# Seismic correlation of Palaeozoic rocks across the northern Baltic Proper – Swedish–Estonian project since 1990, a review

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**Abstract.** After a short historical review of the correlation of Palaeozoic rocks between Estonia and Sweden, this paper focuses on the results of marine seismic studies, achieved during the cooperative Swedish–Estonian project since 1990. The most recent seismic correlation scheme of the Cambrian, Ordovician, and Silurian strata and their distribution at the seafloor across the northern Baltic Proper are presented. Thickness changes and trends, as well as the sedimentary structures, reef bodies, and erosional features of different seismic units, are treated in connection with structural and facies changes in the Palaeobaltic Basin. The immediate background of this project is outlined and the locations of the seismic lines shot during the joint expeditions to the Baltic Sea are shown.

**Key words:** Palaeozoic rocks, Estonia, Sweden, seismic correlation.

## INTRODUCTION

During most of the Early Palaeozoic a shallow cratonic basin extended across the present Baltic Sea, and thus the Estonian and Swedish territories became largely covered by a marine Cambro-Silurian sequence. In Estonia Palaeozoic rocks are still widely present, excellently exposed, and furthermore studied by means of numerous drill cores. However, except for solitary remnants, they have been eroded from the greater part of the Swedish mainland, i.e. from the uplifted Baltic Shield (Fig. 1). The Lower Palaeozoic sequence exposed on the Swedish islands of Gotska Sandön, Fårö, Gotland, and Öland belongs structurally to the East European Platform and is connected with coeval rocks in Estonia via the northern Baltic Proper (Fig. 1).

Although only 150 km apart, the closest Cambrian, Ordovician, and Silurian sequences can vary considerably in lithology and stratigraphy across the Baltic due to the regional structural setting and consequent palaeogeographic and facies conditions. The Cambrian sequences around Gotland and in Estonia were largely formed during different time intervals in separate basins. In the Baltic Ordovician–Silurian Basin, however, Estonia was located in its shallowest northeastern corner, while Gotland remained closer to the open and deeper sea area further to the southwest.

For more than 150 years the well-preserved Estonian and Swedish Ordovician–Silurian sequences have been attracting the geologists all over the world. Although their correlation across the Baltic was outlined already in the mid-19th century, this is still an ongoing process, as new data allow specification of stratigraphic details.

In general, the shallow marine Ordovician and Silurian facies varieties that are widely exposed in Estonia are either concealed (Ordovician) by the younger rocks/sediments or missing (Silurian) around Gotland. Thus, direct comparison of the closest Ordovician and Silurian sequences between Estonia and Sweden is impossible without subsurface data from Gotland and/or detailed micropalaeontological studies. However, the scarcity of drill core data from Gotland has largely hampered the correlation of the trans-Baltic Palaeozoic sequences.

In the late 1980s a Swedish–Estonian project was commenced with the aim of subdividing and correlating the submarine Palaeozoic sequences between Estonia and Sweden by means of high-resolution seismic profiling. The most striking and consistent seismic reflectors that were correlated with the (litho)stratigraphic sections onshore enabled distinction of different submarine Palaeozoic units and following their thickness changes and trends across the Baltic. Also, valuable information was achieved about the sedimentary structures, reef bodies, and erosional features, which are connected to certain stratigraphic levels or the boundaries between them. All this has provided us with more detailed knowledge about the facies distribution/changes, palaeogeography, and the sedimentational and erosional processes in the Palaeobaltic Basin, and thus we can

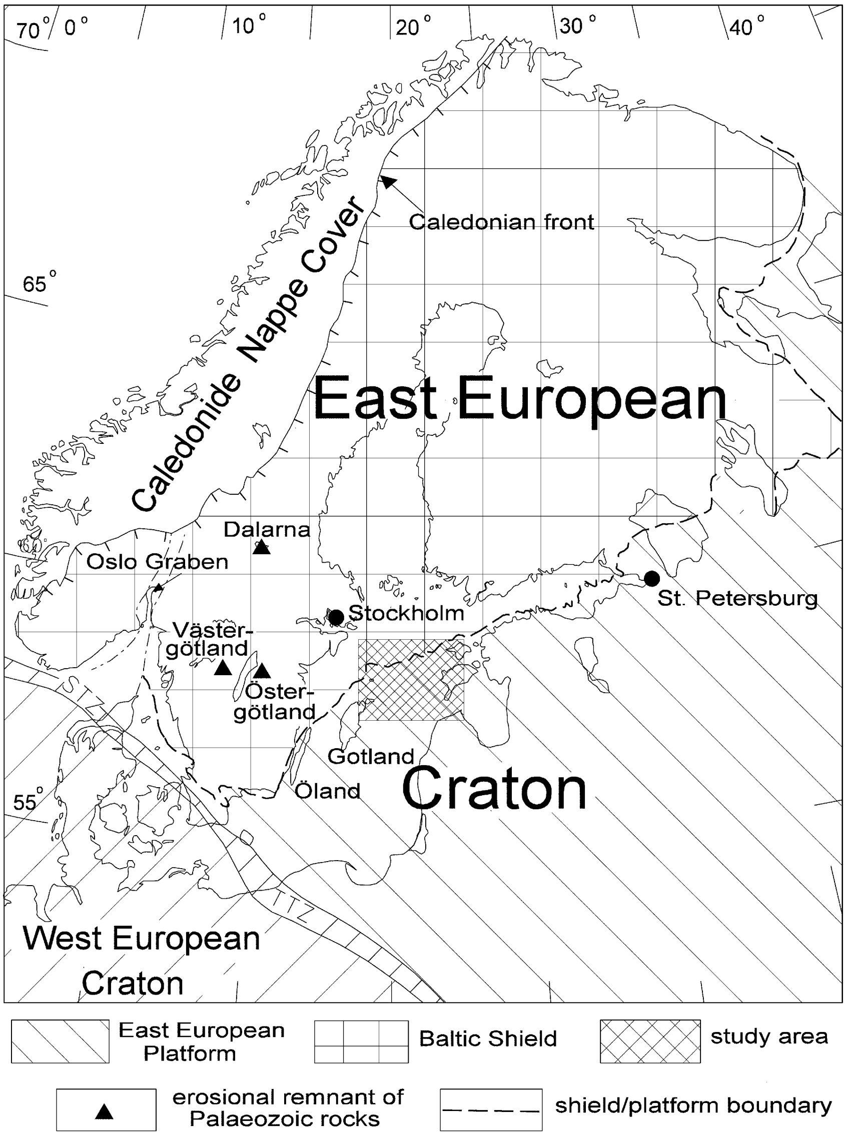


**Fig. 1.** Area of investigation plotted on the regional tectonic map. TTZ, Tornquist–Teisseyre zone; STZ, Sorgenfei–Tornquist zone.

treat the history of this basin in a much broader context than before. In this paper a short review of the joint Swedish–Estonian project is given and its scientific results are summarized.

## HISTORICAL BACKGROUND

### Stratigraphic studies and correlation of Palaeozoic rocks across the Baltic in the second half of the 19th century by Friedrich Schmidt

On the basis of the faunal and lithological similarities with rocks in England and Wales, Murchison (1844) considered the sedimentary bedrocks exposed in Estonia and in Sweden to be of the earliest Palaeozoic age. He suggested that this region represents an early Palaeozoic depression, with the lower Silurian (corresponds roughly to the present Ordovician System) rocks exposed at the margins in Öland and northern Estonia and the upper Silurian (corresponds roughly to the present Silurian System) rocks in the central part on Gotland and Saaremaa. The ideas of Murchison were supported and developed further in a series of publications by Friedrich Schmidt (1858, 1859, 1881, 1891; Figs 2, 3).

Already in the spring of 1857, when still finishing his first manuscript on the subdivision of the 'Silurian

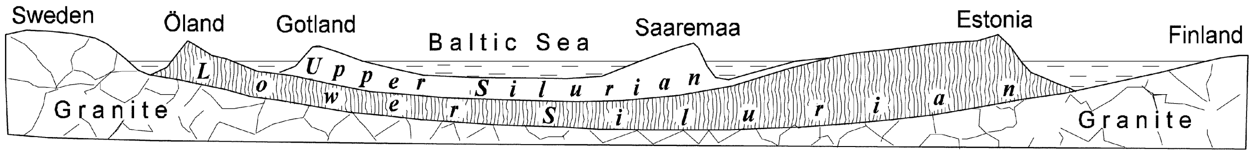


**Fig. 2.** Ideal geological section of the Silurian formation across the supposed Palaeozoic depression from Sweden (Kalmar) to Finland (Vyborg) after Schmidt (1881).

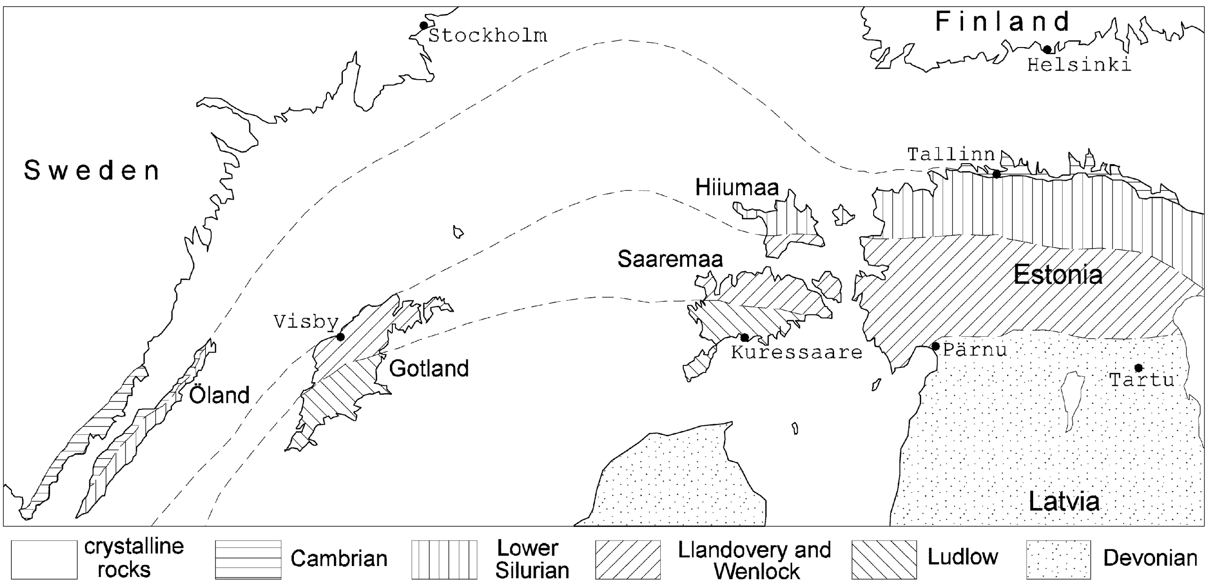


**Fig. 3.** An excerpt of Schmidt's map from 1891 showing the correlation of the exposed Palaeozoic rocks across the Baltic (with modernized/additional place names).

formation' in Estonia, Friedrich Schmidt decided to continue with a study of the equivalent rocks in Sweden (Schmidt 1859). Next summer he spent five weeks on Gotland, made a short visit to Öland, and studied samples from the remnants of early Palaeozoic rocks on the Swedish mainland, namely Östergötland, Västergötland, and Dalarna (Fig. 1). In his report Schmidt (1859) drew the following conclusions: (1) many types of rocks/fossils characteristic of the 'lower Silurian formation' in northern Estonia (*Ungulitensandstein, bituminöse Thonschiefer mit Dictyonema flabelliformis* (Eichw.), *Chloritkalk, Vaginatenkalk, Jewe* (Jõhvi) *Zone*)[1], occur also in the outcrops of the Swedish mainland and/or on Öland; (2) the uppermost zones of the 'lower Silurian formation' in Estonia (*Wesenberg* (Rakvere), *Lyckholm* (Saaremõisa), *Borkholm* (Porkuni)) occur also in Dalarna; (3) the rocks in the *Wisby* (Visby) *Zone* on Gotland are similar to the basal part of the 'upper Silurian formation' in Estonia, i.e. to the *Jörden* (Juuru) *Schicht* and to the rocks exposed in southern Hiiumaa; (4) the middle zone (*die mittlere Zone*) of Gotland resembles the lower Saaremaa Group (*der unteren öeselschen Gruppe*), and the southeastern or Ludlow zone (*der südöstlichen oder Ludlowzone*) on Gotland is similar to the upper Saaremaa Group (*der oberen öselschen Gruppe*). In these conclusions, the correlation of Swedish and Estonian Palaeozoic rocks was outlined for the first time.

On the basis of further studies of the Estonian bedrock sequence Schmidt enhanced the trans-Baltic correlation scheme after his second visit to Gotland and Öland in 1889 (Schmidt 1891). Moreover, he sketched a map where the equivalent layers were for the first time connected across the Baltic, showing thus that the different Palaeozoic units (Cambrian, Lower Silurian, Wenlock–Llandovery, Ludlow) are exposed as east–

[1] The original German names of the lithologic/stratigraphic units from Schmidt (1859) are given in italic type; in case of an obsolete geographic name the modern name is given in brackets.

west extending stripes on the seafloor between Estonia and Sweden (Fig. 3).

Schmidt's scheme has been gradually enhanced up to date concomitantly with the growing amount of stratigraphic data from the bedrock successions on both sides of the Baltic Sea. Due to space limits, the most relevant studies on the correlation/stratigraphy of the Cambrian, Ordovician, and Silurian sequences in Estonia and around Gotland are referred to in the corresponding chapters below. For more details see also the monograph Raukas & Teedumäe (1997), where the study history and the stratigraphy of the Cambrian (pp. 39–51), Ordovician (pp. 52–88), and Silurian (pp. 89–106) sequences in Estonia are summarized by a large number of authors.

### The history of seismic studies

The investigation of submarine Palaeozoic units and their distribution at the seafloor started in the early 1960s, with the commencement of marine seismic studies in the Baltic. However, before that Schmidt's map (Fig. 3) was significantly improved by the use of the bathymetric charts of the sea (Martinsson 1958, fig. 10). This is because in the Baltic region the lithologically contrasting stratigraphic boundaries in the outcropping Cambrian, Ordovician, and Silurian rocks coincide often with noticeable escarpments on the seafloor.

In order to investigate the Palaeozoic sequence below the Baltic, continuous seismic reflection profiling was introduced at Stockholm University by Tom Flodén in 1964. In addition to bathymetry, information from the upper 200–300 m of the underlying bedrock became available. The striking and widespread seismic reflectors in the bedrock succession, coinciding with the sharp and consistent lithological contacts, i.e. with the regional (litho)stratigraphic boundaries, enabled us (1) to subdivide the submarine sequence into different seismic units and correlate them with the (litho)stratigraphic sections onshore; and (2) to follow the distribution and thickness changes of these units, as well as to map them at the seafloor between Sweden and Estonia. The configuration of the reflectors, like the character of the entire seismic signature revealed the internal structure of the bedrock sequence. This gave further information about erosional features, tectonic deformations, sedimentary structures, carbonate buildups, etc.

In the period of 1964–78 about 25 000 km seismic survey lines were shot all over the Baltic. From 1966 the area to the northeast and east of Gotland up to the meridian 21°E was covered with a dense net of profiles with various orientations. The results of this period are presented in a monograph that also includes a detailed geological map of the central and northern Baltic (Flodén 1980). However, due to political restrictions Flodén had access neither to the waters of, nor to the geological information on Estonia. Therefore, after small-scale mapping of the Estonian coastal area in the late 1980s, a mismatch in the correlation between the Ordovician–Silurian boundary layers onshore and offshore was pointed out by Kiipli et al. (1993). This publication includes also the seismic correlation schemes for the Ordovician (fig. 43) and Silurian (fig. 44) sequences between the Estonian islands of Saaremaa and Hiiumaa and the Swedish island of Gotland.

## SWEDISH–ESTONIAN COOPERATION PROJECT 1990–2004

### The birth of the project

The glasnost and perestroika in the Soviet empire in the late 1980s opened new perspectives in the marine geological studies of the Baltic. The removal of the previous political barriers enabled seismic shooting from coast to coast across the Baltic Proper and free information exchange between Estonia and Sweden. Furthermore, the improvement of the seismic technique and equipment during the 1980s had remarkably enhanced the quality of seismic recordings compared to those interpreted by Flodén before 1980. Thus, expecting a new quality in the investigation of the submarine Palaeozoic sequence, the idea of scientific cooperation between Estonian and Swedish geologists was proposed by Tom Flodén. After his visit to Tallinn in 1989 a preliminary cooperation project was signed between Stockholm University and the Institute of Geology of the Estonian Academy of Sciences.

### Seismic data set collected during joint expeditions to the Baltic

Depending on the funding, joint Swedish–Estonian marine expeditions were carried out in the frame of this project, to collect seismic data from different parts of the Baltic. Considering the main goal of the project, the majority of the seismic profiling was concentrated on the northern Baltic Proper. According to the used equipment, as well as the setting of the profiles, two periods, 1990–96 and 1999–2004, can be distinguished in the seismic data collection.

To simplify the interpretation and correlation of the seismic data, the first period focused chiefly on the set of regularly spaced north–south seismic lines across the sublatitudinal zones of the Palaeozoic units at the seafloor. Using analogue single channel seismic equipment (see details in Flodén 1980), seismic profiling was started by a marine geology group at Stockholm University in 1990 from their R/V *Strombus* northeast of Gotland

(Fig. 4). This main set of submeridional profiles was practically finished during the summers of 1991 and 1992 from the Estonian and Russian R/V *Livonia* and *Prof. Multanovski*, respectively. To study the Silurian reefs and to simplify seismic interpretation, an additional set of north–south profiles was shot along the western coast of Saaremaa on board the *Strombus* in 1993 (Fig. 4). In 1995 and 1996, when the main working areas were in Riga Bay and around the impact structure of Neugrund, some auxiliary SW to NE profiles were shot from the *Strombus* across the northern Baltic (Fig. 4).

During the second stage the 'Meridata' digital 'Multimode Sonar System' on a PC computer was used (see details in Tuuling & Flodén 2007). To complement the main set of seismic lines, northeast–southwest profiles, running nearly parallel to the strike of the southeasterly dipping Palaeozoic strata, were shot in the summers of 1999, 2001, 2002, and 2003 (Fig. 4) using the Swedish R/V *Skagerrak*. To support the interpretation and correlation of the Silurian strata, some additional north–south profiles were shot onboard the Swedish R/V *Fyrbyggaren* offshore Gotland during the last joint expedition in 2004. Except for 1999, all the seismic works of this period were performed as part of the marine geology course held by Tom Flodén as a guest professor at the University of Tartu (2001–04).

The north–south seismic lines shot in cooperation with Lithuanian geologists from the R/V *Vejas* in 1993 (V9306–V9311 in Fig. 4) partially covered also the area northeast of Gotland. These profiles were useful in distinguishing and mapping the northerly extension of some seismic reflectors in the uppermost Wenlock layers offshore Gotland.

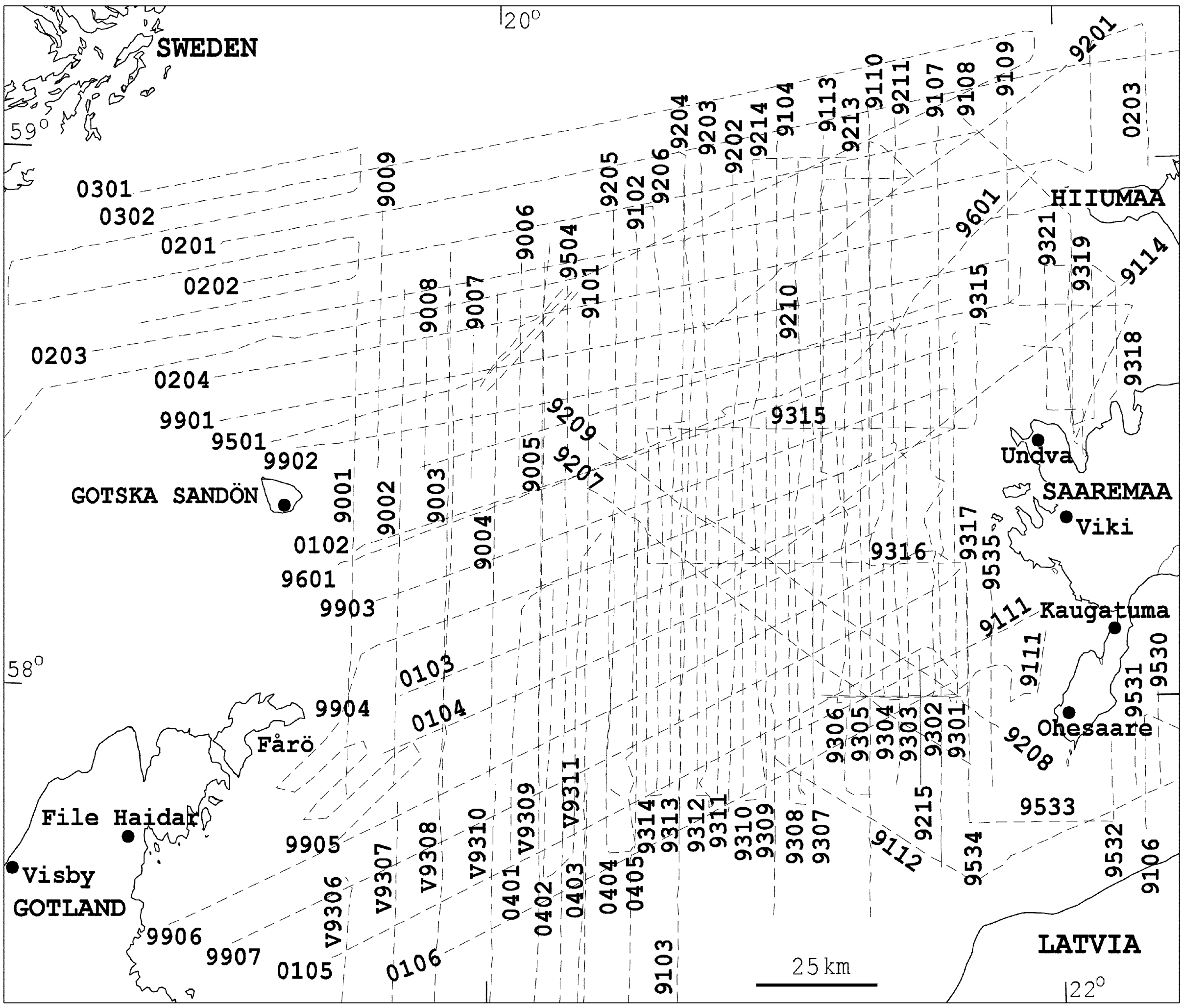


**Fig. 4.** Seismic lines shot in 1990–2004 in the northern Baltic Proper and the main drill cores in the adjacent mainland areas used in seismic correlation.

## THE INTERPRETATION OF SEISMIC PROFILES – SEISMIC SUBDIVISION AND CORRELATION OF THE PALAEOZOIC SEQUENCE ACROSS THE NORTHERN BALTIC PROPER

After the main north–south set of seismic lines was completed in 1992, Igor Tuuling has been systematically dealing with the interpretation of the accumulating seismic data, first at Stockholm University and, after defending his doctoral thesis in 1998, at the University of Tartu. The subdivision and correlation of the Palaeozoic sequence between Estonia and Sweden has been the key issue of his interpretation, as all other topics treated (tectonics, bedrock relief, reef structures, etc.) are largely relying on the stratigraphic framework.

The complexity of the interpretation of the submarine Cambrian, Ordovician, and Silurian sequences between Estonia and Sweden can vary heavily, depending first of all on the variation in the internal structure, i.e. the layers and lithology of these units. The correlation of the onshore and offshore data was mainly hampered by scanty drill core data from Gotland and the shallow marine area with no seismic information offshore Saaremaa.

Considering the local stratigraphy, the submarine area that was covered with seismic lines in 1990–2004 exposes the entire Cambrian and Ordovician sequences. In the Silurian strata, however, the uppermost reflector visible in the seismic lines coincides with the base of the Kuressaare Stage and the Hemse Beds, off the shores of Saaremaa and Gotland, respectively (Table 1). So far only the Cambrian, Ordovician, and lowermost Silurian strata of the correlation scheme and the geological map presented in this paper (Figs 5–7, Table 1) have been discussed in detail (Flodén et al. 1994; Tuuling et al. 1995, 1997; Tuuling 1998; Tuuling & Flodén 2000, 2001, 2006, 2007). The details about the Llandovery and the lowermost Wenlock strata have been submitted for publication (Tuuling & Flodén 2009), whereas the seismic subdivision and trans-Baltic correlation of the Jaagarahu Stage was finished only in the late autumn of 2008.

**Table 1.** The most distinctive seismic reflectors distinguished in the Ordovician and Silurian sequences between Hiiumaa–Saaremaa and Gotska Sandön–Gotland (see also Fig. 6)

| Reflector | Occurrence and stratigraphic position | |
|---|---|---|
| | Offshore Estonia | Offshore Gotland |
| $S_{12}$ | Boundary of the Paadla and Kuressaare stages | Occurrence is unclear due to lack of seismic data |
| $S_{11}$ | Boundary of the Rootsiküla and Paadla stages | Obviously the boundary of the Klinteberg and Hemse beds |
| $S_{10}$ | Boundary of the Jaagarahu and Rootsiküla stages | Obviously the boundary of the Slite and Halla/Mulde beds |
| $S_9$ | Boundary of the Vilsandi and Maasi beds | Its exact position within the Slite Beds is not determined yet |
| $S_8$ | Boundary of the Ninase Member and the Jaagarahu Stage | Missing |
| $S_7$ | Boundary of the Ninase and Mustjala members | Boundary of the Upper Visby and Högklint beds |
| $S_6$ | Appears a bit further offshore Saaremaa, i.e. these layers are probably missing on Saaremaa | Stratigraphically unidentified reflector in the uppermost Llandovery layers |
| $S_5$ | Unidentifiable onshore, probably marks the poorly studied diachronous lower boundary of the Mustjala Member | Unidentified Llandovery reflector, marks probably the diachronous lower boundary of the Mustjala Member |
| $S_4$ | Stratigraphically unidentified Llandovery reflector offshore Saaremaa | Missing |
| $S_3$ | Stratigraphically unidentified Llandovery reflector offshore Saaremaa | Missing |
| $S_2$ | Erosional boundary between the Raikküla and Adavere stages | Erosional boundary between the Raikküla and Adavere stages |
| $S_1$ | Erosional Ordovician–Silurian boundary | Erosional Ordovician Silurian boundary |
| $O_{4–5}$ | Double reflector evoked by the upper and lower boundaries of the Vormsi Stage | Double reflector evoked by the base and top of the Vormsi Stage |
| $O_3$ | Boundary of the Rakvere and Oandu stages | Base of the Rakvere Stage |
| $O_2$ | Boundary of the Tatruse and Vasavere members of the Haljala Stage | A reflector inside the Haljala Stage |
| $O_1$ | Coincides with the boundary of the Lower Ordovician calcareous and terrigenous rocks | Boundary of the Ordovician calcareous and Cambrian terrigenous rocks |

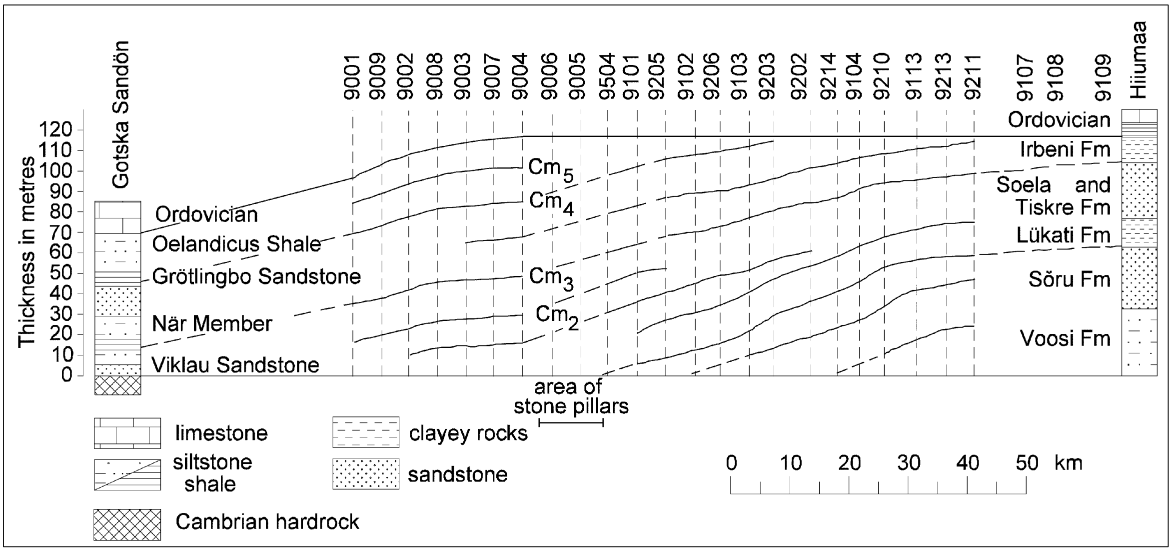


**Fig. 5.** Correlation scheme of the Cambrian sequence across the northern Baltic. Fm, formation.

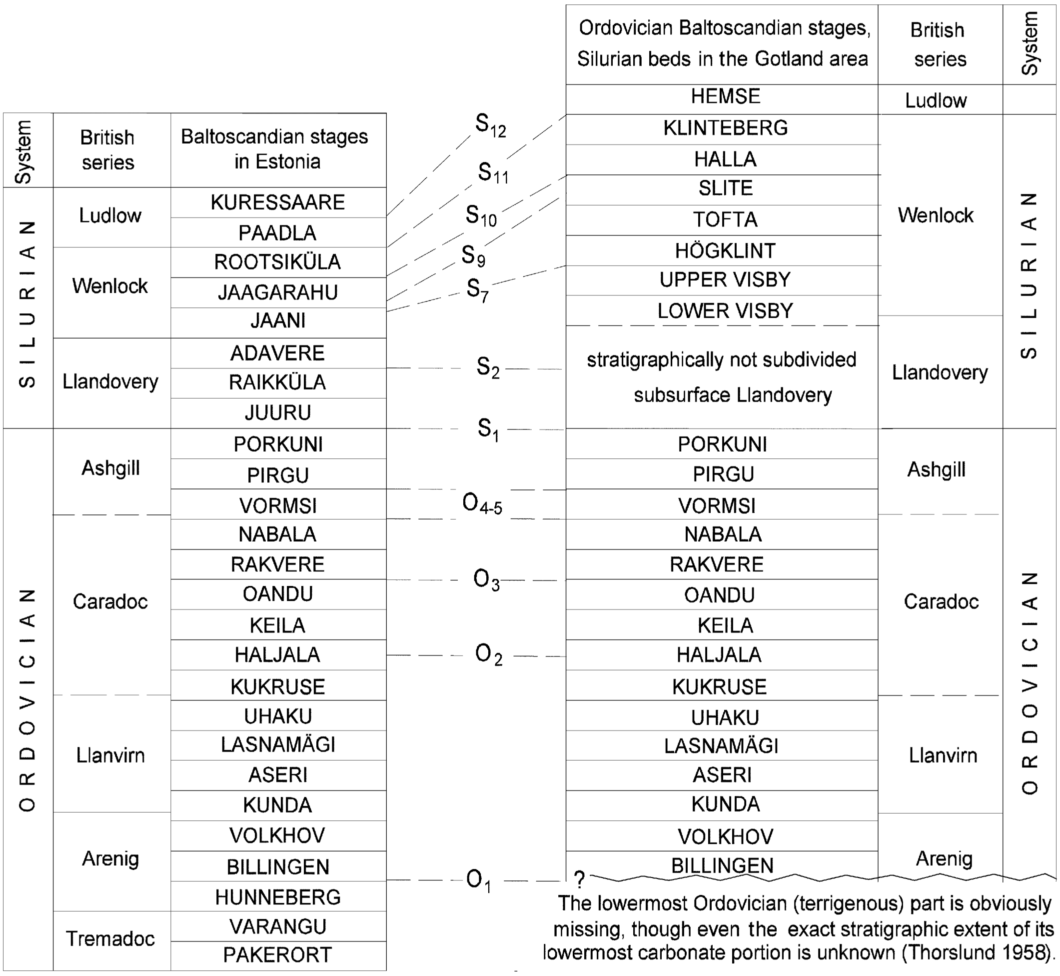


**Fig. 6.** Major Ordovician and Silurian trans-Baltic seismic reflectors and their correlation between Estonia and Gotland (for more stratigraphic details see Table 1). Ordovician stages after Nõlvak (1997) and Nõlvak et al. (2006), Silurian stages after H. Nestor (1997) and beds after Hede (1960) and Jeppsson et al. (1994).

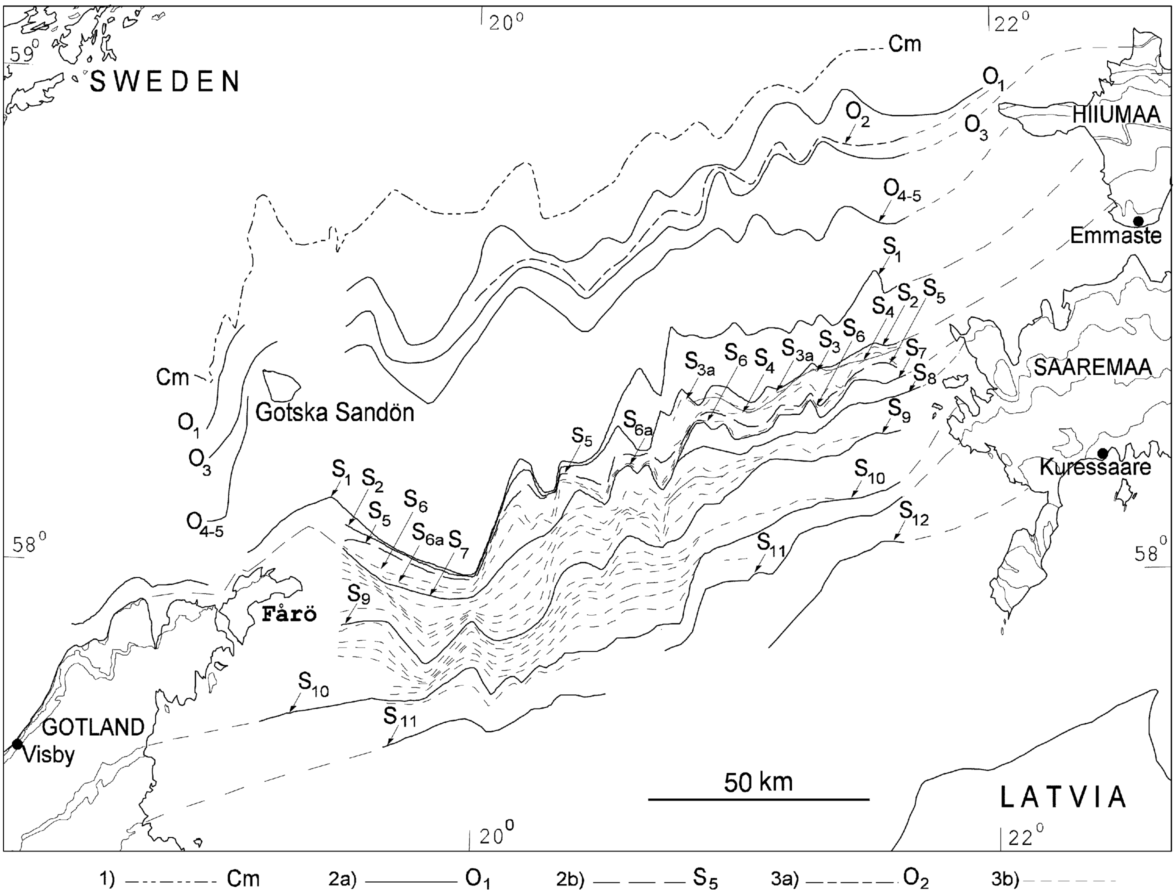


**Fig. 7.** Seismic reflectors/units exposed on the seafloor between Estonia and Sweden and their correlation to the adjacent onshore areas. 1, northern limit of the Cambrian rocks; 2, trans-Baltic reflectors: a) identified, b) unidentified; 3, local reflectors: a) identified, b) unidentified.

**The Cambrian sequence**

The stratigraphy and correlation within the Cambrian sequence around the central Baltic were specified in the 1980s and early 1990s (Kala et al. 1984; Hagenfeldt 1989, 1994; Mens et al. 1990; Hagenfeldt & Bjerkéus 1991). The results reveal shifting palaeogeographic patterns and a striking regional structural rearrangement at the end of the early Cambrian Lontova time (Tuuling 1998). Considering acritarch stratigraphy (Hagenfeldt & Bjerkéus 1991), the Cambrian sequences in Estonia and on Gotland were largely formed during different time intervals. Thus, the number of the Cambrian units distinguished across the Baltic, as well as their lithologies and thicknesses, differ considerably and most of them wedge out beneath the Baltic Sea (Fig. 5). Furthermore, the thickness of the Cambrian sequence, which is rather constant (110–120 m) across most of the Baltic, is only 72.5 m on Gotska Sandön (Thorslund 1958) and varies abnormally around northern Gotland (Hagenfeldt 1994; Tuuling et al. 1997). All these facts make the seismic correlation of the Cambrian sequence across the Baltic extremely arduous. Seismic information from the submarine Cambrian sequence is mainly limited to its outcrop area, being thus largely confined to a 3–10 km wide, northeast to southwest extending strip in front of the Baltic Klint (Fig. 7). Only in the area of extensive glacial erosion, in the Fårö Depth, the width of this strip reaches more than 30 km.

Very scarce data are available from a 15–20 km wide area of the so-called ‘stone pillars’ 50–60 km northeast of Gotska Sandön (Fig. 5), where the Cambrian sequence has become occasionally, within 0.5–4 km wide sections, impenetrable for the seismic pulse. Thus, in profiles 9005 and 9006, these sections appear within the normally layered Cambrian sequence as pillars of nonlayered crystalline rocks. Yet, a closer look reveals traces of the primary bedding structure within these pillars, pointing towards the secondarily altered/cemented Cambrian rocks (Tuuling et al. 1997; Fig. 5). This area divides the submarine Cambrian sequence into two separate, Swedish and Estonian parts, making the seismic correlation across the Baltic rather speculative. These two parts were correlated independently with the presumed major reflector levels in the onshore drill cores on Gotska Sandön and Hiiumaa, respectively.

In the Swedish part the Cambrian sequence yields seven excellently correlating seismic reflectors. The strongest reflectors $Cm_3$ and $Cm_4$ seemingly correspond to levels in the När Member and Grötlingbo Siltstone, where the presence of seismic reflector levels is indicated by lithological boundaries in the Gotska Sandön drill core (Figs 4, 5). On the Estonian side two easily correlated reflectors occur in the seismic profiles (Figs 4, 5). The lower one appears usually as a pair of reflectors and is, according to the drill cores on Hiiumaa, probably generated by the upper and lower boundaries of the strongly clayey Lükati Formation. Another lithological contact with great contrast appears at the boundary of the Irbeni and Soela formations. In both cases, however, the connection between these potential onshore and offshore reflector levels gets vaguer, as the distance of the seismic profiles from Hiiumaa increases. Thus, there exists no unambiguous trans-Baltic reflector in the Cambrian sequence, although the reflector at the base of the Irbeni Formation offshore Estonia may tentatively be correlated with the supposed reflector level in the När Member on Gotska Sandön (Fig. 5, $Cm_3$).

## The Ordovician sequence

In contrast to the conditions in the Cambrian, stable tectonic conditions prevailed during most of the Ordovician and the entire Baltic region was covered with a shallow epicontinental sea, the Palaeobaltic Basin. As a result, layers of similar lithology and thickness were formed across the northern Baltic, from the St Petersburg district to Sweden. In Estonia, where Ordovician rocks are most widely exposed and well studied, such a consistent sequence has enabled elaboration of a detailed stratigraphic scheme (Nõlvak 1997; Nõlvak et al. 2006, 2007). Most of the stages distinguished here have obtained the status of regional standard. Thus, the same (litho)stratigraphic units of the North Estonian Confacies Belt (Jaanusson 1976) are easily recognizable in Estonia, on Gotska Sandön, and on Gotland (Männil 1966; Grahn 1982; Nõlvak & Grahn 1993; Hints et al. 1994, 2005). Consequently, the Ordovician sequence across the Baltic provides excellent seismic correlation.

Four widespread and easily correlated seismic reflectors occur in the Ordovician sequence between Hiiumaa and Gotska Sandön–Fårö (Flodén et al. 1994; Tuuling et al. 1995; Fig. 6, Table 1). Three reflectors, $O_1$, $O_3$, and $O_{4–5}$, can be traced across the Baltic, while $O_2$ vanishes some distance away from Gotska Sandön (Fig. 7). Their stratigraphic correlation with the onshore area (Table 1, Fig. 7) is based on the drill cores from southern Hiiumaa (Fig. 7, Emmaste) and western Saaremaa (Fig. 4, Undva, Viki, Kaugatuma, and Ohesaare).

As expected from the mainland sections, the lower part of the submarine Ordovician sequence, i.e. the lowermost three seismic units ($O_1$–$O_2$, $O_2$–$O_3$, and $O_3$–$O_{4–5}$), exhibits rather stable internal structures and thicknesses between Estonia and Sweden. As an exception, a regular system of channel-like depressions, probably reflecting an old river system or a set of submarine channels, occurs just below the reflector $O_{4–5}$, i.e. in the pre-Vormsi rocks midway between Gotland and Hiiumaa (Tuuling & Flodén 2000, fig. 2). According to chitinozoan correlation, based on drill cores of southern Estonia, Latvia, and the Gotland–Gotska Sandön area, a regional hiatus at the base of the Vormsi Stage has been suggested (Nõlvak & Grahn 1993; Nõlvak 2002). Frequent erosional features and thickness variations in the uppermost part of the Ordovician sequence, i.e. above the reflector $O_{4–5}$, indicate the onset of the Caledonian Orogeny. The growing tectonic instability towards the end of the Ordovician (Tuuling & Flodén 2007), as well as concurrent global glaciation events (Brenchley et al. 2003), emphasize the transition between the Ordovician and Silurian periods.

## The Ordovician–Silurian boundary beds

The stratigraphy of the Ordovician–Silurian boundary strata, which according to mainland data is highly variable around the northern Baltic, was one of the main subjects of our project. This stratigraphic interval has been studied in numerous drill cores of Estonia and treated in many papers (e.g. Kaljo et al. 1988, 1991; Kaljo & Hints 1996; H. Nestor 1997; Nõlvak 1997; Harris et al. 2004, 2005; Hints et al. 2005). The few core data on the Ordovician–Silurian boundary below Gotland are available in Thorslund & Westergård (1938), Martinsson (1967, 1968), Thorslund (1968), Nõlvak & Grahn (1993), Grahn (1995), and Tuuling & Flodén (2007).

In the seismic lines the Ordovician–Silurian boundary beds are confined to two strong reflectors occurring in the uppermost Ordovician ($O_{4–5}$) and in the lowermost Silurian ($S_2$) strata across the Baltic (Tuuling & Flodén 2000, 2007; Fig. 6, Table 1). According to the regional stratigraphic schemes (H. Nestor 1997; Nõlvak 1997), these reflectors bracket the Pirgu and Porkuni stages below and the Juuru and Raikküla stages above the trans-Baltic Ordovician–Silurian boundary reflector $S_1$. These reflectors are easily distinguishable offshore

Saaremaa and the seismic units $O_{4-5}$–$S_1$ and $S_1$–$S_2$ between them reveal no considerable thickness changes. However, westwards of profile 9312 (Fig. 4), a strongly irregular reflector configuration and a southerly thickness diminution appear in units $O_{4-5}$–$S_1$ and $S_1$–$S_2$, respectively.

Offshore Gotland numerous carbonate mounds associated with local seismic reflectors, namely $or_1$ and $or_2$ in the unit $O_{4-5}$–$S_1$, sporadic erosional channels and the decreased thickness of the $S_1$–$S_2$ unit together make the identification of reflectors $S_1$ and $S_2$ very difficult (Tuuling & Flodén 2000, 2007). According to drill core data from Gotland and Estonia, the disturbance features are associated with three regional erosional events, namely at the boundary of the Pirgu and Porkuni stages, at the Ordovician–Silurian boundary, and at the boundary of the Raikküla and Adavere stages. In places these erosional surfaces may 'intertwine' with each other (Tuuling & Flodén 2007, fig. 7). As a result, the stratigraphy of the aforementioned stages, like the time span of the hiatus at these boundaries, can vary considerably around northern Gotland (Nõlvak & Grahn 1993; Grahn 1995; Tuuling & Flodén 2007).

In the latest Ordovician–earliest Silurian Palaeobaltic Basin the areas around northern Gotland and central–south Estonia were structurally and facially situated at the outer shallow shelf to deep shelf (basin) transect. The shallow shelf area was subject to intensive subaerial erosion induced by two rapid sea level falls during the Hirnantian glaciation in the latest Ordovician (Brenchley et al. 2003) and during the extensive regression at the transition between Raikküla and Adavere times. In instable tectonic conditions throughout most of Llandovery time the slope at the shallow to deep shelf (basin) transect was subject to widespread submarine erosion and slumping of muddy sediments (Harris et al. 2004; Tuuling & Flodén 2007, 2009).

## The post-Raikküla Silurian sequence

The Caledonian Orogeny progressed towards its culmination at the transition of the Silurian and Devonian periods. Due to differentiated tectonic movements, the area around Gotland deepened successively in comparison with northern/central Estonia. Thus, during the Silurian the Palaeobaltic Basin around Gotland represented a deeper and more open marine environment.

Based on the outcrops and numerous drill cores, a detailed stratigraphic scheme and facies model has been worked out for the Silurian succession in Estonia (H. Nestor 1997; H. Nestor & Einasto 1997). Very little is known about the subsurface Llandovery layers on Gotland (see Grahn 1995), however, the exposed Silurian rocks have been studied in detail and their present stratigraphy is still largely based on a scheme proposed by Hede (1960). Yet, relying foremost on conodont biostratigraphy, Hede's scheme (13 major units – beds, and more than 60 subunits) has been refined and some new formal and informal units have been proposed during the last 10–15 years (Jeppsson et al. 2006).

The Wenlock and Ludlow strata that crop out on Gotland are thicker, more argillaceous, and contain fewer stratigraphic gaps than those of Saaremaa. Hence, the types of shallow-water facies exposed on Saaremaa never formed on Gotland, whereas the deeper basinal units of Gotland coincide on Saaremaa either with stratigraphic gaps, or most likely are just buried under the younger Silurian rocks further to the south. For that reason a close stratigraphic comparison between these two islands has been difficult without comprehensive micropalaeontological studies. The most detailed study is so far based on direct correlation of conodont faunas in outcrops all over Saaremaa and Gotland (Jeppsson et al. 1994). Similar difficulties appear also in seismic correlation, as the number and positions of the seismic reflectors in the Silurian sequences offshore Saaremaa and offshore Gotland differ markedly (Fig. 7).

The post-Raikküla Silurian sequence included in our correlation scheme (Figs 6, 7; Table 1) can be conditionally divided into three portions: (1) the Llandovery to lowermost Wenlockian part between the seismic reflectors $S_2$ and $S_7$, (2) the Wenlock sequence between the reflectors $S_7$ and $S_{10}$, and (3) the Wenlock–Ludlow sequence between the reflectors $S_{10}$ and $S_{12}$.

### *The Adavere Stage and the Mustjala Member (seismic unit $S_2$–$S_7$)*

The first portion makes up the greater part of the wall of the submarine Silurian Klint. Thus, the reflector $S_7$ marks the sharp boundary between the strongly argillaceous and pure reef-containing limestone units slightly below the crest of the klint. On Saaremaa and on Gotland this contrasting lithologic contact correlates with the boundary between the Mustjala and Ninase members of the Jaani Stage and between the Upper Visby and Högklint beds, respectively (Tuuling & Flodén 2009). According to age control on land based on conodonts (Jeppsson et al. 1994) and chitinozoans (V. Nestor 1997; V. Nestor & Einasto 1997), this reflector does not follow a definite stratigraphic level, i.e. is obviously time-transgressive. On the basis of the Estonian stratigraphic scheme (H. Nestor 1997) the unit $S_2$–$S_7$ includes the Adavere Stage and most of the Jaani Stage. On Gotland this stratigraphic interval is largely concealed by younger Silurian rocks and very poorly studied because of scarce drill core data.

As in the lowermost Silurian unit ($S_1$–$S_2$), also in the unit $S_2$–$S_7$ the profile 9312 (Fig. 4) divides between the Estonian and Swedish types of sections (Tuuling & Flodén 2009). The distinguished reflectors inside the unit $S_2$–$S_7$ occur either in the Estonian ($S_3$, $S_{3a}$, $S_4$) or predominate in the Swedish ($S_6$, $S_{6a}$) type of sections. The only reflector that crosses the Baltic ($S_5$) shifts regularly downwards in the section towards the west. Hence the subunits $S_2$–$S_5$ and $S_5$–$S_7$ decrease and increase respectively in thickness towards Gotland. However, offshore Gotland, both subunits reveal, similarly to the underlying unit $S_1$–$S_2$, also a distinct southerly decrease in thickness, thus indicating continued tectonic instability and submarine erosion around Gotland throughout Llandovery time. The stratigraphic position of the reflector $S_5$ is not unambiguously identifiable in the mainland sections, but may coincide with the still poorly studied diachronous lower boundary of the Mustjala Member (Männik 2007). Thus, the units $S_2$–$S_5$ and $S_5$–$S_7$ reveal the distribution and thickness of the Adavere Stage and the Mustjala Member across the Baltic.

### *The Ninase Member and the Jaagarahu Stage (seismic unit $S_7$–$S_{10}$)*

The last seismic reflector that was traced across the Baltic in our north–south set of seismic lines ($S_{10}$) correlated with the sharp regional discontinuity surface between the Jaagarahu and Rootsiküla stages on Saaremaa (Figs 6, 7; Table 1). Offshore Gotland this reflector seems to coincide with a strong and widespread reflector that was earlier correlated with the base of the Halla/Mulde beds (reflector $S_4$ in Flodén 1980). Thus, the unit $S_7$–$S_{10}$ embraces the Ninase Member of the Jaani Stage and the Jaagarahu Stage in Estonia and the Högklint, Tofta, and Slite beds on Gotland.

The reflector $S_8$, which marks the upper boundary of the Ninase Member on Saaremaa (Table 1), shows that in the east–west direction this unit extends up to the erosional cut around the seismic line 9312 (Figs 4, 7). The trans-Baltic seismic reflector inside the Jaagarahu Stage ($S_9$) correlates with the boundary of the Vilsandi and Maasi beds, dividing thus the Vilsandi ($S_8$–$S_9$ offshore Saaremaa and $S_7$–$S_9$ offshore Gotland) and Maasi–Tagavere ($S_9$–$S_{10}$) seismic units. Both units are followed across the Baltic, though in concord with the deepening of the Silurian Basin and successively appearing new subunits (Fig. 7), their thickness increases considerably towards Gotland.

The first reflector in the Vilsandi unit appears about 20 km off Saaremaa, however, most reflectors emerge successively 40–70 km west of the island (Fig. 7). Offshore Gotland, the Vilsandi unit can be divided into six subunits. In the Maasi–Tagavere seismic unit the first reflector appears some 40 km west of Saaremaa (Fig. 7). All the other new reflectors emerge a bit further west around the area midway in the Baltic. A total of seven subunits appear inside the Maasi–Tagavere unit offshore Gotland.

Although precise correlation of these subunits with the rock sequence of Gotland has yet to be done, we can roughly claim that (1) a large number of the Wenlock units that crop out on northern Gotland (Tofta, lowermost Slite beds) correspond to a stratigraphic gap at the boundary between the Vilsandi and Maasi beds on northern Saaremaa, (2) a great part of the uppermost Slite beds corresponds to a stratigraphic gap between the Jaagarahu and Rootsiküla stages on Saaremaa.

### *The Ludlow sequence confined to the reflectors $S_{10}$–$S_{12}$ offshore Saaremaa*

Two strong and regular reflectors, $S_{11}$ and $S_{12}$, emerged above the reflector $S_{10}$ in the main north–south set of the seismic lines offshore Saaremaa (Figs 4, 7). They were correlated with the disconformities below and above the Paadla Stage onshore (Fig. 6). Further to the south of the outcrop of the reflector $S_{12}$ the bedrock sequence was practically invisible in seismic recordings because of the shallow water and thick Quaternary cover. Offshore Gotland, where most of the main north–south profiles end just after the outcrop of the reflector $S_{10}$, two southward reflectors were distinguished in the V93 profiles (V9306–V9311 in Fig. 4; Fig. 7). The lower reflector which obviously coincides with the boundary of the Klinteberg and Hemse beds ($S_{5A}$ reflector in Flodén 1980; Flodén et al. 2001), can be correlated tentatively with the reflector $S_{11}$ offshore Saaremaa.

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## Paleosoikumi kivimite seismiline korrelatsioon üle Läänemere – Eesti-Rootsi ühisprojekt alates 1990. aastast

Igor Tuuling ja Tom Flodén

Artikli algul on antud lühiülevaade esmasest, 19. sajandi teisel poolel Friedrich Schmidti teostatud Eestis ja Rootsis paljanduvate Ordoviitsiumi ning Siluri kivimite ülemere korrelatsioonist. Pearõhk on aga asetatud viimase 20 aasta jooksul Eesti-Rootsi ühiste mereekspeditsioonide käigus kogutud seismilise pidevsondeerimise andmestiku interpreteerimise tulemuste kokkuvõtmisele, kuid eeskätt Kambriumi, Ordoviitsiumi ja Siluri kivimkomplekside seismilisele korreleerimisele, samuti väljaeraldatud seismiliste üksuste paksuste ruumilistele muutustele. On vaadeldud eri (seismo)stratigraafiliste üksustega seotud erosioonilisi ilminguid, settelisi struktuure ja riffmoodustisi ning analüüsitud neid teadaolevate maismaa faktide valgusel. Artiklis on ära toodud viimastele interpreteerimisandmetele tuginev Hiiumaa-Saaremaa ja Gotska Sandöni-Gotlandi vahelise merepõhja geoloogiline kaart.