

## Conodont dating of the Middle Ordovician breccia cap-rock limestone on Osmussaar Island, northwestern Estonia

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**Abstract.** Various mechanisms have hitherto been suggested to explain the formation of the Kundan (Middle Ordovician) Osmussaar Breccia in northwestern Estonia. Following the recent discovery of L-chondritic chromite in these peculiar, sand-penetrated strata, it seems plausible that the breccia is impact-related. Herein, the conodont faunas of three thin limestone intervals overlying the breccia at Osmussaar Island have been investigated, with the aim of establishing the age of the event in terms of the Baltoscandian conodont-based biostratigraphical scheme. Based on the presence of *Microzarkodina ozarkodella*, the limestone directly overlying the breccia is assigned to the *M. ozarkodella* Subzone of the *Lenodus* (*Eoplacognathus?*) *pseudoplanus* Zone. This is reinforced by means of a faunal shift between this sample interval and the subsequent one, which is directly comparable with a faunal shift in the Mäekalda section, mainland Estonia. The middle, orthoceratite-yielding interval is assigned to the uppermost *L. (E.?) pseudoplanus* Zone (or, alternatively, the lowermost *Eoplacognathus suecicus* Zone), whereas the uppermost interval, an oolitic limestone, is referable to the *E. foliaceus* Subzone, corresponding to the lower part of the Lasnamägi Stage. These results support a connection between the Osmussaar event and the stratigraphic interval yielding abundant meteorites and/or high levels of L-type chromite in Sweden, as they both can be referred to the lower and/or middle part of the Kunda Stage. The minor difference in age between the first limestones deposited after the brecciation and the meteorite and L-chromite-yielding interval in Baltoscandia can be explained as caused by a period of non-deposition, seen as numerous hiatuses of various extent in the Kunda Stage in northwestern Estonia.

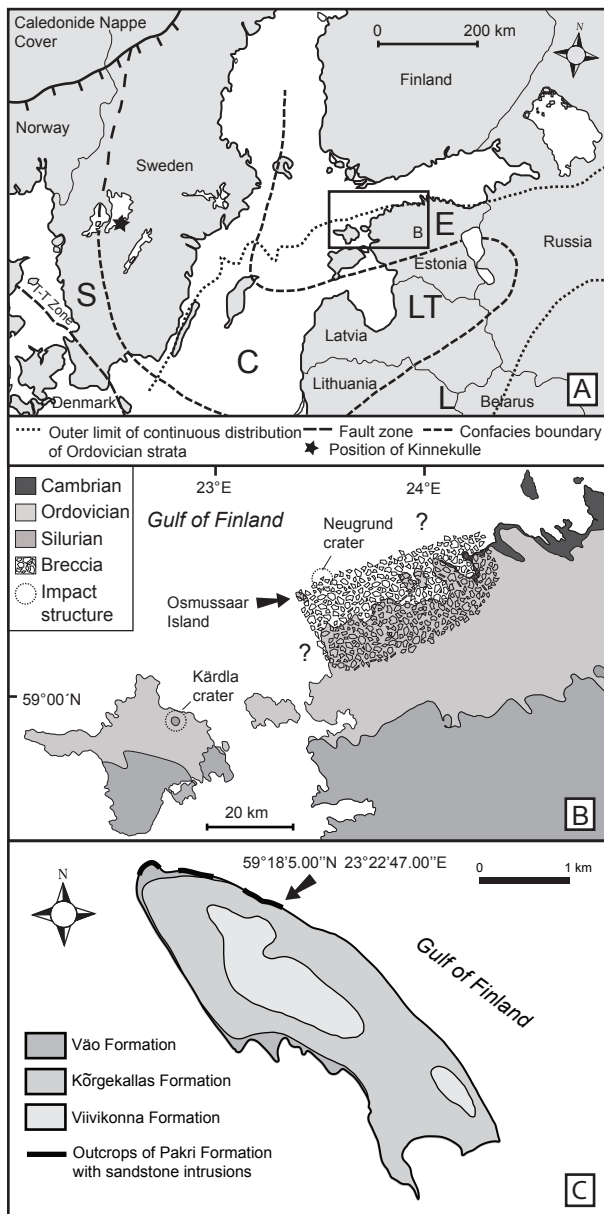
**Key words:** Osmussaar Breccia, conodonts, biostratigraphy, impacts, fossil meteorites, L-chondritic chromite, Estonia.

### INTRODUCTION

The Middle Ordovician Osmussaar Breccia, one of several so-called sedimentary mega-breccias in the Middle Ordovician (Parnell 2009; Meinhold et al. 2010), is named after the small (4.95 km<sup>2</sup>) Osmussaar Island, which is situated in the Baltic Sea outside the northwestern coast of mainland Estonia (Fig. 1). The breccia, consisting of centimetre- to metre-sized limestone fragments plus vein-like sandstones, extends across an area of more than 1000 km<sup>2</sup> and is at its thickest, ca 1.5 m, on Osmussaar Island. A gradual thinning away from Osmussaar Island, together with the west–east oriented elliptical dispersion (Fig. 1B), suggest that the generating event epicentrum is located not too far from the island (Suuroja et al. 2003; Alwmark et al. 2010).

The origin of the breccia has been debated for more than a century and hypotheses about its formation include plate tectonics, earthquakes and impacts (see Suuroja et al. 2003 and references therein). Despite the structure's content of shocked quartz, the impact alternative was only tentatively discussed by Suuroja

et al. (2003) due to the absence of a roughly contemporaneous crater within a reasonable distance. Tinn et al. (2010) studied ostracods recovered from the sandstone veins of the Osmussaar Breccia and concluded that the unusual and variable faunal composition could be explained by rapid mixing and displacement of bottom sediments caused by an impact event. Moreover, Alwmark et al. (2010) demonstrated the presence of non-reworked extraterrestrial L-type chondritic chromite grains in the breccia, which gives further support to an impact origin. This also implies that the impactor was derived from the disintegration of the L-chondrite parent body, an event dated to 467.3 ± 1.6 Ma (Schmitz et al. 2008). This has proven to be the source of the abundant extraterrestrial material found in the early Darriwilian (Middle Ordovician) limestone strata of e.g. Kinnekulle, Sweden, and the Puxi River, south-central China (Schmitz et al. 1996, 1997, 2003, 2008; Schmitz & Häggström 2006; Cronholm & Schmitz 2010). Likewise, Schmitz et al. (2011) demonstrated a similar connection to the impactor likely responsible for the 458 Ma (Upper Ordovician) Lockne crater.



**Fig. 1.** A. Overview of the Baltoscandian region, after Jaanusson (1976, 1995) and Rasmussen et al. (2009). The rectangle indicates the area of Fig. 1B. Abbreviations: C = Central Baltoscandian Confacies Belt, E = North Estonian Confacies Belt, L = Lithuanian Confacies Belt, LT = Livonian Tongue, S = Scanian Confacies Belt. B. Close-up of northwestern Estonia showing the position of Osmussaar Island and the known distribution of the Osmussaar Breccia, after Alwmark et al. (2010). The question marks signify that the distribution of the breccia to the north and to the west is uncertain. C. Map of Osmussaar Island, showing the most widespread limestone formations as seen from above, and coastline outcrops where the breccia is exposed (thick black lines). The coordinates and arrow indicate the position of the sampling site. Modified from Suuroja et al. (1999).

A connection between the elevated levels of sediment-dispersed extraterrestrial chromite and fossil meteorites from Kinnekulle, and the Osmussaar Breccia, was synoptically discussed by Suuroja et al. (2003). However, the latter authors pointed out that the disparate biostratigraphical schemes – chitinozoans for the breccia and conodonts for the Kinnekulle strata – did not allow for any precise correlation. Nevertheless, given previous age determinations, the possibility of equivalence between the extraterrestrial material at Kinnekulle and that of the Osmussaar Breccia is not farfetched, as both are dated to be of Kunda age (Fig. 2).

In terms of conodont biostratigraphy and following Schmitz et al. (2008), the drastically elevated levels of L-chondritic material at Kinnekulle are found in the *Lenodus variabilis* Zone and the *Yangtzeplacognathus crassus* Zone. In the Killeröd and Fågelsång sections of Scania, southern Sweden, such elevated levels extend also into the lowermost *Microzarkodina haegtiana* Subzone of the *Lenodus* (or possibly *Eoplacognathus*) *pseudoplanus* Zone (Schmitz et al. 2008, fig. 2). In terms of Kunda substages, this interval corresponds to the Hunderum–lower Valaste substages (Fig. 2). By comparison, the suggested timing for the formation of the Osmussaar Breccia is somewhat more broadly defined. Suuroja et al. (2003) stated that the brecciation event was stratigraphically confined to the lower half of the Kunda Stage. Their opinion was based on lithological correlation with sections on the Estonian mainland and the stratigraphical distribution of the chitinozoan *Cyathochitina regnelli sensu* Nölvak & Grahn (1993). Following Nölvak & Grahn (1993, fig. 2) and Nölvak et al. (2006, fig. 1), the *C. regnelli* Zone extends all the way from the lower Kunda Stage until approximately the mid-Aseri Stage, whereas in Grahn & Nölvak (2010, text-figs 27–29), the same zone extends until the lower part, or base, of the Aseri Stage (Fig. 2). Hence, the timing of the brecciation event suggested by Suuroja et al. (2003) can be regarded as a rather rough estimate. The latter authors furthermore considered the first post-event deposits to represent the upper Kunda Stage (Aluoja Substage; Suuroja et al. 2003, fig. 4), whereas Alwmark et al. (2010) regarded the limestones covering the breccia to be of Aseri through Uhaku age (Fig. 2). Accordingly, following the timescales of Webby et al. (2004) and Nölvak et al. (2006), Alwmark et al. (2010, fig. 2) suggested that the breccia event took place during the latest Kunda time.

In order to attain a more precise age determination of the breccia, sampling for biostratigraphical dating of the strata immediately overlying the breccia is required, as is the utilization of a fossil group that allows for relatively high biostratigraphical resolution. Conodonts are generally abundant and well preserved in the

GLOBAL		REGIONAL		CONODONTS		FORMATIONS			
		Stage	Substage	Zones/subzones	NW Estonia	North Estonia	Central Estonia		
Middle Ordovician	Dairiivilian	C <sub>1c</sub>	Uhaku		<i>Pygodus anserinus</i>	<i>Sagittodontina kielcerensis</i>	Kõrgekallas Formation		
					<i>E. lindstroemi</i>	<i>E. protoramosus</i>			
		C <sub>1b</sub>	Lasnamägi		<i>Pygodus serra</i>	<i>E. reclinator</i>	Väo Formation		Stirnas Fm
					<i>Eoplacognathus foliaceus</i>				
		C <sub>1a</sub>	Aseri		<i>Eoplacognathus suecicus</i>		Kandle Formation	Rokishkis Fm	
		B <sub>III</sub>	Kunda	Aluoja B <sub>IIIγ</sub>	<i>Lenodus (E?) pseudoplanus</i>	<i>M. ozarkodella</i>	Pakri Fm	Loobu Formation	
				Valaste B <sub>IIIβ</sub>	<i>M. hegetiana</i>	<i>Y. crassus</i>			
				Hunderum B <sub>IIIα</sub>	<i>Lenodus variabilis</i>				
B <sub>II</sub>	Volkhov	Langevoja B <sub>IIγ</sub>	<i>Baltoniodus nordlandicus</i>			Upper Sillaoru Fm			
		Vääna B <sub>IIβ</sub>	<i>Paroistodus originalis</i>				Lower Sillaoru Fm		
		Saka B <sub>IIα</sub>	<i>Baltoniodus navis</i>	<i>Baltoniodus triangularis</i>					
L. Ord.	Dapingian	B <sub>1b</sub>	Billingen	<i>Oepikodus evae</i>					
		B <sub>1a</sub>	Hunneberg	<i>Prioniodus elegans</i>			Leetse Formation		

**Fig. 2.** Chrono-, bio- and lithostratigraphical chart of the upper part of the Lower Ordovician throughout the Middle Ordovician, correlating the global series and stages with the corresponding Baltoscandian units (left), conodont zones (middle) and the major formations of northwestern, northern and central Estonia (right). Stippled intervals denote missing strata. Dotted lines separating conodont zones indicate that boundaries are not fixed. *Yangtzeplacognathus crassus* (where present) is known to co-occur with both *Lenodus variabilis* and *L. (E?) pseudoplanus*. After Bergström (1971), Löfgren (1995, 2000), Zhang (1998a), Viira et al. (2001), Nölvak et al. (2006), Tinn et al. (2006), Mellgren & Eriksson (2010). Abbreviated genera: *E.* = *Eoplacognathus*, *M.* = *Microzarkodina*, *Y.* = *Yangtzeplacognathus*.

Ordovician limestones of Estonia (Viira & Männik 1997), and the extensive work on the Middle Ordovician conodont biozonation in Baltoscandia during the last decades enables correlations with a resolution far exceeding that of chitinozoans (see Nölvak et al. 2006, fig. 1).

Based on this background, the aim of this study is to examine the conodont fauna from the limestones directly superposing the brecciate layers on Osmussaar Island, and to provide a conodont dating of this event structure. Using the results, the timing of the brecciation event, and its relation to the extraterrestrial material-yielding interval at Kinnekulle, are discussed.

### GEOLOGICAL SETTING

The Ordovician limestone strata of the Baltoscandian region were deposited in an epicontinental sea covering extensive parts of the palaeocontinent Baltica. Following Baltica's drift from temperate latitudes on the southern hemisphere towards the equator, the Lower and Middle

Ordovician condensed, 'cool-water' type limestones were replaced by the Upper Ordovician 'warm-water' carbonates (Nestor & Einasto 1997; Nielsen 2004). Based on their sedimentological and palaeontological signature, Jaanusson (1976) subdivided these limestone deposits into separate composite facies belts (also commonly referred to as Confacies Belt; CB). The North Estonian CB (Jaanusson 1995) is considered to represent the shallowest part of the basin, whereas the palaeodepth increases to the west-southwest in the Central Baltoscandian and the Scania CB, respectively (Fig. 1A).

The exposures of the North Estonian CB limestones are found along the Baltic Klint – an extensive NE–SW escarpment system of Cambrian–Ordovician sedimentary rocks that can be followed from Lake Ladoga in Russia to the southern end of Öland, Sweden (Miidel 1997). As an elevated part of an otherwise submerged peninsula, Osmussaar Island (Fig. 1B, C) forms the westernmost point of exposure of the North Estonian Klint; the part of the Baltic Klint extending between this point and the Narva River.

The limestone exposed on Osmussaar Island ranges in age from approximately the middle Dapingian (lower Middle Ordovician) through the Darriwilian (Suuroja et al. 1999). The transition from clastic to carbonate sedimentation is at the top of the Leetse Formation. Older Ordovician strata (i.e. the Kallavere, Türisalu and Varangu formations, and most of the Leetse Formation) are terrigenous, mainly consisting of glauconitic and/or quartzose sandstones and shales (Suuroja et al. 1999). Thus, lime deposition was prevailing during the time of formation of the Osmussaar Breccia, although this part of the basin still had a varying influx of sand. The setting was fairly shallow-marine, corresponding to approximately inner ramp (Nestor & Einasto 1997). Sedimentation was quite irregular, possibly due to fluctuating sea levels (Viira et al. 2001), as suggested by the occurrence of frequent discontinuity surfaces and hardgrounds.

As described by Suuroja et al. (1999, 2003), the Osmussaar Breccia consists of fragmented and displaced glauconitic limestones of the Toila Formation (Billingen and Volkhov regional stages; Fig. 2). These, in turn, are enclosed in and penetrated by a matrix of cemented lime-rich sandstone, commonly described as light-grey (or more rarely dark-grey/brown) veins. Also, to a lesser extent, these penetrating sandstone veins enclose parts of the kerogenous sandy limestones (or lime sandstones) of the Suurupi Member of the Pakri Formation. For a more comprehensive description of sediment texture and composition of the sandstone veins, see Suuroja et al. (2003), Alwmark et al. (2010) and Tinn et al. (2010).

Accurately interpreting the alteration from strata that are affected by sandstone veins to those of undisturbed, post-event limestone is naturally critical for dating the breccia. In the interpretation of Suuroja et al. (2003, fig. 4), the Suurupi Member is unconformably overlain by a unit that is referred to as post-event limestones of Kunda (Aluoja Substage) affinity. From Suuroja et al. (1999) it is, however, evident that the demarcation between pre- and post-event strata is somewhat more ambiguous. The same authors recognized a highly complex interval characterized by irregular sedimentation, in which pre-event strata are variously affected by the intruding sandstone veins. Accordingly, the Osmussaar Member of the Pakri Formation, which overlies the Suurupi Member, is vital for identifying the post-event strata. Suuroja et al. (1999) subdivided the  $\leq 45$  cm thick Osmussaar Member into lower and upper parts, both intermittently distributed horizontally, and both with a thickness from 0 to approximately 25 cm. Furthermore, both parts contain less than 5% quartz sand, and individually consist of several thin, undulating layers of greenish-grey skeletal limestone that are separated by pyritic discontinuity surfaces. The most important difference between the upper and lower parts of the

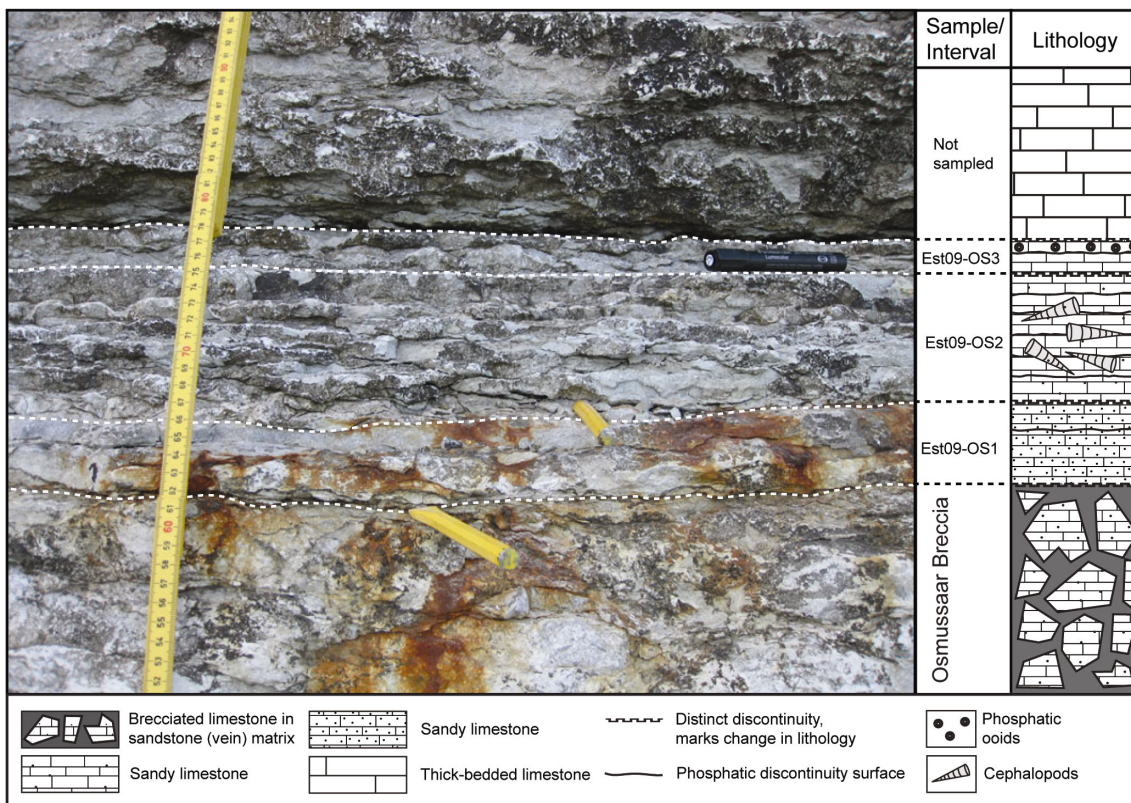
Osmussaar Member is that only the limestone beds of the lower part supposedly contain small fragments of older strata and show signs of distortion (arching) connected to sandstone veins. This makes the lower part of the Osmussaar Member the youngest layers affected by the brecciation event, and the upper part of the member the oldest strata unaffected by the same event.

## MATERIALS AND METHODS

Three intervals, together comprising a ca 16 cm undisturbed limestone succession directly above the breccia, were sampled in the northern part of Osmussaar Island (Fig. 1C). The sample intervals were labelled Est09:OS1 (0–4 cm), Est09:OS2 (4–13 cm) and Est09:OS3 (13–16 cm), respectively (Fig. 3). As no distortion from sandstone veins could be traced horizontally, the intervals of the two lower samples (Est09:OS1 and Est09:OS2) were considered to represent what Suuroja et al. (1999) referred to as the erratically developed upper part of the Osmussaar Member. In turn, based on the rare presence of iron ooids, the upper sample interval (Est09:OS3) was regarded to represent the Kandle Formation (= Aseri Formation by Suuroja et al. 1999; see also Orviku 1940).

The lowermost 4 cm above the breccia comprise sample interval Est09:OS1, which extends over two thin, slightly undulating beds that almost conflate with the breccia due to exterior similarities (Fig. 3). These limestone beds are furthermore relatively rich in sand, and are separated from the breccia by a marked discontinuity surface. The subsequent sample interval (Est09:OS2) is composed of several thin, undulating beds, separated by phosphatic discontinuity surfaces. The limestone beds of this interval are somewhat less sandy and characterized by the occurrence of decimetre-long cephalopods. Finally, sample Est09:OS3 represents the uppermost 3 cm before the marked discontinuity surface (Fig. 3). This interval consists of two thin, undulating limestone beds, containing light grey-coloured ooids. Contrary to underlying strata, this interval is virtually devoid of sand.

The samples were dissolved using dilute, buffered acetic acid, and the residues were separated in heavy liquids following the technique described by Jeppsson et al. (1999; see also Jeppsson 2005). The acid-resistant residues were washed through a 0.063-mm sieve, after which all conodont elements  $\geq 0.063$  mm were electrostatically hand-picked and sorted into microfossil slides under a binocular microscope. A few heavily fragmented elements (i.e. absence of the base or a greater part of the cusp) were excluded from the element count, as these could not be taxonomically classified with certainty. Apart from these, the state of preservation was very



**Fig. 3.** Photograph and log over the sampled Osmussaar section. Dotted lines (white in the photograph) mark sample interval boundaries. For details, see the legend and the ‘Materials and Methods’ and ‘Results’ chapters.

good. The CAI value for all elements is 1 (thermally unaltered), following the scale of Epstein et al. (1977).

All figured elements (repository number LO for Lund Original) are stored in the type collection at the Department of Geology, Lund University.

### COMMENTS ON CONODONT BIOSTRATIGRAPHY AND ZONAL INDICES

It must be noted that since the early works on fossil meteorites from Kinnekulle, in which Schmitz et al. (1996, 1997) used the *Amorphognathus variabilis*–*Microzarkodina flabellum* Zone for correlation, the Baltoscandian conodont zonation has been further refined. Consequently, the conodont biostratigraphy referred to by Suuroja et al. (2003; in their remarks on hypothetical parallels with the Osmussaar Breccia) is no longer applied. The *A. variabilis* Zone *sensu* Lindström (1971) and Bergström (1971) comprised basically the entire Kunda Stage, whereas the *Eoplacognathus?* *variabilis*–*M. flabellum* Zone of Löfgren (1978) instead covered roughly the lower half of this regional stage. Continuous

minor revisions were subsequently proposed by Löfgren (1993, 1994, 1995), Stouge (1989), Stouge & Bagnoli (1990) and Bagnoli & Stouge (1997), but for a little more than a decade, the biostratigraphical scheme established by Zhang (1998a) has been considered as the standard Baltoscandian conodont zonation for this interval (e.g. Löfgren 2000; Löfgren & Zhang 2003). The exception is Norwegian strata where conodont faunal composition is influenced by the near platform margin depositional environment, thus not being directly comparable to the faunas of inner- and mid-platform affinity (see Rasmussen 2001). In summary, the old *E.?* *variabilis*–*M. flabellum* Zone of Löfgren (1978) is today further subdivided into the *Lenodus variabilis*, the *Yangtzeplacognathus crassus* and the lower *Lenodus* (or possibly *Eoplacognathus*) *pseudoplanus* zones (Fig. 2). In comparison with the original *Amorphognathus variabilis* Zone (see above), also the upper *L. (E.?) pseudoplanus* Zone should be included, as well as the lowermost *Eoplacognathus suecicus* Zone.

The name *Lenodus (Eoplacognathus?) pseudoplanus* is herein used to indicate an uncertainty in generic affinity, as sometimes the zonal indicating species

*Eoplacognathus pseudoplanus* is ascribed to the genus *Lenodus* (e.g. by Stouge & Nielsen 2003 and Schmitz et al. 2008). See further discussion under ‘Results’ below.

In the transition from the *L. (E.?) pseudoplanus* Zone to the *E. suecicus* Zone, which roughly corresponds to the Kunda–Aseri regional stages boundary (Fig. 2), some inconsistency is unfortunately evident in the recognition and application of these two zonal indices. According to Zhang (1999), the direct ancestor–descendant relationship between these two taxa makes the presence of a secondary postero-lateral process in the Pa platform elements of *E. suecicus* a key in discriminating it from late forms of *L. (E.?) pseudoplanus*. This was also discussed by Löfgren & Zhang (2003), where amendments on the *E. suecicus* Zone of Löfgren (1978) were made based on this morphological criterion. However, the use of this character seems to vary between workers, which might well be because it was not mentioned in the original description of Bergström (1971). For example, the *E. suecicus* element illustrated by Viira et al. (2001, fig. 8m) from the Mäekalda section lacks this character. Instead, that same element has a secondary, denticulate process bifurcating out of the posterior process.

Following Zhang (1999), and from inspection of parts of the material referred to therein (i.e. the Lunne section, the specimens of which are stored at the Department of Geology, Lund), it is evident that a secondary posterior process is present also in elements of *E. suecicus*. Smaller (subadult) Pa elements of the same taxon instead have a marked expansion of the platform ledge in the equivalent position (Zhang 1999, fig. 3). Such a secondary posterior process is also present in elements considered as late *L. (E.?) pseudoplanus* (transitional to *E. suecicus*) by Zhang (see, e.g., Löfgren 1978, pl. 15, figs 16–18). Thus, although not clearly expressed, it seems as if the diagnostic criterion for late *L. (E.?) pseudoplanus* is the presence of a secondary posterior process in the Pa elements. Pa elements of *E. suecicus sensu* Zhang (1999) should, in addition to the secondary posterior process, also have a secondary postero-lateral process.

All *Eoplacognathus pseudoplanus* elements illustrated by Viira et al. (2001) lack both secondary processes (see also Löfgren 2004), and thus, it may be speculated that those authors used different criteria for separating their *E. pseudoplanus* and *E. suecicus*. In short, it seems as it comes down to whether or not to ‘allow’ a secondary posterior process in *L. (E.?) pseudoplanus*, or to allow the lack of a secondary postero-lateral process in *E. suecicus*. Because this is not a taxonomic paper, with a complete review of papers and relevant material, no definite solution is offered. However, the current authors acknowledge the fact that even though *E. pseudoplanus*

was recognized by Viira (1974), the Pa element was brought to the apparatus by Dzik (1976). In turn, the latter author illustrated Pa elements with, as well as without, a secondary posterior process (see Dzik 1976, figs 7, 30), among which the former were assigned as late forms. Hence, the occurrence of an established secondary posterior process (or, in juvenile/subadult Pa elements, an evident expansion of the platform ledge that signals its forthcoming establishment) is in the current study taken as indicative of a late form of *L. (E.?) pseudoplanus*. If this feature is combined also with an established secondary postero-lateral process, the element is assigned to *E. suecicus*.

## RESULTS

The samples are discussed in stratigraphically ascending order (Fig. 3). Ranges of individual conodont taxa are shown in Fig. 4.

The North Estonian mainland Mäekalda section covers roughly contemporaneous strata, and has been investigated fairly recently in terms of conodont biostratigraphy (Mägi 1990; Viira et al. 2001). Due to its proximity to Osmussaar Island, this section was regarded especially suitable for biostratigraphical correlation and comparison of conodont faunal composition.

The relative frequencies (%) calculated for different taxa are rounded off to the closest integer. In the frequency calculations for species of the genus *Eoplacognathus*, M and S elements are included. No such elements have previously been described and discussed as part of the apparatus of *E. suecicus*, the type species of the genus. However, M and S elements are recognized in apparatuses of the genus *Lenodus* (see Stouge & Bagnoli 1990), whose platform elements most certainly are the predecessors of the *Eoplacognathus*-type platforms. Löfgren & Zhang (2003) introduced equivalent M and S elements to the latter genera through transferring *Lenodus pseudoplanus sensu* Stouge & Bagnoli (1990) to *Eoplacognathus* (hence the use of *L. (E.?) pseudoplanus* herein). Moreover, in the currently investigated interval such elements are found also associated with stratigraphically later *Eoplacognathus* platforms (see below), which motivates a future reassessment of the two genera *Lenodus* and *Eoplacognathus*.

### Sample interval 1: Est09:OS1

Among the three samples, Est09:OS1 proved to be the one with the lowest conodont element abundance; the 1205.3 g sample yielded 281 elements, i.e. 233 elements per kg of rock. The fauna is dominated by *Baltoniodus medius* (47%; Fig. 5M, S), *Drepanoistodus* sp. (17%),

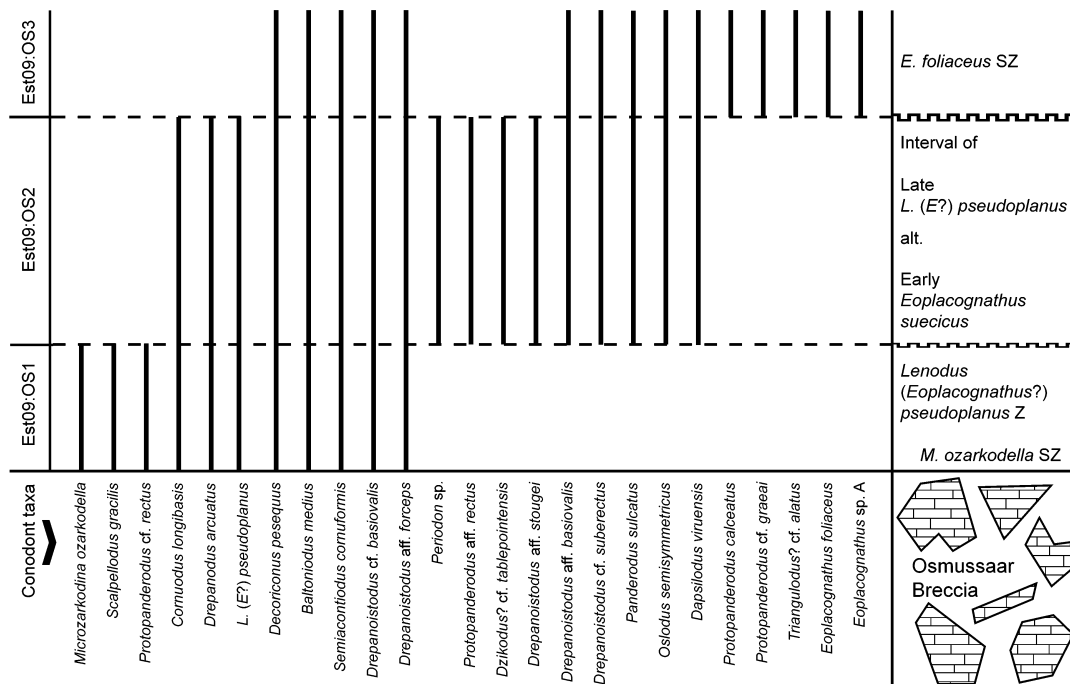


Fig. 4. Stratigraphical ranges of the conodont taxa recorded in the three intervals sampled; see Fig. 3.

*Semiacontiodus cornuiformis* (14%; Fig. 5Q, R) and *Scalpellodus gracilis* (10%; Fig. 5I, J), all frequent constituents in lower Darriwilian conodont faunas in Central and North Estonian CB areas (e.g. Löfgren 2003, 2004). Species of *Drepanoistodus* are mainly recognized on the basis of their M (geniculate) elements, whereas the associated S and P elements are more difficult to allocate to the separate taxa (Stouge & Bagnoli 1990). Herein, the morphology of the geniculate element type forms the basis for open nomenclature taxonomy. The elements at hand are closely similar to those of *D. cf. basiovalis* and *D. aff. forceps sensu* Mellgren & Eriksson (2010) and are therefore assigned the same taxonomical epithets (Fig. 5E, F). The former type, characterized by a low cusp to base ratio, is likely what Viira et al. (2001) referred to as *D. cf. D. venustus* from the Mäekalda section. Similar elements have also been brought to *Venoistodus balticus* by Löfgren (2006); however, see Mellgren & Eriksson (2010) for a brief discussion on the ambiguousness concerning this taxon.

Aside from the indefinite forms of *Drepanoistodus*, the taxa listed above are known to be fairly long-ranging, i.e. they may occur in the lower as well as in the upper Kunda Stage and can also range into the Aseri Stage. The same is true for most of the remaining faunal components, e.g. *Decoriconus pesequus* (Fig. 5Y), *Drepanodus arcuatus* (Fig. 5A), *Cornuodus longibasis*

(Fig. 5K) and *Protopanderodus cf. rectus* (Fig. 5G), each one comprising  $\leq 1\%$  of the fauna. Among zonal indices (i.e. *Lenodus*, *Eoplacognathus*), the only complete platform element retrieved is a Pb element (Fig. 6D). By comparison, the Pa element pair shows a more apparent morphological evolution through the stratigraphic column (see Löfgren & Zhang 2003), and thus, such elements are also needed for a more precise age determination (i.e. to determine early-mid-late Kunda affinity). However, based on the presence of *Microzarkodina ozarkodella* (5%; Fig. 5B, C), the Pb platform element has been provisionally assigned to *Lenodus (E.?) cf. pseudoplanus* (Fig. 6D).

The occurrence of *M. ozarkodella* is known to indicate the upper subzone of the *E. pseudoplanus* Zone *sensu* Zhang (1998a) and Löfgren (2004), i.e. suggesting approximately the Aluoja Regional Substage (Fig. 2). However, depending on the criteria used for classification, the stratigraphical distribution of *M. ozarkodella* varies between publications, since elements characteristic of this species appear already in the middle Kunda Stage. Following the original description of Lindström (1971), *M. ozarkodella* is recognized by the presence of two or more anterior denticles on the P element. However, this character has lately been assigned also to (and in some instances again withdrawn from) the stratigraphically older taxa

*M. bella*, *M. hagetiana* and *M. russica* (see Löfgren 2000, 2003, 2004; Löfgren & Tolmacheva 2008; and Mellgren & Eriksson 2010, section 3.2.2). Regardless of the somewhat confused taxonomy, it seems as if P elements equipped with two anterior denticles (e.g. *M. bella* in Löfgren 2000, *M. cf. ozarkodella* in Mellgren & Eriksson 2010) are more common in the *Lenodus variabilis*–*Yangtzeplacognathus crassus* interval (approx. Valaste Substage of the Kunda Stage; Fig. 2), whereas three

anterior denticles become more prevalent higher up in the stratigraphy. The presence of three anterior denticles in the P elements retrieved from the interval Est09:OS1 thus makes them more indicative of the *L. (E.?) pseudo-planus* Zone than of the two preceding conodont zones. This zonal determination is, however, also supported by changes in faunal composition between this sample level and the next one (Est09:OS2). Accordingly, also the more long-ranging taxa listed initially become valuable, as





they provide a consistent correlation with the Mäekalda section. In that section *S. gracilis* abruptly terminates at the discontinuity surface separating the Ubari and Valgejögi members of the Loobu Formation. This level also marks the base of the *E. suecicus* Zone *sensu* Viira et al. (2001, figs 2, 7). Throughout the preceding *E. pseudoplanus* Zone of the same authors, *S. gracilis* is listed as abundant. Similarly, in the sampled Osmussaar section the frequency of *S. gracilis* changes from fairly abundant to absent from Est09:OS1 to Est09:OS2 (Fig. 4; see also below). Thus, assuming that the discontinuity surface between these two sample levels corresponds to the one in Mäekalda, *S. gracilis* can be considered indicative of the *E. pseudoplanus* Zone *sensu* Viira et al. (2001).

### Sample interval 2: Est09:OS2

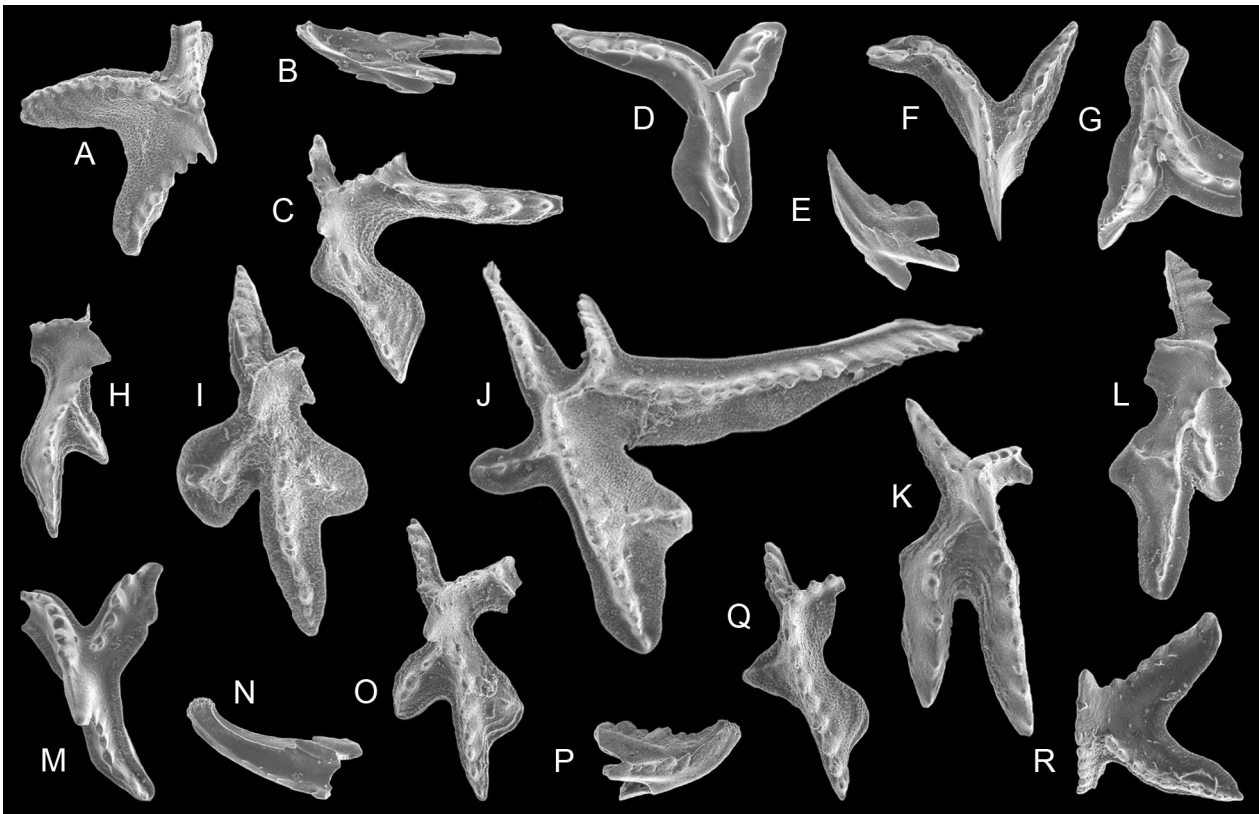
By contrast to the previous sample interval, the conodont element abundance in Est09:OS2 must be considered fairly high; the 2047.2 g sample yielded 2851 elements, i.e. 1393 elements per kg of rock. Also, obvious changes in faunal composition between this interval and the preceding one can be noted. While elements of *B. medius* (44%), *S. cornuformis* (14%) and *Drepanoistodus* sp. (10%) remain important faunal constituents, *Panderodus sulcatus* (Fig. 5AF, AG) has emerged as the second most frequent taxon, comprising 27% of the fauna. Such a situation, combined with the disappearance of both

*S. gracilis* and *M. ozarkodella*, suggests that a rather significant gap in sedimentation is represented by the discontinuity surface between this and the Est09:OS1 interval.

In the case of the genus *Drepanoistodus*, the two provisional species recognized from the previous sample (*D. cf. basiovalis* and *D. aff. forceps*) are here joined by other morphotypes sharing the character of having M elements with a low cusp to base ratio. These elements are, furthermore, virtually identical to some of the elements collectively assigned to *D. aff. basiovalis* by Mellgren & Eriksson (2010, fig. 7), which – like herein – included ‘*D. stougei*’-like forms (see Rasmussen 2001, pl. 6, figs 12, 13). In the range-chart herein (Fig. 4), however, these morphotypes are separated into *D. aff. basiovalis* (Fig. 5U) and *D. aff. stougei* (Fig. 5V). In addition, the Est09:OS2 interval also includes a few *Drepanoistodus* M elements characterized by high cusp to base ratios and rounded, alternatively somewhat more pointed, anterio-basal outlines. These are referred to as *D. cf. suberectus* (Fig. 5AH, AI).

The small *Protopanderodus* collection (ca 2% of the total) is somewhat peculiar, as the elements are reminiscent of those of *P. rectus*, with the exception of comparably higher bases in some of the elements of the S series (Fig. 5L, P). These elements may represent an ecophenotype, but they may as well represent a transitional form to one of the *Protopanderodus* species known to succeed *P. rectus*, as this taxon above all is

**Fig. 5.** **A**, *Drepanodus arcuatus* Pander, 1856, S element, LO11354t, ×51, sample Est09:OS2. **B–D**, *Microzarkodina ozarkodella* Lindström, 1971; B, P element, LO11355t, ×109, C, P element, LO11356t, ×61, D, M element, LO11357t, ×70, all from sample Est09:OS1. **E**, *Drepanoistodus cf. basiovalis* (Sergeeva, 1963), M element, LO11358t, ×89, sample Est09:OS2. **F**, *Drepanoistodus aff. forceps* (Lindström, 1955), M element, LO11359t, ×59, sample Est09:OS2. **G**, *Protopanderodus cf. rectus* (Lindström, 1955), S element, LO11360t, ×75, sample Est09:OS1. **H**, *Periodon* sp., S element, LO11361t, ×71, sample Est09:OS2. **I, J**, *Scalpellodus gracilis* (Sergeeva, 1974); I, Scandodontiform element, LO11362t, ×83, J, Drepanodontiform element, LO11363t, ×84, both from sample Est09:OS1. **K**, *Cornuodus longibasis* (Lindström, 1955), S element, LO11364t, ×91, sample Est09:OS1. **L**, *Protopanderodus aff. rectus* (Lindström, 1955), S element, LO11365t, ×84, sample Est09:OS2. **M**, *Baltoniodus medius* Dzik, 1976, S element, LO11366t, ×83, sample Est09:OS1. **N, O**, *Dapsilodus viruensis* (Fähræus, 1966); N, Acontiodontiform element, LO11367t, ×78, O, Acontiodontiform element, LO11368t, ×107, both from sample Est09:OS2. **P**, *Protopanderodus aff. rectus* (Lindström, 1955), S element, LO11369t, ×79, sample Est09:OS2. Element broken during preparation. **Q, R**, *Semiacontiodus cornuformis* (Sergeeva, 1963); Q, S element, LO11370t, ×80, sample Est09:OS2, R, S element, LO11371t, ×73, sample Est09:OS1. **S**, *Baltoniodus medius* Dzik, 1976, S element, LO11372t, ×70, sample Est09:OS2. **T**, *Protopanderodus cf. graeai* (Hamar, 1964), S element, LO11373t, ×82, sample Est09:OS3. **U**, *Drepanoistodus aff. basiovalis* (Sergeeva, 1963), M element, LO11374t, ×62, sample Est09:OS2. **V**, *Drepanoistodus aff. stougei* (Rasmussen, 1991), M element, LO11375t, ×61, sample Est09:OS2. **W, X**, *Protopanderodus calceatus* Bagnoli & Stouge, 1997; W, P element, LO11376t, ×53, X, S element, LO1137t, ×64, both from sample Est09:OS3. **Y**, *Decoriconus pesequus* Löfgren 1998, S element, LO11378t, ×78, sample Est09:OS2. **Z**, *Dzikodus? cf. tablepointensis* (Stouge, 1984), M element, LO11379t, ×72, sample Est09:OS2. **AA**, *Oslodus semisymmetricus* (Hamar, 1966), S element, LO11380t, ×54, sample Est09:OS3. **AB, AC**, *Triangulodus? cf. alatus* (Dzik, 1976); AB, S(?) element, LO11381t, ×79, AC, P(?) element, LO11382t, ×51, both from sample Est09:OS3. **AD**, *Oslodus semisymmetricus* (Hamar, 1966), M element, LO11383t, ×58, sample Est09:OS3. **AE**, *Protopanderodus cf. graeai* (Hamar, 1964), M element, LO11384t, ×67, sample Est09:OS3. **AF, AG**, *Panderodus sulcatus* (Fähræus, 1966); AF, falciform element, LO11385t, ×72, sample Est09:OS2, AG, graciliform element, LO11386t, ×75, sample Est09:OS3. **AH, AI**, *Drepanoistodus cf. suberectus* (Branson & Mehl, 1933); AH, S element, LO11387t, ×65, AI, M element, LO11388t, ×60, both from sample Est09:OS3. **AJ**, *Protopanderodus cf. graeai* (Hamar, 1964), S element, LO11389t, ×69, sample Est09:OS3.



**Fig. 6.** **A**, *Eoplacognathus foliaceus* (Fähræus, 1966), Pb element, LO11390t,  $\times 74$ , sample Est09:OS3. **B**, *Eoplacognathus* S element, LO11391t,  $\times 70$ , sample Est09:OS3. **C**, *Eoplacognathus foliaceus* (Fähræus, 1966), Pa element, LO11392t,  $\times 92$ , sample Est09:OS3. **D**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974), Pb element, LO11393t,  $\times 58$ , sample Est09:OS1. Note the non-belonging element debris near the cusp. **E**, *Eoplacognathus* S element, LO11394t,  $\times 67$ , sample Est09:OS3. **F**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974), Pb element, LO11395t,  $\times 74$ , sample Est09:OS2. **G**, *Eoplacognathus* Pb element, LO11396t,  $\times 48$ , sample Est09:OS3. **H**, **I**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974); H, Pa element, LO11397t,  $\times 74$ , I, Pa element, LO11398t,  $\times 77$ , both from sample Est09:OS2. **J**, *Eoplacognathus* sp. A (only one Pa element was found), LO11399t,  $\times 64$ , sample Est09:OS3. **K–M**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974); K, Pa element, LO11400t,  $\times 76$ , L, Pa element, LO11401t,  $\times 62$ , M, Pb element, LO11402t,  $\times 71$ , all from sample Est09:OS2. **N**, *Eoplacognathus* S element, LO11403t,  $\times 88$ , sample Est09:OS2. **O**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974), Pa element, LO11404t,  $\times 80$ , sample Est09:OS2. Note the expanded platform ledge, and compare to the larger element (I) with a fully developed secondary posterior process; see further the ‘Comments on conodont biostratigraphy and zonal indices’ chapter. **P**, *Eoplacognathus* S element, LO11405t,  $\times 70$ , sample Est09:OS3. **Q**, *Eoplacognathus foliaceus* (Fähræus, 1966), Pa element, LO11406t,  $\times 87$ , sample Est09:OS3. **R**, *Lenodus* (*Eoplacognathus*?) *pseudoplanus* (Viira, 1974), Pb element, LO11407t,  $\times 69$ , sample Est09:OS2.

known to occur in somewhat older strata (Mellgren & Eriksson 2006, fig. 10). Due to this uncertainty and the limited material at hand, they are referred to as *Protopanderodus* aff. *rectus*.

Other subordinate faunal constituents ( $\leq 1\%$ ) include *Decoriconus pesequus*, *Drepanodus arcuatus* and *Cornuodus longibasis*, just as in the preceding Est09:OS1 interval, but here they are accompanied by *Dapsilodus viruensis* (Fig. 5N, O), *Periodon* sp. (Fig. 5H), *Osلودus semisymmetricus* (Fig. 5AA, AD) and a few M elements of the type associated with the platform taxon *Dzikodus tablepointensis* sensu Zhang (1998b). Viira et al. (2001) listed low occurrences of *Polonodus tablepointensis* in

the *E. pseudoplanus* Zone at Mäekalda. Although no illustrations were provided, it is possible that the latter authors referred to equivalent elements. See Zhang (1998b) and references therein for a background to the separation of the two genera *Polonodus* Dzik, 1976, and *Dzikodus* Zhang, 1998b. As the retrieved M elements were not associated with any S or P elements, they are herein referred to as *Dzikodus*? cf. *tablepointensis* (Fig. 5Z).

The zonal index platform taxa merely constitute 1% of the fauna; nevertheless, the excellent preservation of the Pa and Pb elements facilitates unambiguous identification. Following ‘Comments on conodont bio-

stratigraphy and zonal indices' above, due to the absence of a secondary postero-lateral process in the Pa elements, they are assigned to late *L. (E.?) pseudoplanus* (Fig. 6H, I, K, L, O). At the same time, as imperative to the correlation with the Mäekalda section, these elements can be regarded as indicative of the *E. suecicus* Zone *sensu* Viira et al. (2001), which is present in the Valgejögi Member of the Loobu Formation at Mäekalda. As mentioned above, the absence of *S. gracilis* supports this correlation, as does the presence of *P. sulcatus* (see Viira et al. 2001, fig. 7).

### Sample interval 3: Est09:OS3

The element abundance in the third sample interval is roughly comparable to the preceding one; the 1607.1 g sample Est09:OS3 yielded 1784 elements, that is, 1110 elements per kg of rock. The faunal composition of this interval compared to that of Est09:OS2 suggests that the discontinuity surface separating the two intervals represents an extensive break and thus a significant time-gap.

As in Est09:OS2, *B. medius* (41%), *P. sulcatus* (18%), *S. cornuformis* (13%) and *Drepanoistodus* sp. (9%) are the most common faunal components. However, there are clear differences in the *Drepanoistodus* fauna. In the two preceding samples, this genus is dominated by forms carrying M elements with a low cusp to base ratio, whereas the sample interval Est09:OS3 yields a relatively higher portion of *D. cf. suberectus*. Furthermore, the long-based M elements and associated non-geniculate elements present in this interval are markedly smaller. Even so, their shape signifies (with the exception of the absent *D. aff. stougei*) the same morphotypes as recognized in the preceding sample interval.

In the whole conodont fauna of the Est09:OS3 interval, *Protopanderodus* has increased to 9% (from 1–2% in the previous two samples), which is largely due to the appearance of *P. calceatus* (Fig. 5W, X), one of the two multicostate *Protopanderodus* taxa recognized in the Middle Ordovician of Baltoscandia. In this sample, *P. calceatus* constitutes approximately 50% of the representatives of the genus. However, the bicostate part of the *Protopanderodus* fauna is more interesting as it includes elements identical to those assigned to *P. aff. rectus* above, but also Sb and Sc elements that nearly fit the element type morphologies of *P. graeai* (see Mellgren & Eriksson 2006, and references therein). Moreover, while the overall shape and high base of the M elements suggest the latter species, the same elements lack the characteristic costa on the inner side (Mellgren & Eriksson 2006, figs 9V, 12E). Furthermore, the bases of the Sb elements are not as high as those of fully

developed *P. graeai*. Hence, based on their resemblance to elements of *P. graeai* and the morphological connection to *P. aff. rectus* (see above), it is tentatively suggested that the bicostate *Protopanderodus* elements of Est09:OS3 represent a transition from the *P. rectus* to the *P. graeai* morphology. This would concurrently suggest that *P. aff. rectus* represents an earlier phase in this development. Naturally, the assessment of a larger number of elements is needed to verify this, and meanwhile the elements in question are referred to as *P. cf. graeai* (Fig. 5T, AE, AJ). However, from a stratigraphical perspective, if the above scenario is accurate, the apparent morphological change from one sample to the next supports the presence of a hiatus.

The best evidence for a significant stratigraphical hiatus is, however, seen among the zonal indices. The platform elements retrieved are mainly juvenile and subadult *Eoplacognathus foliaceus* (ca 2%; Fig. 6A, C, Q), which implies correlation to the lower part of the Lasnamägi Regional Stage (Fig. 2; cf. Orviku 1940; Hints 1997).

In addition to the numerically dominating taxa listed above, other faunal constituents of sample Est09:OS3 include *Oslodus semisymmetricus* (5%), *Decoriconus pesequus* (1%) and *Triangulodus? cf. alatus* (1%; Fig. 5AB, AC). The tentative terminology used for the last taxon originates from uncertainties in apparatus reconstructions and generic designations of various hyaline coniform elements of the Middle Ordovician, including *Triangulodus*; see e.g. Bauer (1987, p. 30) and Zhen et al. (2006, p. 196) for summary. The few elements at hand morphologically best correspond to *Triangulodus alatus sensu* Dzik (1976), a species that the same author subsequently brought to *Eoneoprioniodus* that, in turn, forms a junior synonym of *Pteracontiodus*. However, today *Triangulodus* is regarded as a genus separate from *Pteracontiodus* (Zhen et al. 2006 and references therein), and the fact that *T. alatus* occasionally appears in conodont distribution charts (e.g. Saadre et al. 2004; Viira et al. 2006) suggests that various workers regard this as a valid taxon, present in the upper Middle Ordovician.

### CORRELATION

Despite the relatively low abundance of conodont elements in general, and zonal index platforms in particular, the lowermost interval sampled (Est09:OS1) can be assigned to a level within the *M. ozarkodella* Subzone of the *L. (E.?) pseudoplanus* Zone (Fig. 7). The registered faunal shift suggests the presence of a hiatus between Est09:OS1 and Est09:OS2, which is also

Stages/Substages		Conodont zones	Samples
↳ Uhaku		<i>E. lindstroemi</i> <i>E. protoramosus</i> <i>E. robustus</i>	
Lasnamägi		<i>Pygodus serra</i> ..... <i>E. reclinator</i> ..... <i>Eoplacognathus foliaceus</i>	★ Est09:OS3
Aseri		<i>Eoplacognathus suecicus</i>	
Kunda	Aluoja	<i>Lenodus</i> (E?) <i>pseudoplanus</i> ..... <i>M. ozarkodella</i>	★ Est09:OS2 ★ Est09:OS1
	Valaste	<i>M. hageliana</i> ..... <i>Y. crassus</i>	Meteorites + EC-chromite
	Hunderum	<i>Lenodus variabilis</i>	
↵ Volkhov	Langevoja	<i>Baltoniodus norlandicus</i>	

**Fig. 7.** Chrono- and biostratigraphical chart (trimmed and modified from Fig. 2), showing the approximate stratigraphical positions of the investigated samples, as well as the interval of particularly high abundances of extraterrestrial material (meteorites and sediment-dispersed L-type chondritic grains; after Schmitz et al. 2008). Abbreviations as in Fig. 2.

supported by the change in lithology and in conodont element abundance. A limited diversity combined with low element abundance (characteristic of the Est09:OS1 interval) is also described for the Kallaste Member of the Pakri Formation at Mäekalda (sample interval Mä95-37 to Mä95-34 of Viira et al. 2001). Even though it might be stretching the correlation between Osmussaar and Mäekalda, the similarities in conodont fauna between the two sections suggest that also their lithological development can be directly comparable (see also below). However, it must be acknowledged that even though two fairly adjacent limestone intervals are considered broadly contemporaneous, the composition of their conodont faunas may differ somewhat due to e.g. depth-preferences of different taxa and other ecological factors that we may only speculate about.

The conodont fauna of the Est09:OS2 sample interval indicates an uppermost Kunda (late Aluoja) age (Fig. 7). This 11 cm interval, characterized by the undulating limestone banks and pyritic discontinuity surfaces that Suuroja et al. (1999) described for the entire upper part of the Osmussaar Member, is herein provisionally suggested to represent instead a condensed development of the upper Loobu Formation. This suggestion is based on the similarities of the conodont fauna between this interval and the *E. suecicus* interval below the phosphatic ooids at Mäekalda (Viira et al. 2001, figs 2, 7), as well as on the occurrence of cephalopods in these strata. Furthermore, it is supported by correlations

based on the trilobite *Pseudoasaphus globifrons* (see Meidla 1997). The cephalopod-rich Loobu Formation is frequently exposed along the North Estonian limestone escarpment, and decreases in thickness from east to west. Following Meidla (1997), the Loobu Formation constitutes the main part of the Kunda Stage in northern and northeastern Estonia, where it is subdivided into the lower (clayey) Nõmmeveski Member and the upper (glaucoponic) Ubari Member. In northeastern Estonia, on the other hand, the Loobu Formation is described as consisting of the lower (glaucoponic) Utria Member and the upper (clayey) Valgejõgi Member. However, it appears that the nature of the formation and its members may shift laterally, as Viira et al. (2001) identified the Valgejõgi Member at Mäekalda, there describing it as a light-grey, fine-grained skeletal limestone.

In the last sample interval discussed (Est09:OS3), the platform conodont fauna, containing elements of the zonal index *E. foliaceus*, indicates a lower Lasnamägi age (Fig. 7). This same interval had previously been considered to represent the Aseri Stage, alternatively the basal Lasnamägi Stage, on the basis of the above-mentioned ooids (Suuroja et al. 1999). By comparison, according to the chitinozoan data in the Pakri Peninsula (40 km eastwards), 0.1 m of the Aseri Stage and 2.5 m of the Lasnamägi Stage are represented (Tammekänd et al. 2010).

**DISCUSSION**

As indicated in the ‘Geological setting’ above, and in view of the inconsistent development of the two parts of the Osmussaar Member (Suuroja et al. 1999), interpretation of the post-event strata can be intricate. Evidently, at some sites along the exposure (Fig. 1C), only one part may be developed, and its vertical distribution can be highly variable. At the particular site from where the samples at hand derive, no thin-bedded limestone showing distortion from the intrusions could be seen. Moreover, such a feature could not be traced laterally. Still, in order to further delimit the stratigraphical interval in which the brecciation took place, identification and sampling of such layers could be of use. Conodonts from the brecciated and sand-penetrated limestones could also be indicative in this respect. In addition, bed-by-bed sampling of unaffected, post-event strata at different spots along the coastline is likely to give a better picture of the complex stratification and ages of all layers represented. In view of the high prevalence of variously extensive hiatuses, it could also be worthwhile to try and sample individual layers in as much detail as possible. For example, the current Est09:OS1 interval,

which obviously is most important for the dating of the breccia, comprises two limestone banks, and it is impossible to evaluate if e.g. the *M. ozarkodella* elements derive from both of them, or just one.

Considering the connection between the Osmussaar Breccia and the strata yielding fossil meteorites and elevated levels of extraterrestrial chromite, this study tentatively favours a correlation. The biostratigraphical range of the extraterrestrial material at Kinnekulle, Killeröd and Fågelsång (see ‘Introduction’ and Fig. 7), combined with the relative age of the limestone directly overlying the Osmussaar Breccia (*M. ozarkodella* Subzone), indicate that the events were roughly coincident. This, in turn, further supports a larger L-chondritic impactor to be responsible for the brecciation. The missing strata, representing the lower (and possibly the middle) *L. (E.?) pseudoplanus* Zone, could well be explained by the strongly intermittent lime-deposition characterizing the North Estonian CB at that time. Indeed, this study has revealed that the many discontinuity surfaces seen in these vertically limited strata may correspond to extensive missing time-spans.

Unfortunately, the mechanisms behind the formation of the Osmussaar Breccia remains speculative until a contemporaneous impact crater is located, or cogent support for another explanation is provided. Alwmark et al. (2010) discussed this problem, and stressed that an impact crater could be deeply buried, hence undetectable by geophysical surveys, or intensely eroded. The same authors also considered it likely that an impact could have triggered an earthquake, which in turn was responsible for the brecciation.

## CONCLUSIONS

1. By means of conodont biozonation this study has shown that the succession of thin-bedded limestone found directly above the Osmussaar Breccia mainly represents the Aluoja Substage of the Kunda Regional Stage. The thin development of ooid-yielding limestone in the top of this succession, however, proved to be of early Lasnamägi age.
2. The studied conodont faunas from Osmussaar Island are closely similar to those reported from contemporaneous strata in the Estonian mainland Mäekalda section. Comparable faunal shifts combined with lithological similarities indicate that the lithological development at these two localities can be directly compared.
3. The conodont dating confirms a minimum age of the brecciation event in parity with that suggested by Suuroja et al. (2003), that is, the lower or middle part

of the Kunda Stage. Confined to the same stratigraphical interval is the increased influx of extraterrestrial material following the L-chondrite parent-body break-up at  $467.3 \pm 1.6$  Myr. This correlation reinforces the hypothesis of the Osmussaar Breccia resulting from a larger L-chondritic impactor.

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## Kesk-Ordoviitsiumi bretšat katva lubjakivikihi dateerimine konodontide abil Osmussaarel Loode-Eestis

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Hiljutised L-kondriitse kromiidi leiud Kunda lademe Osmussaare bretšas toetavad hüpoteesi, et selle liivakivisoontega läbitud kompleksi teke on seotud meteoriiidiplahvatusega. Käesolevas töös uuriti konodontifaunat vahetult bretšastunud tasemel lasuvates lubjakivikihtides Osmussaarel eesmärgiga täpsustada selle sündmuse vanus Baltoskandia konodontitsoonide suhtes. Konodonti *Microzarkodina ozarkodella* esinemine vahetult bretšal lasuvas kihis viitab *Lenodus (Eoplacognathus?) pseudoplanus*'e biotsooni *M. ozarkodella* alamtsoonile. Keskmise ortotseratiididerikas intervall kuulub tõenäoliselt *L. (E.?) pseudoplanus*'e tsooni ülemisse ossa. Ülemine, ooide sisaldav kiht korreleerub *Eoplacognathus foliaceus*'e alamtsooniga, mis vastab Lasnamäe lademe alumisele osale. Tulemused toetavad hüpoteesi, et Osmussaare sündmus ja meteoriiitide ning L-kondriitse kromiidi rikas intervall Rootsis on omavahel seotud, kuna mõlema vanus vastab Kunda lademe alumisele ja/või keskmisele osale. Ajaline nihe meteoriiidisaju ja bretšat katva lubjakivi vanuse vahel on seletatav ulatuslike settekatkestustega Loode-Eestis sellel perioodil.