Pa-93-7	— / —	0.03 / —	49.79 / 0.15	43.69 / —	5.63 / 0.017	0.69
Pa-93-6	— / —	0.04 / —	22.38 / 0.06	62.22 / 0.19	14.39 / 0.08	0.64
Pa-93-5	0.01 / —	0.024 / 0.006	17.87 / 0.36	64.53 / 0.19	16.11 / 0.18	0.72
Pa-93-4	— / —	0.017 / 0.003	22.83 / 0.39	51.58 / 0.16	16.00 / 0.16	8.86
Pa-93-3	— / —	0.11 / 0.02	33.09 / 0.57	53.61 / 0.7	9.9 / 0.2	1.80
Tiskre Formation						
Pa-93-2	— / —	0.02 / —	0.43 / —	29.25 / —	69.14 / —	1.16
Pa-93-1	0.01 / —	0.01 / —	1.43 / —	47.75 / —	50.42 / —	0.38

* bioclastic component not analysed;
— not detected.

In the Kallavere Formation the bioclastic component is mainly represented by phosphatic skeletal fragments of lingulate brachiopods and scarce conodont fragments. In the Pakri Cape section the phosphatic debris has been recorded only from the Maardu Member (samples 3—11), whereas its content exceeds 1% of the total rock only in samples 3 and 11 (Table 1).

The skeletal debris consists predominately of light brown, poorly rounded fragments of lingulate brachiopods. In the lower beds of the section (samples 3 and 4) some fragments are covered with phosphatic films. The Suurjõgi Member and the upper part of the Maardu Member (samples 12—15) did not yield skeletal debris. The distribution of the debris by grain size is shown in Table 1.

MINERALOGY

Optical microscopy of the very fine sand fraction

Light and heavy minerals of the very fine sand fraction (0.1—0.05 mm) were separated in a heavy liquid (bromoform, $\varrho = 2.88$ g/cm^3) and studied by optical microscopy using immersion liquids. The results are presented in Table 2 according to the counting scheme recommended by Viiding (Вийдинг, 1976). Altogether 13 samples from the Kallavere Formation and two samples from the underlying Tiskre Formation were studied (Fig. 1, Table 2).

The light mineral suite is mostly composed of allogenic minerals represented predominantly by quartz, feldspars, and very rare flacks of muscovite. Among the authigenic minerals (generalized as one group, Table 2), gypsum occurs in large amounts in two samples of the Suurjõgi Member, reaching nearly 60 and 40% in samples 13 and 14, respectively. Other samples yield rare grains of glauconite (samples 7, 8, 13, and 14) or carbonate minerals (samples 5 and 15).

Quartz, the most abundant mineral among sand grains of the Kallavere rocks, is mostly characterized by rounded, more rarely well-rounded monocrystalline non-undulatory grains. The number of undulatory and polycrystalline grains is limited. The feldspar fraction, mostly K-feldspars, ranges from 2 to 10%, but is usually between 3 and 7%. Two kinds of feldspar grains are present: rounded detrital grains weathered to various degrees and those overgrown with fresh authigenic K-feldspar exhibiting rhombic faces. About half of feldspar grains in the Maardu Member are surrounded by a thin (less than 30 μm) fragmentary overgrowth. In the grains from the Suurjõgi Member overgrowths are thicker (30—50 μm) and commonly continuous around the detrital core; grains of that kind constitute about 70% of feldspars in this member. This phenomenon has also been observed in the rocks of the Kallavere Formation, particularly in the Suurjõgi Member in other localities, such as Ülgase, Mäekalda, and Saka (Mens et al., 1989; Хейнсалу et al., 1987, 1991).

The heavy fraction rarely exceeds 1% (Table 2). It is composed of allogenic (detrital) and authigenic minerals; the authigenic minerals prevail in the basal and top layers of the Kallavere Formation. In the group of allogenic heavy minerals, opaque and transparent minerals occur in almost equal quantities, whereas micaceous minerals (mainly muscovite) are uncommon.

Among opaque minerals (including leucoxene frequently occurring in detrital form), ilmenite prevails, particularly in the rocks of the Suurjõgi Member. Magnetite is lacking throughout the Kallavere Formation.

Among transparent allogenic heavy minerals zircon, tourmaline, and titano-minerals are common, but their ratio varies greatly. However, titano-minerals (represented mainly by rutile) amounting to 2—19% are associated neither with a particular rock type nor stratigraphical level. The general pattern known for the Kallavere Formation implies the prevalence of zircon over tourmaline, especially in the Suurjõgi Member

255

Table 2

Mineral composition of the very fine sand fraction (0.1—0.05 mm), %

Minerals or their groups	Samples Pa-93-1—Pa-93-15														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LIGHT MINERALS															
Quartz	81.7	72.5	96.7	95.7	89.0	94.7	97.3	91.7	93.0	95.3	94.0	96.0	35.0	52.7	93.3
Feldspars	18.0	27.3	3.3	4.3	10.0	5.3	2.0	7.7	7.0	4.7	6.0	4.0	3.7	7.3	5.7
Micas	0.3	0.2	—	—	0.3	—	0.3	—	—	—	—	—	—	0.3	—
Authigenic	—	—	—	—	0.7	—	0.4	0.6	—	—	—	—	61.3	39.7	1.0
HEAVY MINERALS															
Total	0.04	1.45*	0.34	0.34	0.25	0.08	0.22	0.28	0.32	0.41	0.19	0.83	0.77	1.6	0.77
Allogenic opaque	19.6		25.2	21.4	15.5	25.9	39.1	36.9	47.0	43.3	31.9	42.7	19.4	29.5	19.4
Allogenic transparent	15.6		17.1	16.3	21.8	20.7	53.4	46.8	39.1	44.4	37.4	43.7	18.6	36.9	24.3
Micas	0.7		0.3	0.2	3.9	—	—	—	—	0.2	—	—	—	—	—
Authigenic	64.1		57.4	62.1	58.8	53.4	7.5	16.3	13.9	12.1	30.9	13.6	62.0	33.6	56.3
Allogenic/authigenic ratio	0.56		0.74	0.61	0.7	0.87	12.38	5.14	6.21	7.23	2.24	6.33	0.61	1.98	0.77
Ilmenite/leucoxene ratio	0.21		1.96	1.97	1.38	3.05	8.78	4.51	7.39	4.35	3.43	60.0	31.33	23.58	10.41
ALLOGENIC TRANSPARENT MINERALS															
Zircon	17.0		1.9	4.1	2.6	4.5	50.3	35.1	41.9	26.2	29.6	50.0	81.9	81.2	80.8
Tourmaline	69.8		81.9	89.2	83.8	83.1	32.1	47.4	41.0	49.2	51.4	33.6	4.5	2.7	8.0
Titano-minerals	12.3		13.3	2.7	7.7	6.8	15.2	16.4	14.3	19.0	12.0	16.4	8.3	10.1	8.8
Garnet	0.9		—	—	2.6	1.1	0.8	0.4	0.5	2.4	1.2	—	4.5	5.0	2.4
Apatite	—		2.9	4.1	3.3	4.5	1.6	0.7	2.3	3.2	5.8	—	0.8	—	—
Unstable heavy minerals	—		+	+	+	—	—	—	—	—	—	—	—	—	—
AUTHIGENIC MINERALS															
Iron oxide and hydroxide	63.3		10.5	14.8	42.5	45.4	70.6	53.6	80.5	66.7	63.2	46.2	99.1	95.5	56.5
Pyrite	10.3		24.9	48.6	24.8	45.8	23.5	35.1	16.9	26.1	34.4	42.3	0.9	3.0	2.4
Anatase	25.7		5.4	2.8	3.5	7.0	5.9	11.3	2.6	7.2	2.4	11.5	—	—	2.0
Carbonate	0.7		0.3	0.7	—	—	—	—	—	—	—	—	—	1.5	39.1
Phosphate	—		58.9	33.1	29.2	1.8	—	—	—	—	—	—	—	—	—

\+ traces;
* sample strongly pyritized, data not obtained;
— not detected.

(Mens et al., 1989; Хейнсалу et al., 1987, 1991). In the Pakri Cape section, the prevalence of tourmaline over zircon in the lower part of the Maardu Member (samples 3—6) was recorded for the first time. The occurrence of medium-stable minerals (garnet, apatite) is variable and does not reflect certain stratigraphical dependence. It should be noted that apatite is not common in the Suurjõgi Member.

The finds of unstable minerals are random and very rare. They occur only in the lower part of the Maardu Member and consist of strongly altered pyroxene and amphibole.

Authigenic heavy minerals are represented by pyrite and Fe-oxides and hydroxides throughout the studied section. Anatase and phosphate minerals are characteristic of the lower part of the Maardu Member. The phosphatic rims around the detrital grains of ilmenite, tourmaline, rutile, zircon, and occasionally quartz in the light fraction are observed only in the Maardu Member. Carbonate minerals occur sporadically and, at the topmost level of the formation, in considerable amounts.

XRD of clay minerals

Qualitative and semiquantitative study of the mineralogical composition of the <2 μm fraction was carried out by X-ray diffraction analysis (XRD) on a DRON-0.5 diffractometer using Mn-filtered Fe-Kα radiation. Air-dried, glycolated, and heated (500 °C) oriented samples were prepared for qualitative clay mineral identification. The relative content of clay minerals was estimated semiquantitatively by using empirical correction factors of XRD peak intensities based on earlier clay mineral studies at the X-ray laboratory of the Institute of Geology, University of Tartu. The illite, illite-smectite, smectite, chlorite, and kaolinite peak intensities were corrected by factors 0.55, 0.16, 0.09, 0.45, and 1.0, respectively.

The last five clay minerals comprise up to 0.5 wt% of the whole rock (Fig. 2). The main components of the clay material in sandstone pores are illite and illite-smectite making up from 80 to 100% of the cement. Alongside with normal illite, a degraded form was also distinguished, displaying an asymmetry of the $d(001)=10.1$ Å reflection towards the low angle side; illite-smectite has basal (001) reflections according to d-spacing 10.45—11.0 Å.

In the Kallavere Formation the illite content decreases and the illite-smectite content increases gradually from base to top. These changes correlate to the general trend of increase in grain size.

At some levels (Fig. 2) smectite was identified. It is represented by a quite well crystallized (Thorez, 1976) variety having $d(001)=12.8$—13.0 Å in normal and $d(001)=17.4$—17.5 Å in glycolated samples.

Chlorite occurs in small amounts (up to 18%) throughout the section. It seems to be a rather Mg-rich detrital variety displaying a quite high basal reflection at 14.2—14.4 Å and about equal to the (002) reflection intensity (Thorez, 1976). This variety differs from the Fe-rich varieties described from the Cambrian sandstone pores in Latvia (Апините, 1971) and Estonia (Пиррус, 1970). The asymmetry of the (002) reflection in an air-dried sample and structure contraction after heating (500 °C) suggest that the detrital chlorite, which can be easily destroyed by changes in the chemical environment (Velde, 1985), has been somewhat degraded by weathering processes in the outcrop.

Kaolinite occurs at certain levels (Fig. 2); its amount does not usually exceed 10% of the <2 μm fraction. The kaolinite content is highest at the top of the Tiskre Formation and in the basal Maardu Member (samples 3—6). For most of the kaolinite in the lower part of the Maardu Member, diagenetic origin is suggested, because it occurs at the levels closely

257

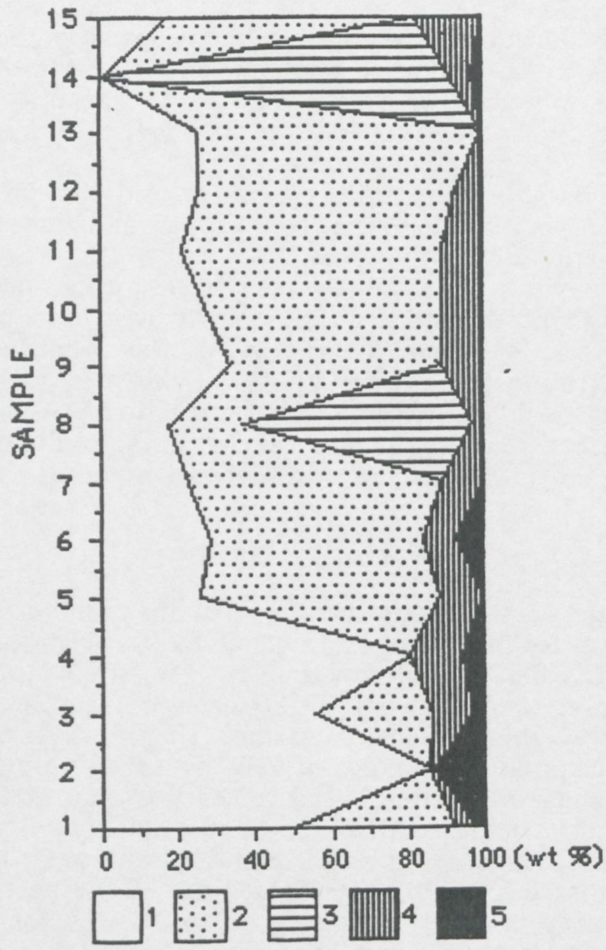


Fig. 2. Mineral composition of clay fraction (<2 μm) in the Pakri Cape section. Legend: *1*, illite; *2*, illite-smectite; *3*, smectite; *4*, chlorite; *5*, kaolinite.

related to the kerogenous shale layer. According to Curtis (1987), the dissolution of source minerals favoured by acidic conditions and the presence of relict organic matter is followed by a pH rise due to acid consumption. This would lead to kaolinite precipitation during diagenesis but kaolinite is moderately ordered, which is not typical of authigenic kaolinite (Chamley, 1989).

An abrupt change in the clay mineral content occurs at the boundary of the Tiskre and Kallavere formations. The top of the Tiskre Formation is characterized by a relatively high content of kaolinite, low chlorite content, and well-crystallized illite; the latter is characteristic of repeated wetting-drying processes (Srodon & Eberl, 1984). Such a mineralogy is interpreted as resulting from weathering processes during a long hiatus in sedimentation.

DISCUSSION AND CONCLUSIONS

According to current conventional use of the conodont zonation, the lower boundary of the Pakerort Stage is tentatively defined by the appearance of the genus *Cordylodus*, i.e. with the base of the *Cordylodus andresi* Zone (Kaljo et al., 1986; Männil, 1990).

In the studied Pakri Cape section, the only conodont zone established is the *Cordylodus proavus* Zone corresponding to the lower part of the

Maardu Member (samples 3—6). Owing to the scarcity and poor preservation of conodonts in the upper beds of the Maardu Member (samples 7—11), the upper boundary of the *C. proavus* Zone and the boundaries of younger conodont zones cannot be defined with confidence in this section. At the level of a change in conodont abundance and preservation, in the lower part of the Maardu Member (between samples 6 and 7), notable differences in the depositional conditions and mineralogical compositions are observed. Most likely they reflect increasing hydrodynamic activity and changes in bottom topography of the sedimentary basin.

The lenses of the basal conglomerate found in about 200 m of the section (Nemliher & Puura, 1996) yield lingulate brachiopods *Ungula convexa* and *Ungula ingrica* known from the Upper Cambrian of Baltoscandia (Попов & Хазанович, 1989; Puura & Holmer, 1993). Conodonts and acritarchs have not been studied from these conglomerate lenses as yet.

Considering the presently known fossil evidence from the Pakri Cape section and knowledge on the biostratigraphy and distribution of the Cambrian—Ordovician boundary beds of Estonia (Kaljo et al., 1986; Mens et al., 1993), three possible options for the age of the basal conglomerate should be considered: the conglomerate may be correlative either to the *Proconodontus* Subzone of the *Westergaardodina* Zone, the *Cordylodus andresi* Zone or the *C. proavus* Zone.

The deposits of the *Proconodontus* Subzone, represented by the Tsitre Formation, are known to occur in restricted areas east of Tallinn (Попов & Хазанович, 1989). Still, we cannot exclude the possibility that in the Ülgase section the conodont assemblage from the lower part of the Kallavere Formation belongs to this subzone (Хейнсалу et al., 1987; Mens et al., 1993). The upper part of the range of *Ungula convexa* and the lowermost part of the range of *Ungula ingrica* are tentatively correlative to this subzone.

The deposits of the *C. andresi* Zone are widely distributed in northern Estonia. They are found in the Ülgase, Valkla, Toolse, and Vihula sections east of Tallinn, in the M-9 core south of Maardu, and in the Kidaste core on Hiiumaa Island (Kaljo et al., 1986; Mens et al., 1993). On the other hand, the *Cordylodus andresi* Zone is missing in stratigraphically less complete sections in Tallinn and westwards (Kaljo et al., 1988; Mens et al., 1989, 1993; Попов & Хазанович, 1989), including the studied Pakri Cape section.

As discussed above, the beds of the Maardu Member above the basal conglomerate in the Pakri Cape section yield the conodonts of the *Cordylodus proavus* Zone, i.e., the conglomerate formation might have occurred before or during the *C. proavus* time. At the present stage of the study, the question about the existence of the two oldest conodont zones in the Pakri Peninsula sections remains open.

To sum up, with regard to the current concept of the Pakerort Stage, the Pakri Cape section, where only the *C. proavus* Zone can be defined with confidence, is biostratigraphically not representative of the lower part of the Pakerort Stage. Further studies of the sections on the Pakri Peninsula are necessary for estimating the stratigraphical extent of the Pakerort Stage in its stratotype area.

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25p

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KAMBRIUMI JA ORDOVIITSIUMI PIIRIKIHID PAKRI NEEME LÄBILÕIKES, LOODE-EESTI

Kaisa MENS, Heljo HEINSALU, Kalmer JEGONJAN, Tiia KURVITS, Ivar PUURA, Viive VIIRA

Pakri neeme läbilõike kambriumi ja ordoviitsiumi piiriintervall kuulub litostratigraafiliselt Kallavere kihistusse, mis on jaotatud Maardu ja Suurjõe kihistikeks.

Artiklis on toodud Kallavere kihistu paleontoloogilise ja mineraloogilise uurimise tulemused.

Uuritud läbilõikes algab kihistu *Cordylodus proavus*'e tsooni tasemel. Fossiilide vähese säilimuse või puudumise tõttu ei ole kihistu ülemise osa biostratigraafilist kuuluvust täpsemalt võimalik määrata. Kallavere kihistut iseloomustab väga väike biogeense komponendi sisaldus, turmaliini valdamine läbipaistvate raskete mineraalide rühmas ja laialdane kipsi levik Suurjõe kihistiku ülemises osas.

КЕМБРИЙСКО-ОРДОВИКСКИЕ ПОГРАНИЧНЫЕ ОТЛОЖЕНИЯ В РАЗРЕЗЕ МЫСА ПАКРИ, СЕВЕРО-ЗАПАДНАЯ ЭСТОНИЯ

Кайса МЕНС, Хельо ХЕЙНСАЛУ, Калмер ЕГОНЯН, Тийа КУРВИТС, Ивар ПУУРА, Вийве ВИЙРА

В разрезе мыса Пакри кембрийско-ордовикский пограничный интервал сложен отложениями каллавереской свиты, состоящей из маардуской и суурйыгиской пачек. В статье дана минералогическая характеристика тонкопесчаной и пелитовой фракций пород каллавереской свиты. Палеонтологическое изучение позволяет заключить, что в этом разрезе каллавереская свита начинается на уровне конодонтовой зоны *Cordylodus proavus*. Верхняя половина каллавереской свиты из-за плохой палеонтологической представленности биостратиграфически не определена.

261

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SHELL MINERALOGY OF LINGULATE BRACHIOPODS FROM THE EAST BALTIC CAMBRIAN-ORDOVICIAN "OBOLUS PHOSPHORITE"

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In northern Estonia and Ingria (Leningrad district of Russia), mass accumulations of lingulate brachiopod valves in Upper Cambrian to Tremadocian *Obolus* Sandstone form deposits of "*Obolus* phosphorite". In modern stratigraphic terms, the phosphorite-bearing *Obolus* Sandstone corresponds to the Ülgase, Tsitre and Kallavere formations in Estonia, and the Ladoga, Lomashka and Tosna formations in Ingria. The commercial phosphorite deposits occur mostly in the Kallavere and Tosna formations (Kaljo *et al.*, 1986; Heinsalu, 1987; Popov *et al.*, 1989).

The present article deals with the shell mineralogy of the lingulates from the *Obolus* Sandstone. Our objective is to study the lattice parameters of apatite in lingulate shells in statistically representative material and to discuss possible pathways leading to the observed mineralogical composition.

PREVIOUS STUDIES ON FOSSIL LINGULATE SHELL MINERALOGY

In a pioneer study of chemical composition of a sample from Yamburg in Russia (presently Kingissepp; Fig. 1), Schmidt (1861) concluded that the obolid shells are composed of amorphous fluorapatite close to vertebrate bone tissue and expressed the idea of their potential use as a fertilizer. Mineral composition derived from an independent chemical analysis of a sample from the same locality by Kupffer (1870) coincided with that suggested by Schmidt. Chemical analysis of the valves of "*Obolus*" (= *Ungula*; see Puura and Holmer,

1993) from Vikarbyn and Boda in the Siljan District of Dalarna, Sweden was carried out by Andersson and Sahlbom (1900) who concluded that the fluorapatite of the fossil valves is of primary origin because its fluorine content was close to that of Recent *Lingula anatina*.

Mickwitz (1896) observed the lamellar structure of the cross-section of the shells of "*Obolus apollinis*" (= *Ungula ingrica*) from Jägala-Joa by light microscopy and suggested the presence of calcite and gypsum lamellae. Niggli and Beyer (*in* Wrangell, 1920) studied the optical parameters of apatite in thin sections and concluded that the shell mineral is an apatite containing carbonate. Providing new chemical data from Ülgase and reviewing the earlier chemical analyses and thin section observations, Öpik (1929) concluded that the obolid shells are composed of a non-homogeneous mixture of phosphatic and other minerals and proposed the term "Obolenphosphorit" or "Obolus phosphorite". Koch (1958) reviewed the earlier chemical studies leaving the question of the mineralogical composition open.

Loog (1962) carried out chemical analysis and X-ray powder diffraction analysis (XRD) of the valves of *Ungula ingrica* and *Schmidtites celatus* from Iru and Ontika in Estonia, concluding that the valves are composed of francolite, a carbonate fluorapatite. The conclusion was based on chemical data and the intensities of selected XRD peaks; lattice parameters were not calculated, but cited after an earlier unpublished report (Kurman *et al.* 1955, cited after Loog, 1962). Further studies have dealt with the mineral composition of phosphate in concentrates of "Obolus phosphorite" from the Maardu and Kingissepp mines, reporting the average stoichiometric formula (Veiderma and Veskimäe, 1971), lattice parameters: $a = 9.356$, $c = 6.887$ for Maardu and $a = 9.353$, $c = 6.887$ for Kingissepp and structural characteristics revealed by infrared spectroscopy (Veiderma and Knubovets, 1972). Ushatinskaya *et al.* (1988) carried out a comparative X- ray study of seven species from the Cambrian and Lower Ordovician of Canada, Siberia, Kirgizia and Leningrad region, including three species from the "Obolus sandstone" of Ingria (Table 1). They concluded that all the species are composed of carbonate fluorapatite with different stoichiometric proportions. Paying attention to the fact that the unit cell parameters of some species were stable in different localities, they did not make further conclusions because of the lack of statistically representative material.

GEOLOGICAL SETTING

In the western part of the Baltoscandian palaeobasin, the Upper Cambrian and lowermost Tremadocian (Lower Ordovician) are represented mostly by alum shales, while in Estonia and Ingria, a sandstone facies prevails (Mens *et al.*, 1993). Thin conglomerates in northern Öland, the South Bothnian submarine district and the Siljan district containing lingulate brachiopods identical to the species occurring in Estonia, indicate that the sandstone facies has extended westwards to Sweden (Puura and Holmer, 1993).

According to biostratigraphic studies (Kaljo *et al.*, 1986, 1988; Popov *et al.*, 1989; Mens *et al.*, 1993), the most extensive accumulations of the shelly phosphorites correspond to the *Cordylodus andresi-C. proavus* conodont zones. Most of the lithostratigraphic units related to the "Obolus Sandstone" (Heinsalu, 1987) have characteristic features of high energy environments. In most sequences, only transgressive parts of the cycles, commencing with coarse-grained sandstones and terminating by fine-grained sandstones or siltstones have been preserved (Heinsalu *et al.*, 1987; Popov *et al.*, 1989). The sandstones contain lenses of black shales and are overlain by Dictyonema Shale, up to 7 m thick, considered to be formed mostly in an oxygen-poor environment (Heinsalu, 1990). In some eastern localities in Ingria, the presence of trace fossils, e.g., *Skolithus*, suggests a more oxygen-rich environment (Popov *et al.*, 1989). Lingulate shells can be found at many levels, though their higher frequency and larger average size in coarse-grained fractions indicate hydrodynamical sorting. "Obolus conglomerate", a coquina containing lingulate brachiopod shells and phosphatic pebbles occurs at the base of some transgressive cycles. The shells, redeposited from older parts of the section, and sometimes enclosed in the pebbles, can be encountered in the coquinas (Kaljo *et al.*, 1986, 1988, Heinsalu *et al.*, 1987, Mens *et al.*, 1989; Popov *et al.*, 1989).

SAMPLING AND X-RAY ANALYSIS

Brachiopods were sampled from 14 outcrops in northern Estonia and Ingria (Fig. 1). The three most common obolid species forming mass accumulations, *Ungula ingrica* (Eichwald), *Schmidtites celatus* (Volborth) and *Obolus apollinis* (Eichwald), were systematically sampled. Selected samples of Middle and Upper Cambrian obolids *Ungula convexa* (Pander), *Oepikites macilentus* (Khazanovitch and Popov), *Oepikites koltchanovi* (Khazanovitch and Popov) and *Helmersenia ladogensis* (Jeremejew) were taken for comparative analyses (Table 1), as were some phosphatized pebbles.

Shells were selected for X-ray powder diffraction analysis from all the samples. The shells or pebbles were powdered in an agate mortar and then analyzed with an X-ray diffractometer DRON- 0.5 with Ni-filtered Fe Kα radiation using quartz as an internal standard. In the interval of 12-76^{o} (2 Θ), 25 reflections of apatite were registered. The angle correction for apatite reflections was calculated against the 101 and 112 reflections of the quartz standard. Lattice parameters were calculated using the least squares method, including the data of all the 25 reflections (Aruväli, 1990). The structural CO_2 content was calculated by the formula proposed by Gulbrandsen (1969).

The results of the X-ray diffraction analysis and the comparative data from Ushatinskaya *et al.* (1988) are presented in Table 1. The presence of pyrite in some shells, observed by light microscopy, was also detected by X-ray analysis.

Table 1. Lattice parameters and calculated CO_2 content of apatite in lingulate brachiopod valves and phosphatized pebbles from the East Baltic Cambrian-Ordovician "Obolus phosphorite". Locality numbers correspond to those in Fig. 1.

Species	*a*	*c*	CO_2	n
Obolus apollinis	9.333-9.350	6.877-6.889	1.3-3.2	14
Schmidtites celatus	9.351-9.363	6.884-6.894	1.2-2.4	13
Ungula ingrica	9.335-9.366	6.890-6.905	1.0-3.4	12
Ungula convexa	9.346-9.367	6.880-6.896	1.4-2.2	6
Oepikites fragilis	9.348-9.356	6.878-6.895	1.0-2.0	3
Oepikites macilentus	9.362-9.363	6.881-6.896	0.3-2.1	2
Ungula inornata	9.352	6.890	2.1	1
Helmersenia ladogensis	9.350	6.886	1.9	1
Pebbles, Ingria	9.342-9.347	6.885-6.888	2.3-2.5	3
Pebble, Tallinn	9.36	6.903	3.13	1
Comparative data from Ushatinskaya *et al.* (1988)				
Helmersenia ladogensis	9.35	6.88		1
Oepikites koltchanovi	9.36	6.89		1
Keyserlingia buchii	9.33	6.88		1

DISCUSSION

The data relevant for interpreting the factors and pathways governing the mineral composition in fossil lingulates can be obtained from a knowledge of shell structure and mineralogy of Recent lingulate brachiopods, ion substitutions in apatite during post-mortem mineralogical changes of apatitic skeletal parts, mechanisms of bacterial degradation and phosphatization of organic tissues, and apatite precipitation in sea water and pore space.

Structure and mineral composition of Recent lingulate shells

A study by X-ray diffraction, infrared absorption and X-ray microprobe analyses has shown that the shell mineral of Recent lingulates is F-containing carbonate-OH-apatite (LeGeros *et al.*, 1985). The lattice parameters of the Recent lingulate shell mineral are between those of hydroxyapatite and fluorapatite (Table 2, comp. Slansky, 1986, Table 5, p. 31).

In general terms, the shells of Recent lingulates of the genera *Lingula* and *Glottidia* are composed of alternating layers of organic tissue and carbonate-apatite (Iwata, 1981, 1982; Watabe and Pan, 1984). The proportion of the organic vs. mineral tissue appears to be taxon-specific: the organic content in the shells of *Glottidia pyramidata* and *Lingula anatina* reaches 60 and 50 wt%, respectively (Pan and Watabe, 1988a,b; Iwata, 1981). The carbonate content in *Glottidia* apatite is higher than that in *Lingula*: 3.6 vs 1.8 wt%; the fluor content varies according to the shell layer and averages 2.58 in highly calcified layers of *Lingula* and *Glottidia* (Watabe, 1990). A study of *Discina* by Williams *et al.* (1992) revealed that the mineralized and organic layers actually correspond to the zones of differential mineral content, termed as laminae. Still, the compact laminae, corresponding to the mineralized layer of earlier authors have significantly higher mineral content than other four types of laminae, equivalent to organic layer of earlier authors. For the purpose of the following discussion of diagenetic changes in buried lingulate shells, we use the simplified model of the alternating mineral and organic layers discussed above.

269

Table 2. Reported lattice parameters of Recent lingulate brachiopod shell apatite.

Species	*a*	*c*	Reference
Lingula anatina	9.402	6.880	Watabe and Pan, 1984
Lingula anatina	9.389	6.880	LeGeros *et al.*, 1985
Lingula anatina	9.373	6.869	Zezina *et al.*, 1993
Lingula anatina	9.395	6.867	Zezina *et al.*, 1993
Lingula anatina	9.383	6.859	Iijima *et al.*, 1991
Lingula adamsi	9.396	6.880	LeGeros *et al.*, 1985
Lingula reevei	9.383	6.871	Zezina *et al.*, 1993
Lingula shantougensis	9.381	6.863	Iijima *et al.*, 1991
Glottidia pyramidata	9.380	6.890	LeGeros *et al.*, 1985
Glottidia pyramidata	9.394	6.890	Watabe and Pan, 1984
Discinisca lamellosa	9.383	6.871	Zezina *et al.*, 1993

Mineralogy of fossil lingulate shells

The lattice parameters of fossil lingulate shells studied here and reported by Ushatinskaya *et al.* (1988) are in the range corresponding to apatite species between fluorapatite and carbonate fluorapatite (Table 1, comp. Slansky, 1986, Table 5, p. 31).

Compared to Recent lingulate brachiopods (Table 2), the studied fossil lingulates have considerably lower values of the unit cell parameter *a*. This systematic difference can be explained by substitution of different ions into the apatite lattice (Hughes *et al.*, 1989).

The fluor-containing carbonate-OH-apatite in hard tissues of living brachiopods and vertebrates has a tendency for crystallographic maturation by replacement of OH^- by F^- and $(PO_4)^{3-}$ by $(CO_3)^{2-}$ and F^-. Thus, additional F is incorporated to the lattice with carbonate, as the apatite becomes a carbonate-fluorapatite. According to Lucas and Prévôt (1991), this aquisition of fluorine and carbonate is initiated *in vivo* and continues during diagenesis.

Provided that most apatite species produced in skeletal biomineralization in Recent invertebrates and vertebrates have relatively high hydroxyl contents (Watabe, 1990; Skinner, 1991), we are inclined to interpret the significantly different mineralogy of fossil shells as influenced in some extent by diagenetic alteration.

Other processes that can influence the composition of shell apatite are bacterially mediated replacement of the organic tissue by a new generation of apatite, degradation of organic matter and subsequent precipitation of carbonate-F-apatite to the free space. Furthermore, the substitution of $(CO_3)^{2-}$ vs $(PO_4)^{3-}$ in the course of diagenetic alteration decreases crystal size and increases apatite solubility (Jahnke, 1984) that in turn increases the possibility of recrystallization. The precipitated cryptocrystalline carbonate apatite (CCP) may also dissolve if the geochemistry of the microenvironment changes.

Pyritized and phosphatized fossil bacteria-like bodies, as well as living Recent chemolitotrophic bacteria, have been isolated from the studied fossil lingulates (Nemliher, 1993). Experimental work has demonstrated that bacteria are able to mediate apatite formation through the action of their enzymes (Lucas and Prévôt, 1991). In some cases, rapid phosphatization can lead to exclusive preservation of organic tissues, as has been demonstrated both by laboratory experiments and fossil record, e.g., Upper Cambrian 'orsten' arthropods from the western alum shale facies of "Obolus phosphorite" basin (Briggs and Kear, 1994; Walossek, 1993 and references therein). In other cases, organic tissue can be completely degraded by anaerobic bacteria. An experimental study by Arnosti *et al.* (1994) has shown that degradation of polysaccharides by consortia of anaerobic bacteria can be rapid in anoxic environments, that is, by different groups of bacteria working in concert in transformation of complex substrates. Possible pathways of bacterially mediated mineralization of organic tissue depending on burial conditions and early diagenetic environment can be viewed in the context of the sequence of oxic, suboxic, anoxic zones in the bottom water and sediment column (e.g., Allison, 1988).

After burial in sediment, a pore-space like microenvironment may develop in a lingulate valve, where the organic matter or the space left after its degradation is enveloped by the mineral part. Light microscopy observations supported by X-ray analysis and back-scattered electron imaging show that the space occupied *in vivo* by organic tissue is filled with pyrite in many valves. The sedimentary pyrite precipitation is considered to be initiated by sulphate reducing bacteria (Berner, 1984) and to occur below oxic-suboxic interface in the water or sedimentary column or in pore space with similar geochemical regime (Allison, 1988). The observation of distinct alternating layers of phosphate and pyrite in thin sections provides a clue for understanding analogous precipitation of secondary apatite, as close phosphate phases cannot be visually distinguished.

In microenvironments richer in oxygen, an expected mineral to replace the organic tissue is carbonate-fluorapatite (syn. francolite; Clark, 1993). We assume that the organic matter was first degraded by bacteria and the free space was subsequently filled with secondary

271

apatite. This assumption is supported by SEM observations in *Ungula ingrica* by Holmer (1989, Fig. 14, p. 32): the cryptocrystalline calcium phosphate (CCP) fills the space between rod-like baculae, the preserved parts of the original structure. As yet, no evidence has been found for phosphatization of organic tissues of the "Obolus Sandstone" lingulates.

Infraspecific variation range of the lattice parameter *a* is from 0.01 to more than 0.03 Å, being most stable in *Schmidtites celatus* and *Obolus apollinis* and least stable in the species of the genus *Ungula*. For instance, the variation of the lattice parameters of *Ungula ingrica* is as wide, and in about the same range, as lattice parameters for eight Cambrian and Early Ordovician lingulates reported by Ushatinskaya *et al.* (1988).

Preliminary results of the shell structure studies to be published separately have revealed that among the studied genera, *Ungula* has the thickest organic layers and, consequently, the highest content of organic tissue that has been subsequently replaced by secondary apatite. The varying amount of secondary apatite (CCP), differentially filling the space between mineral layers, results in a varying bulk composition of the shells.

Compared to *Ungula*, the shells of a smaller obolid, *Schmidtites celatus* had thinner organic layers. The variation of lattice parameters *a* and *c* is only slightly over 0.01 Å (Table 1). The lattice parameters of a related genus *Oepikites* are approximately in the same range as for *Schmidtites*.

The shells of *Obolus apollinis* from Ingria have the lowest values of lattice parameter *a* and a high carbonate content, close to the corresponding values of the phosphatized pebbles from the same area. Preliminary SEM observations suggest that the shell apatite has been recrystallized in many cases. Thus, it can be suggested that the carbonate content in the recrystallized shells approached the equilibrium with seawater (Jahnke, 1984). The question of the impact of possible change to shell mineralogy in non-marine conditions remains open.

CONCLUSIONS

In contrast to the opinion expressed in most earlier studies, the mineralogical composition of fossil and Recent lingulate shells differs significantly. Recent lingulate shell mineral is a F-containing carbonate hydroxylapatite with a F-content higher than in dahllite with the lattice parameters $a = 9.38\text{-}9.40$ and $c = 6.87\text{-}6.89$. The bulk composition of the studied fossil shells corresponds to the apatite species between fluorapatite and carbonate fluorapatite with the lattice parameters $a = 9.33\text{-}9.36$ and $c = 6.87\text{-}6.90$. Previously reported lattice parameters of fossil lingulates (Ushatinskaya *et al.*, 1988) are also within this range.

The original composition of the fossil lingulate shells was possibly close to that of the Recent shells. In each particular case, the change of the mineralogical composition of a fossil shell could have been caused by one or a combination of a variety of processes, such as (1) diagenetic substitution of OH^- by F^- and $(PO_4)^{3-}$ by $(CO_3)^{2-}$ and F^-, (2) degradation of organic tissues by bacteria and precipitation of CCP (or pyrite) in the free space and (3) dissolution and recrystallization of $(CO_3)^{2-}$- enriched fossil shell apatite due to high solubility.

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275

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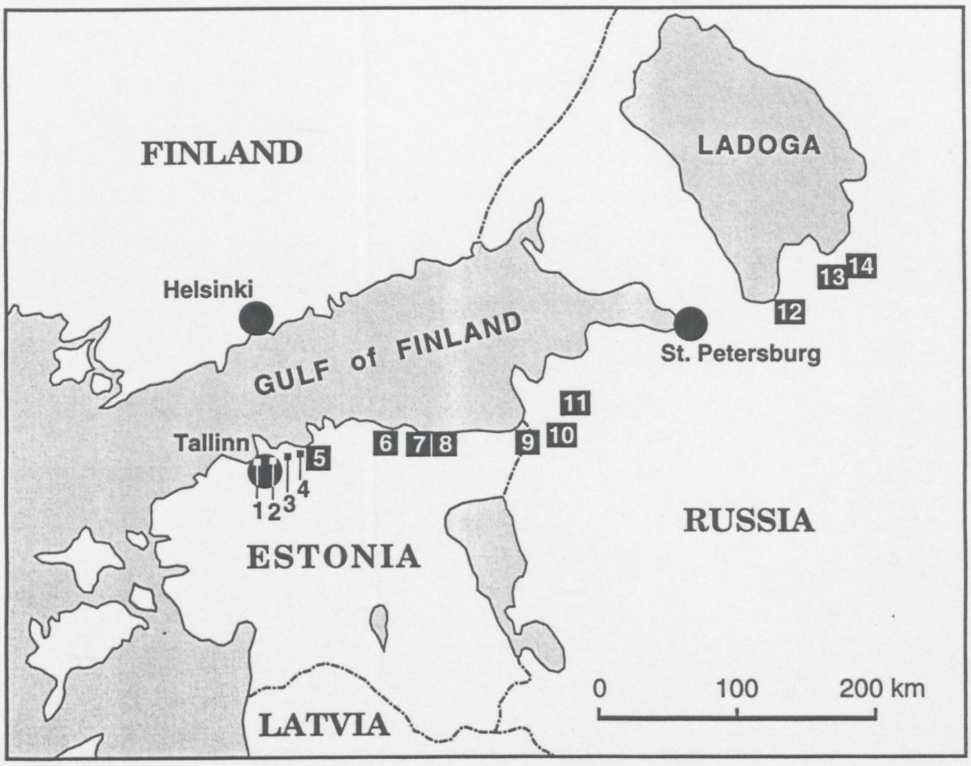

Figure. Outline map of Estonia and Ingria (St. Petersburg region of Russia), with studied localities: 1 - Mäekalda, 2 - Iru, 3 - Ülgase, 4 - Valkla, 5 - Turjekelder, 6 - Toolse, 7 - Kalvi, 8 - Saka, 9 - Narva River, 10 - Kingisepp quarry, 11 - Suma River, 12 - Lava River, 13 - Volkhov River, 14 - Syas River.

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Lingulate brachiopods and biostratigraphy of the Cambrian- Ordovician boundary beds in Baltoscandia.

Doctoral dissertation submitted to the Faculty of Sciences and Technology, Uppsala University, to be publicly examined in the lecture theatre, Palaeontology Building, Institute of Earth Sciences, on November 26, 1996, at 10.15 a.m. The discussion will be in English.

ABSTRACT
Puura, I. 1996: Lingulate brachiopods and biostratigraphy of the Cambrian-Ordovician boundary beds in Baltoscandia. *Comprehensive Summary of Doctoral Dissertation.* Institute of Earth Sciences. Department of Historical Geology and Palaeontology. Uppsala University , 19 pp. Uppsala.

This study evaluates the taxonomy and stratigraphic utility of lingulate brachiopods from the Cambrian-Ordovician boundary beds in outcrops and core sections in Estonia, Ingria (St. Petersburg district of Russia) and Sweden.

From Middle Cambrian to Hunneberg (Lower Ordovician) strata of Estonia and Ingria, thirty-seven species (32 named) are described, assigned to 26 named genera (of which one is new). The distribution of lingulates is documented from more than 40 outcrops and 10 drill cores. Seven lingulate biozones, defined by the first appearance of the zonal species, are distinguished (in ascending order): *Obolus ruchini*, *O. transversus*, *Ungula inornata*, *U. convexa*, *U. ingrica*, *Obolus apollinis*, "*Eurytreta*" and *Thysanotos siluricus* biozones. Co-occurrences of lingulates and conodonts permit tentative correlation between the East Baltic lingulate biozones and conodont biozones.

Closely related Cambrian-Ordovician lingulates in the Siljan District, South Bothnian submarine district and the island of Öland, Sweden, occur mostly in condensed sandstones or conglomerates referred to as "*Obolus*" beds. The Swedish "*Obolus*" beds are interpreted as having formed during several phases of reworking in the time interval from the Late Cambrian to Hunneberg.

Differences in apatite lattice parameters of fossil and Recent lingulate shells have been established by means of powder XRD. The apatite variety in Recent lingulate shells is a F-containing carbonate hydroxyapatite with a fluorine content higher than in dahllite, with the lattice parameters $a = 9.38$-9.40 and $c = 6.87$-6.89. The apatite lattice parameters for the fossil shells, $a = 9.33$-9.36 and $c = 6.87$-6.90 correspond to the apatite species between fluorapatite and carbonate fluorapatite (francolite); in many cases, more than one apatite phase is distinguished. These differences are explained by various *post mortem* processes, in particular, by microbial degradation of organic tissues and precipitation of authigenic apatite.

Key words: Brachiopoda, Lingulata, Cambrian, Lower Ordovician, systematics, biostratigraphy, taphonomy, XRD, Estonia, Russia, Sweden.

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