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The Ordovician-Silurian boundary beds between Saaremaa and Gotland, Baltic Sea, based on high resolution seismic data

Igor TUULING and Tom FLODÉN

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New seismic profiles have been used to revise earlier interpretations of the Ordovician-Silurian boundary beds between Saaremaa and Gotland. A trans-Baltic reflector with erosional features (S_2) above the erosional Ordovician-Silurian boundary reflector (S_1) correlates with the boundary between the Raikküla and Adavere stages. The sporadic reflector or_2 below the S_1 reflector offshore from Gotland represents the erosional boundary between the Pirgu and Porkuni stages. Three stratigraphic gaps occur in the Ordovician-Silurian boundary beds offshore from Gotland. The amount of eroded rocks between the Pirgu and Porkuni stages, the Ordovician and Silurian systems and the Raikküla and Adavere stages can change rapidly. Consequently, the thickness and stratigraphy of the Ordovician-Silurian boundary beds around Gotland can change considerably across short distances. The O_{4-5}–S_1 unit offshore from Gotland, including carbonate buildups and erosional incisions infilled with Porkuni strata, belongs facially to the transitional belt between the Estonian Shelf and the Livonian Tongue. The thickness changes in the S_1–S_2 unit (Juuru and Raikküla stages) indicate an extensive submarine erosional channel, streching from north of Estonia across the Baltic Sea and central Gotland, which developed in the Baltic Basin along a shelf to deep-basin transect during Llandovery time.

Igor Tuuling, Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia, e-mail: igor.tuuling@ut.ee; Tom Flodén, Institute of Geology and Geochemistry, Stockholm University, 10691 Stockholm, Sweden, e-mail: tom@geo.su.se *(received: August 8, 2006; accepted: May 14, 2007).*

Key words: Baltic Basin, Ordovician-Silurian boundary, seismostratigraphy, carbonate buildups, erosional features, stratigraphic gaps.

INTRODUCTION

The Ordovician-Silurian transitional beds around the Baltic Sea (henceforth the Baltic) are exposed only in Estonia (Fig. 1), where mostly near-shore shallow marine sections are accessible to direct geological studies (Kaljo *et al*., 1988). East of the Baltic, a north-south transect of the Ordovician-Silurian boundary strata have been studied using numerous borehole cores from all the Baltic countries (Kaljo *et al*., 1988, 1991; Kaljo and Hints, 1996; Nestor *et al*., 2003; Harris *et al*., 2004; Hints *et al*., 2005).

Very little is known about the Ordovician-Silurian boundary beds west of the Baltic countries. On the offshore Swedish islands Öland and Gotska Sandön (Figs. 1 and 2), where outcropping Ordovician rocks have been studied more closely; the bedrock sequence is truncated by a modern erosional surface below the uppermost Ordovician layers. On Gotland and Fårö (Fig. 2), however, Silurian strata more than 100 m thick overlie the Ordovician-Silurian boundary.

Although there are many borehuoles, mostly related to oil prospecting on Gotland and Fårö, core samples for further investigations have been taken from only a few of them. The stratigraphy of the Ordovician-Silurian boundary beds here has been discussed either on the basis of rare macrofossils (Thorslund and Westergård, 1938; Martinsson, 1967; Thorslund, 1968) or by detailed studies on chitinozoans (Grahn, 1982; Nõlvak and Grahn, 1993; Grahn, 1995). These few attempts have revealed noticeably different Ordovician-Silurian boundary beds below Gotland compared to those in Northern Estonia. Moreover, Gotland itself reveals a considerable variability in stratigraphy and thicknesses of the Ordovician-Silurian boundary beds.

Ample seismic data, reflecting the submarine Lower Palaeozoic sequence between Estonia and Sweden, has been amassed during the joint Swedish-Estonian expeditions to the Baltic in 1990–2004. In the framework of this project, the geology of the trans-Baltic Ordovician-Silurian transitional beds has been discussed earlier, based on the first north-south seismic lines shot in 1990–1992 (Fig. 2; Flodén *et al*., 1994; Tuuling *et al*., 1995). Based largely on the same data, the Ordovician-Silurian boundary

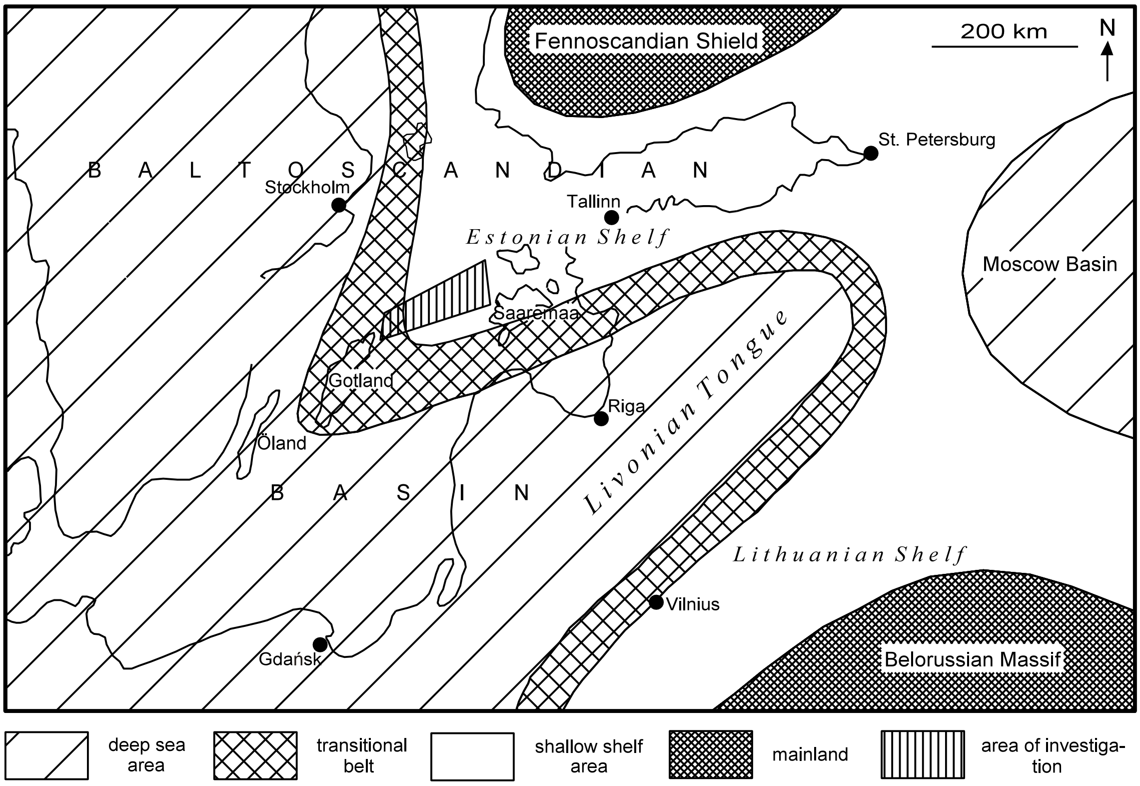

Fig. 1. Location of study area and major tectonic and palaeogeographic features of the Baltic region at the transition of the Ordovician and Silurian periods (modified from Jaanusson, 1976; Harris *et al.*, 2004)

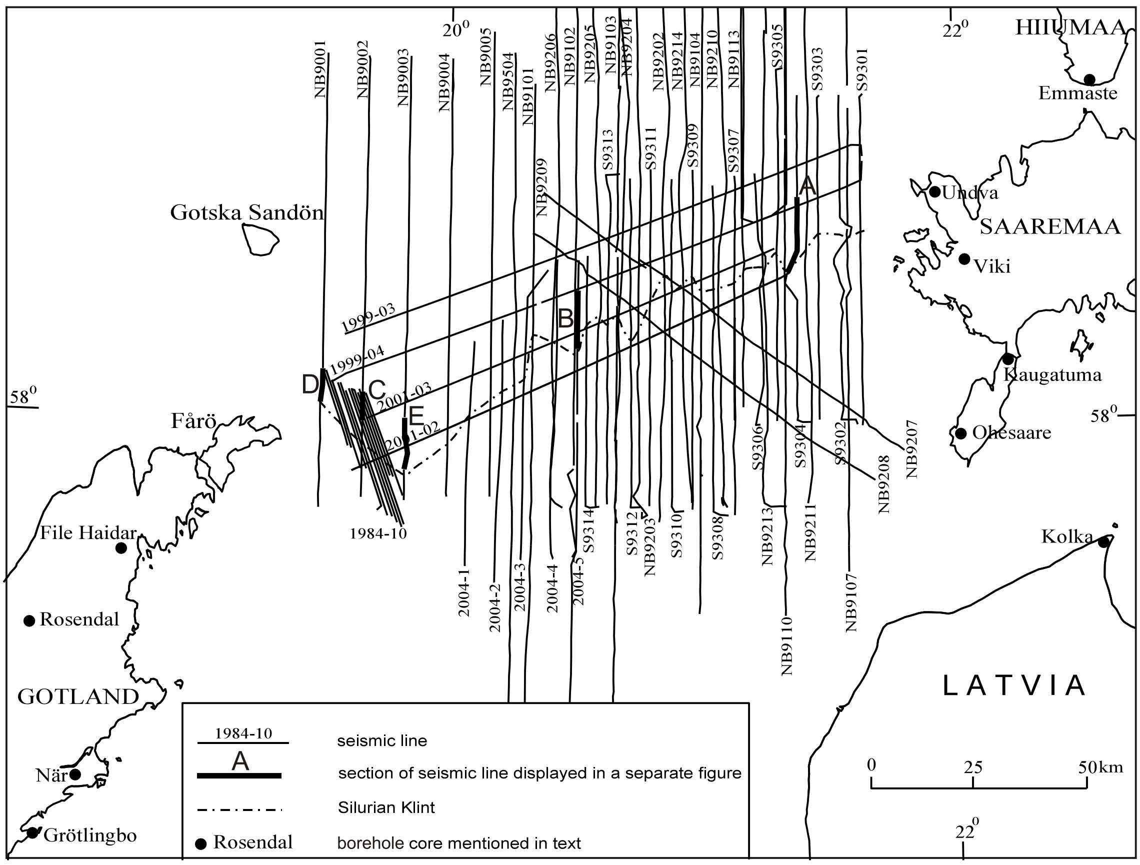

Fig. 2. Location map of the seismic profiles and borehole cores used in this study and sections of the seismic lines (A–E) displayed in Figures 4, 5, 7, 8 and 9

and geology of the uppermost Ordovician layers have also been discussed in connection with the Upper Ordovician carbonate buildups and erosional features offshore from northeastern Gotland (Tuuling and Flodén, 2000*a*). In all these cases, however, seismic data shot after 1992 was either still not available, or it was not relevant to the topics discussed.

Enhanced technology has improved the quality of the seismic recordings made after 1992. In all, the new data and improved quality have provoked reinterpretation of the seismic data and revealed details that were undistinguishable in the older profiles. This paper aims to advance and revise the earlier interpretations (Flodén *et al*., 1994; Tuuling *et al*., 1995; Tuuling and Flodén, 2000*a*) and to estimate the thickness values and trends in the Ordovician-Silurian transitional beds between Estonia and Sweden.

GEOLOGICAL SETTING

During most of the Early Palaeozoic, a shallow sedimentary basin extended across a large part of the East European Craton (Männil, 1966; Jaanusson, 1976; Nestor, 1990; Nestor and Einasto, 1997). One of its depocenters, the Baltoscandian Basin, was evolving close to the western margin of the craton (Fig. 1). The shallower, eastern part of this basin on the southern slope of the Fennoscandian Shield (Fig. 1) has been traditionally treated as the Baltic Basin. The contours of the Baltic Basin became most clearly pronounced during the Ordovician and Silurian periods, when concomitantly with the progressing Caledonian Orogeny, a syneclise started to develop around the present southern Baltic. This resulted in formation of a northeasterly elongated depression, the Livonian Tongue (Jaanusson, 1973; Livonian Basin according to Harris *et al*., 2004), which extended from Northern Poland across Western Lithuania and Latvia up to the southeastern corner of Estonia (Fig. 1). As a deepest part of the Baltic Basin, this depression separated shallow shelf areas in Estonia (Estonian Shelf in Harris *et al*., 2004; North Estonian facies belt in Põlma, 1982; Hints *et al*., 2005) from those in Lithuania (Fig. 1), where, due to its equatorial position (Torsvik, 1998), mostly calcareous sediments were accumulating.

Throughout most of the Ordovician, the Estonian Shelf took the form of a flat slope, deepening, gently towards the Livonian Tongue, with a gradual, shallow- to deep-water facies transition. In stable tectonic conditions, strata of similar lithology and thickness were formed along the shelf from the St. Petersburg district, across Northern Estonia up to the Swedish islands Gotska Sandön and Gotland (Männil, 1966; Jaanusson, 1976; Nõlvak and Grahn, 1993; Hints *et al*., 1994, 2005; Nielsen, 2004; Fig. 1). In Estonia, where Ordovician rocks are most widely exposed and studied, such a consistent sequence has enabled construction of a detailed stratigraphic scheme (Nõlvak, 1997). Most of the stages distinguished in Estonia are easily extendable all over Baltoscandia, and have thus obtained the status of regional standards (Männil, 1966; Bergström, 1971; Jaanusson, 1973; Podhlańska, 1980; Nõlvak and Grahn, 1993; Nielsen, 2004; Webby *et al*., 2004).

Due to the progressing Caledonian Orogeny and steadily deepening Baltic Syneclise, the evenly southwards dipping slope of the Baltic Basin become more topographically varied close to the end of Ordovician, as a distally steepening slope started to develop between the flat shoal and deep basinal areas (Nestor, 1990). This structural rearrangement led to a much sharper sediment distribution from north to south and formation of a distinct facies zone between the shallow shelf and deep basinal areas (transitional belt in Põlma, 1982; Harris *et al*., 2004; Hints *et al*., 2005; Fig. 1). By the Silurian, tectonic movements on the southern slope of the Baltic Shield had caused the subsidence of the area around Gotland and rearranged the eastwesterly distribution of shallow shelf, slope and deep basinal areas between Estonia and Gotland.

The uppermost Ordovician units distinguished around Gotland are still comparable with the coeval units in Estonia (Männil, 1966; Jaanusson, 1976; Nõlvak and Grahn, 1993), whereas the Silurian sequences across the Baltic are already difficult to compare directly. The Wenlock and Ludlow rocks, cropping out on Saaremaa and Gotland, show explicitly that the strata further west are thicker, more argillaceous and contain less stratigraphic gaps, hence pointing to a deeper and more open basinal environment around Gotland (Jeppsson *et al*., 1994). Furthermore, based on the lithological and faunal differences (Martinsson, 1967; Jeppsson *et al*., 1994), a similar westerly depth increase is even better defined between the eastern and western parts of Gotland.

MATERIAL AND METHODS

Since 1993, the Ordovician-Silurian transitional layers have been revealed in numerous seismic lines, oriented approximately N–S, offshore from Saaremaa (S9301–S9314), as well as in the middle/western half of the area between Saaremaa and Gotland (NB9504; 2004-1–2004 -5; Fig. 2). These lines, running parallel to and between the profiles of those from 1990–1992, have considerable improved the previous data set. The average distance between the approximately N–S lines S9301–S9314 and S9314–NB9004 is 2.5 km and 5km, respectively (Fig. 2). Further west, the N–S profiles are still only 10 km apart. However, some high quality north-west to south-east and north-east to south-west oriented profiles, respectively from 1984 and 1999 (Fig. 2), occasionally reveal excellent Ordovician-Silurian boundary sections just east of Gotland.

In 1999–2004, an additional set of north-east to south-west directed profiles, nearly parallel to the strike of the southeasterly dipping Ordovician-Silurian strata were shot between Saaremaa and Gotland. Ordovician-Silurian boundary beds have been intermittently revealed in four of these profiles (1999-03, 1999-04, 2001-03 and 2001-04; Fig. 2). This enabled for the first time the tracing of different seismic units along a single seismic profile between Saaremaa and Gotland.

An analogue single channel seismic reflection profiler, described earlier (Flodén, 1980, 1981; Tuuling, 1998; Flodén *et al*., 2001) was used to perform the seismic study. All the seismic lines, except for 1984-10, were shot by means of a *PAR 1600B* air gun. The latter profile just north-east of Gotland (Fig. 2) is exceptionally based on a high resolution *Sodera* water gun with a very clean pulse. Before 1999, a 50-element

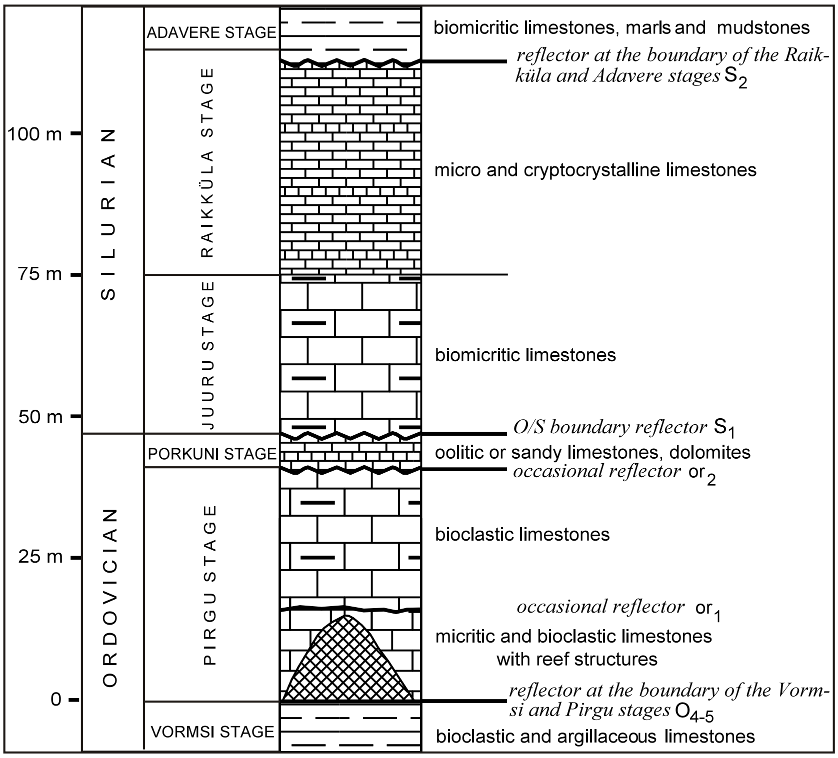

Fig. 3. Stratigraphic sketch with positions of the seismic reflectors ($O_{4\text{–}5}$, or_1, or_2, S_1, S_2) in the Ordovician-Silurian boundary beds based on the Undva, Viki and Kaugatuma cores on Saaremaa

hydrophone eel received the reflected signal, which was then filtered and displayed on an EPC precision graphic recorder within the time and frequency intervals of 0.5 s and 250–500 Hz, respectively.

Since 1999, a *Meridata* digital *Multi-mode Sonar System* on a PC computer has been used to run the profiler. A reflected air gun pulse was received with a 16 m hydrophone "eel", consisting of 100 elements coupled in parallel. The unfiltered and unprocessed signal was first recorded in the computer files, which, using the *Meridata* software package *SVIEW*, were later processed, filtered and finally displayed on an EPC graphic recorder at the frequency rate 100–1000 Hz.

As the seismic reflectors are induced by sharp lithological contacts, lithostratigraphical analysis of the onshore borehole cores (Fig. 2) was used to correlate offshore seismic data with the regional stratigraphic units. In the calcareous sequence of the Baltic Basin, particularly in its shelf facies, the sharpest lithological interfaces are produced by clayey transgressive interlayers (marl- and mudstones) and they commonly mark also the boundaries of the regional stages (Fig. 3). The thickness comparison of the on- and offshore units, and the positions of reef structures, which occur only at certain stratigraphic levels, furthermore supported the correlation. The positions of different boundaries and units in the Ordovician-Silurian transitional beds are also firmly fixed with reference to a conspicuous submarine escarpment, the Silurian Klint (Fig. 2; Tuuling *et al*., 2004). This morphological feature also had a paramount role in correlation of the on- and offshore sequences.

For the thickness estimations, a seismic wave velocity of 3500 m/s was used both for the uppermost Ordovician ($O_{4\text{–}5}$–S_1) and lowermost Silurian seismic unit (S_1–S_2), discussed in the text. This mean value is based on refraction sounding data and is typical for the argillaceous Upper Ordovician limestone offshore from Gotland (Flodén, 1975). In the borehole cores on Saaremaa, both the uppermost Ordovician and lowermost Silurian sequences are lithologically rather similar to the uppermost Ordovician layers around Gotland, being clearly distinguishable from the rest of the overlying highly argillaceous Llandovery sequence above the S_2 reflector.

SEISMOSTRATIGRAPHIC OUTLINES OF THE ORDOVICIAN-SILURIAN BOUNDARY BEDS

OLD INTERPRETATION BASED ON THE PROFILES FROM 1990–1992

In the previous studies (Flodén *et al*., 1994; Tuuling *et al*., 1995), three more or less consistent seismic reflectors were distinguished in the Ordovician-Silurian boundary beds across the Baltic ($O_{4\text{–}5}$, S_1 and $S_{2\ old}$ in Fig. 4). Based on the borehole cores in Estonia, the lowermost, most striking and consistent one in the Ordovician strata ($O_{4\text{–}5}$) was correlated with the boundary of the Vormsi and Pirgu stages. Above the Ordovician-Silurian boundary reflector (S_1), two closely set seismic reflectors ($S_{2\ old}$ and S_3 in Fig. 4) appeared in the Llandovery strata, at the base of Silurian Klint offshore from Saaremaa (Flodén *et al*., 1994, figs. 5 and 6A, B). They were correlated with the lower and upper boundary of the Raikküla Stage, respectively. Halfway between Saaremaa and Gotland, however, the latter pair of reflectors became indistinct as S_3 got very vague and the S_2 turned into one of the most striking reflectors offshore from Gotland (Flodén *et al*., 1994).

NEW DETAILS REVEALED AFTER 1992

In some profiles shot after 1992, an additional strong reflector with rare erosional features appeared offshore from Saaremaa between the former S_2 and S_3 reflectors ($S_{2\ new}$ in Fig. 4). Offshore from Gotland, this new reflector merges with the old S_2 reflector and its erosional nature has in some profiles (e.g. 2004-5 in Fig. 5) become even more pronounced. In the latter profile, this reflector southwards steadily approaches the underlying Ordovician-Silurian boundary reflector S_1, until the S_2 and S_1 reflectors become entirely indistinguishable. Thus, a strong and consistent trans-Baltic reflector with erosional features occurs in the lowermost Silurian strata between Saaremaa and Gotland.

The facts just described made us revise the earlier interpretation of the seismic boundary between the Raikküla and Adavere stages. Instead of the irregular and weak S_3 reflector (Tuuling *et al*., 1995; Fig. 4), this boundary is fixed as the stron-

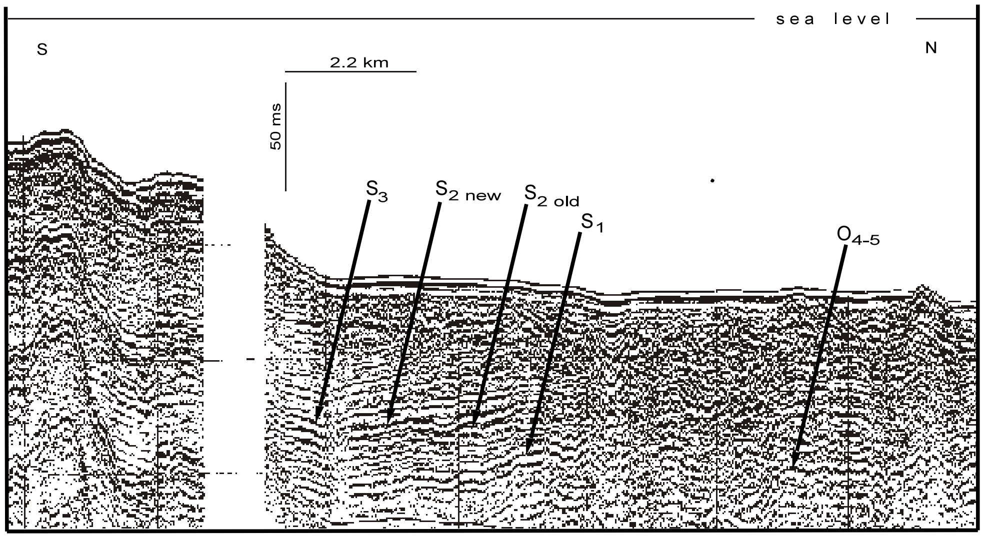

Fig. 4. Seismic profile S9304 offshore from Saaremaa (for location see section A in Fig. 2) with major seismic reflectors in the Ordovician-Silurian boundary beds (for stratigraphic positions of reflectors see Fig. 3)

Vertical scale: 50 milliseconds equals to *c*. 36 m at water velocity

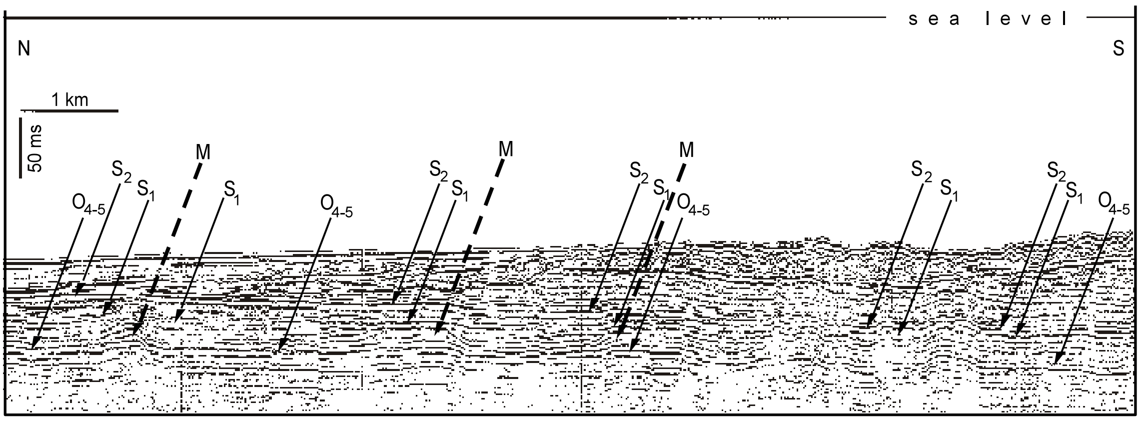

Fig. 5. Seismic profile 2004-5 from the central Baltic (for location see section B in Fig. 2) showing southerly thinning S_1–S_2 unit

M — Upper Ordovician carbonate buildups; other explanations as in Figure 4

gest trans-Baltic seismic reflector with erosional features in the lowermost part of the Silurian succession between Saaremaa and Gotland ($S_{2\ new}$ in Fig. 4). This is in a much better accordance with the adjacent mainland data in Estonia, where the boundary of the Raikküla and Adavere stages appears as a lithologically very sharp regional discontinuity of erosional origin (Einasto, 1986; Nestor, 1997). Therefore, in the present study the S_2 reflector marks the boundary between the Raikküla and Adavere stages (Fig. 3). So far we have not been able to correlate the reflectors just below and above it (the $S_{2\ old}$ and S_3 reflectors in Fig. 4) with any firmly fixed lithostratigraphic boundaries onshore.

THE SUBMARINE ORDOVICIAN-SILURIAN BOUNDARY LAYERS, SEISMIC REFLECTORS AND UNITS

The Ordovician-Silurian boundary beds discussed in this study are confined within two continuous seismic reflectors $O_{4–5}$ and S_2 (Figs. 3 and 4). According to the cores on Saaremaa, these layers include two regional stages both in the uppermost Ordovician (Pirgu and Porkuni) and the lowermost Silurian (Juuru and Raikküla) strata (Fig. 3). Below Gotland, however, the distribution of the coeval Ordovician-Silurian boundary units, due to the scarce core data, is poorly known. Still, the studies on chitinozoans have proved that the equivalents of the Pirgu, Porkuni and pre-Adavere (Juuru and Raikküla) strata show great thickness variations in the subsurface of Gotland (Nõlvak and Grahn, 1993; Grahn, 1995; Nõlvak and Grahn, unpubl. data).

THE AREA OF VISIBLE SEISMIC REFLECTORS O_{4-5}–S_1–S_2

Offshore, the northerly extension of the Pirgu Stage is limited by the outcropping O_{4-5} reflector (Fig. 6). The overlying pre- and post Raikküla units of the Silurian emerge successively further south, at the S_1 and S_2 reflectors, respectively. In the approximately N–S trending seismic profiles offshore from Saaremaa, up to the seismic line S9312 (Fig. 2), all three reflectors are simultaneously visible within a zone about ten kilometres wide just north of the Silurian Klint (Figs. 2 and 6). South of the klint crest, the Ordovician-Silurian transitional beds are obscured by shallow water multiples (e.g. in Fig. 4). From the profile S9312 (Fig. 2) westwards, Pleistocene glaciers have largely eroded the Silurian Klint and due to the increased water depth, the visibility of the seismic unit O_{4-5}–S_2 has in many profiles widened several tens of kilometres southwards (e.g. in Fig. 5). Furthermore, in the extensive glacier incisions offshore from Gotland, the seismic unit O_{4-5}–S_2 appears also in three north-east to south-west oriented profiles (1999-04, 2001-03 and 2001-04 in Fig. 2). Offshore from Saaremaa, where the glacier incisions are narrower and more limited to the south, this unit appears intermittently only in profile1999-04 (Fig. 2).

THE O_{4-5}– S_1 UNIT AND CARBONATE BUILDUPS

The configuration of the seismic reflectors, i.e. the number, position, undulation, tilt and so on, of the reflectors within the seismic unit O_{4-5}–S_1 is highly dependent on carbonate buildups (Flodén *et al*., 1994; Tuuling *et al*., 1995; Tuuling and Flodén, 2000*a*). Between Saaremaa and Gotland, the Upper Ordovician carbonate buildups are unequally distributed and differ clearly in measurements (Fig. 6), shapes and internal structures (Tuuling and Flodén, 2000*a*).

East of Gotska Sandön–Fårö, up to seismic line NB9504 (Fig. 2), the Upper Ordovician carbonate buildups appear abundantly already close to the northern limit of the O_{4-5}–S_1 unit (Fig. 6). The largest mound structures, more than 2 km in diameter, occur in a zone a few km wide, a little south of the O_{4-5} boundary (Fig. 6; see Tuuling and Flodén, 2000*a*, fig.2). As they usually have a steep basinward slope and separate fore and back reef environments, then these large mounds were interpreted as analogues to the modern barrier reef-like structures. Southwards, down-slope in the ancient Ordovician basin, the number and diameter of the mound structures gradually decrease and instead of flat shallow water patch reefs, conical or pinnacle reefs often appear in the seismic lines (see Tuuling and Flodén, 2000*a*, figs. 9, 10, 11).

As a whole, this mound-rich zone offshore from northeastern Gotland embraces an irregular area, about 60 km long and 50 km wide (Fig. 6). As the carbonate mounds have been traced extensively both on northern Gotland and Fårö and offshore from them (see Flodén, 1980, figs. 49, 50; unpubl. OPAB Well Completion Reports from 1972–1981), then westwards this reef-rich zone obviously extends beyond the currently discussed area.

East of the seismic line NB9504 (Fig. 2), the barrier reef-like structure and thus also the facies zonation is abruptly terminated (see Tuuling and Flodén, 2000*a*, fig. 2) and the submarine area of the outcropping O_{4-5}–S_1 unit is largely void of

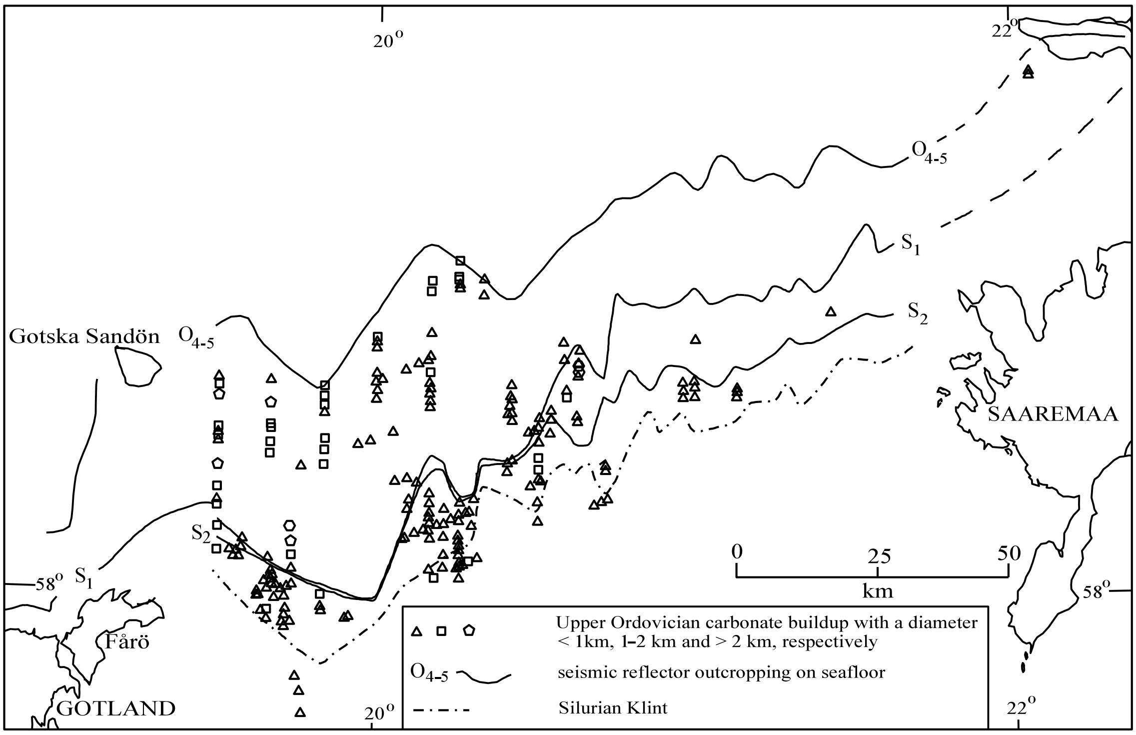

Fig. 6. The outcropping Ordovician-Silurian boundary beds (for stratigraphic positions of reflectors see Fig. 3) and distribution of Upper Ordovician carbonate buildups between Hiiumaa–Saaremaa and Gotland–Gotska Sandön

reef-like structures (Fig. 6). Still, up to seismic line S9312 (Fig. 2) the coeval mound-like structures, mostly several hundred metres in width, appear copiously further south below the Silurian rocks (Fig. 6). From the latter profile eastwards, the Upper Ordovician carbonate buildups occur as rare solitary structures, except for two small swarms along the profiles S9309 and S9307 (Figs. 2 and 6).

OCCASIONAL REFLECTORS AND THE BOUNDARY OF THE PIRGU AND PORKUNI STAGES WITHIN THE O_{4-5}–S_1 UNIT OFFSHORE FROM GOTLAND

Due to the lithologically and structurally highly variable reef environment, the O_{4-5}–S_1 unit offshore from Gotland is characterized by a strongly irregular bedding configuration. Nonetheless, two strong and occasional reflectors, or_1 and or_2 were traced inside this unit (Tuuling and Flodén, 2000). The more consistent or_1 reflector obviously delineates a lithologically different unit in the lowermost part of the Pirgu Stage. The or_2 reflector, a little higher up in the section, was distinguished as an occasional erosional surface, which in the mound-rich area delineates the channel-like depressions between the mounds (Tuuling and Flodén, 2000*a*). Neither or_1 nor or_2 were at that time correlated with any known stratigraphic boundaries onshore. However, recent onshore data point towards a widespread erosional boundary and channelling between the Pirgu and Porkuni stages east of the Baltic (Ainsaar, 1995; Perens, 1995; Nõlvak, 1997; Harris *et al.*, 2004; Hints *et al.*, 2005). This has evoked us to interpret the erosional or_2 reflector as the analogous boundary offshore from Gotland.

Furthermore, we assume that the lowermost, abruptly southwards deepening erosional surface around the southern border of the mound-rich area, present in some profiles offshore from Gotland (Figs. 2 and 6), most likely marks the boundary of the Pirgu and Porkuni stages (or_2 in Figs.7–9). This surface was previously always considered as the Ordovician-Silurian boundary reflector S_1 (see Tuuling and Flodén, 2000*a*, figs. 10, 14). The erosional Ordovician-Silurian boundary, however, is less pronounced and appears a little higher up in the section and often intertwines with the S_2 reflector (Figs. 7–9). Onshore, similar erosional incisions along the boundary of the Pirgu and Porkuni stages and an increased thickness of the Porkuni layer are evident in many places in Central-Southern Estonia (Hints and Meidla, 1997*b*; Harris *et al.*, 2004; Hints *et al.*, 2005) and according to rare core data (Nõlvak and Grahn, unpubl. data) also in northern-central Gotland. In the best examples offshore, namely in the two neighbouring profiles NB9003 and NB9002 (Fig. 2), the steeply southwards deepening erosional boundary of the Pirgu and Porkuni stages cuts some 25–30 m into the O_{4-5}–S_1 unit over a distance of 2–3 km (Figs. 7 and 9).

THE ORDOVICIAN-SILURIAN BOUNDARY REFLECTOR S_1

Based on the strength, steadiness and erosional features of the Ordovician-Silurian boundary reflector S_1, as well as on its relation to under- and overlying or_2 and S_2 reflectors, three separate sections can be distinguished between Saaremaa and Gotland. Firstly, in the area offshore from Saaremaa up to the seismic line NB9312 (Fig. 2), there is a strong and consistent Ordovician-Silurian boundary reflector without distinct erosional features (Fig. 4). Secondly, in the area between the seismic lines S9312 and S9314 (Fig. 2), the S_1 reflector is weaker, and in places indistinguishable. The truncation and levelling of sedimentary structures along the S_1 reflector (see Flodén *et al.*, 1994, fig. 6D) point for the first time towards an erosional origin of this boundary.

Due to the intricate reflector configuration and the erosional features, the Ordovician-Silurian boundary identification offshore from Gotland is difficult. The erosional surfaces offshore Gotland are widespread, more varied and pronounced, appearing distinctly at three different levels (or_2, S_1 and S_2). The highly varying (diminished/increased) thicknesses of the Ordovician-Silurian boundary units and the occasional outwedging of the pre-Adavere portion of Silurian (S_1–S_2) and Porkuni

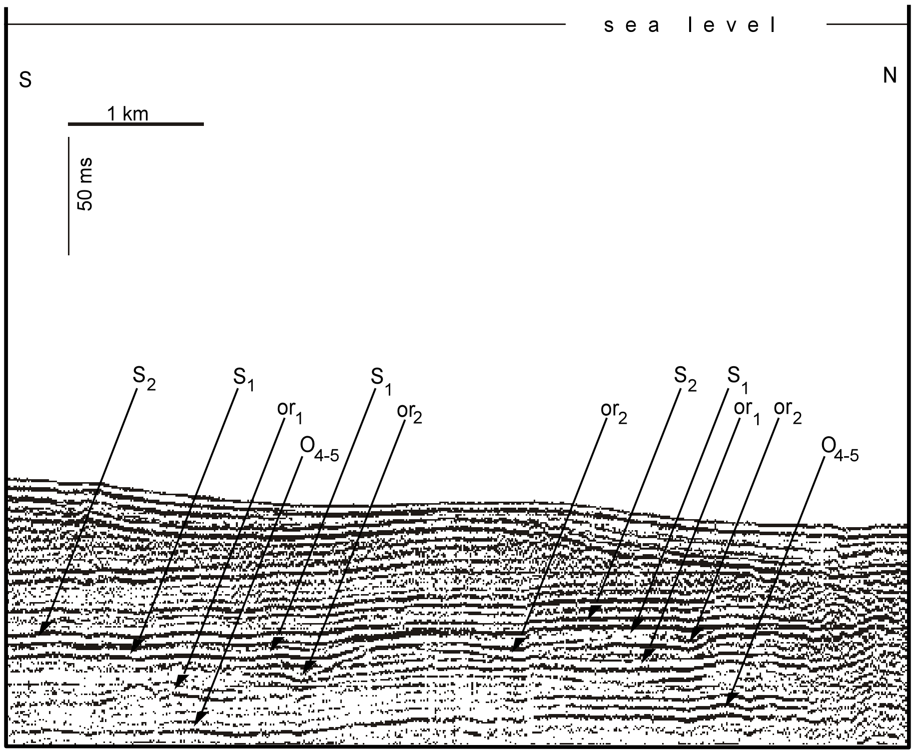

Fig. 7. Seismic profile NB9002 offshore from Gotland (for location see section C in Fig. 2), showing interlacing erosional reflectors or_2, S_1 and S_2

Explanations as in Figure 4

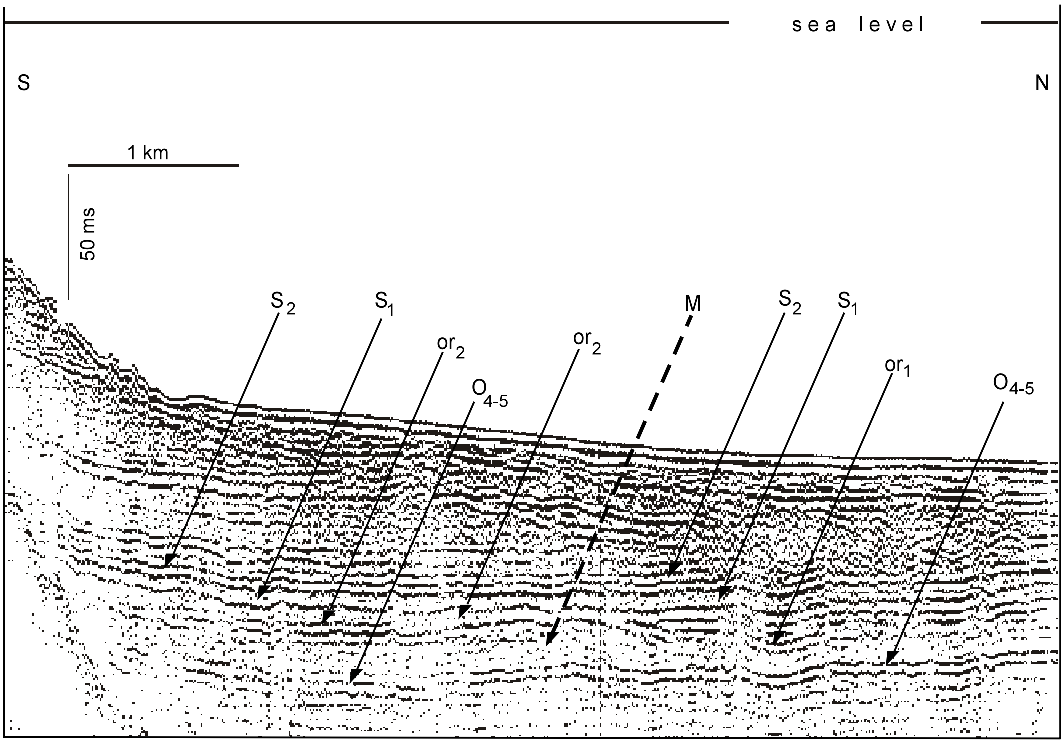

Fig. 8. Seismic profile NB9001 offshore from Gotland (for location see section D in Fig. 2), showing erosional incision along the or_2 reflector

Explanations as in Figure 5

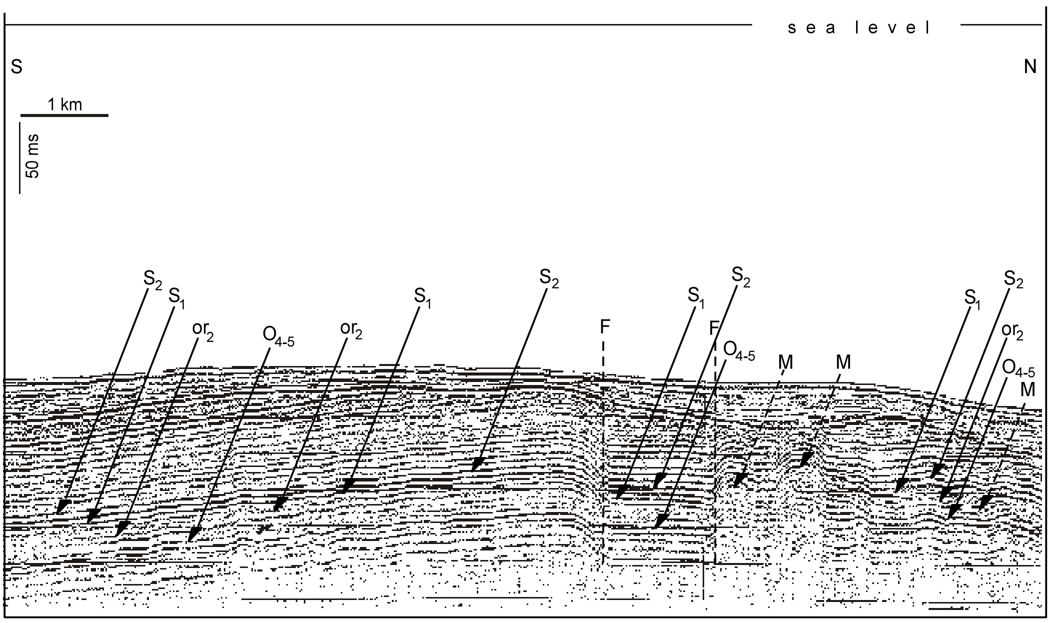

Fig. 9. Seismic profile NB9003 offshore from Gotland (for location see section E in Fig. 2), showing erosional incision along the or_2 reflector and thickness changes of the Ordovician-Silurian transitional beds around the carbonate mounds (M)

F — faults; other explanations as in Figure 5

Stage (or_2–S_1) have brought about interlacing of all three erosional reflectors, thus complicating their identification.

A striking example with closely spaced and intertwining erosional S_2, S_1 and or_2 reflectors occurs along profile NB9002 (Fig. 7). The lowermost or_2 reflector is distinguished from the S_1 one only inside a pre-Porkuni erosional channel inside the Pirgu Stage. The S_1 reflector is indistinguishable from the S_2 one in the northern part of the section, almost merges with the or_2 reflector

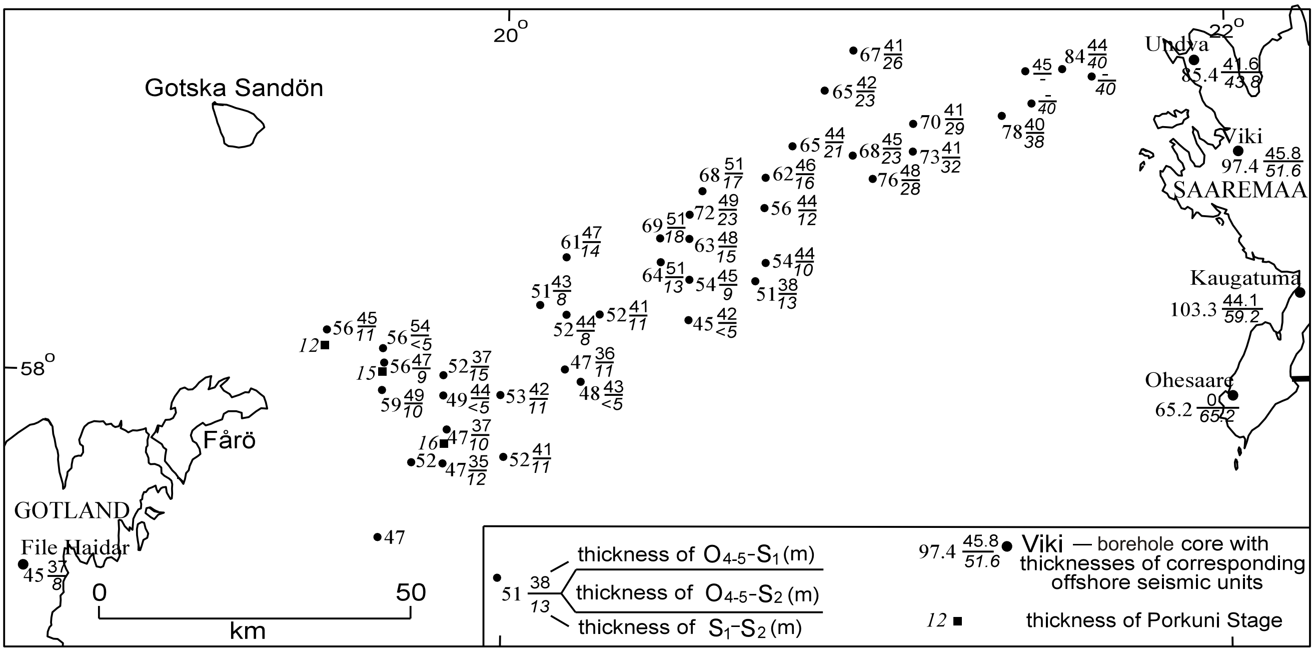

Fig. 10. Estimated thickness values of the seismic units $O_{4–5}$–S_2, $O_{4–5}$–S_1 and S_1–S_2 between Saaremaa and Gotland

in the middle of the section, then, running separately over the pre-Porkuni channel, coincides again with the or_2 reflector on the southern side of the channel (Fig. 7).

TENTATIVE THICKNESS VALUES OF THE SEISMIC UNITS

The trans-Baltic seismic units $O_{4–5}$–S_1 and S_1–S_2 provide an opportunity to assess the thicknesses of the lowermost Silurian and uppermost Ordovician layers between Saaremaa and Gotland. Since thickness calculation of a seismic unit is highly dependent on the accuracy of interpretation and the seismic wave velocities used, the numbers presented (Fig. 10) should be taken as estimates. As the position of the Ordovician-Silurian boundary reflector S_1 offshore Gotland is often ambiguous, the thickness values for the subunits $O_{4–5}$–S_1 and S_1–S_2 are more tentative than the thickness of the entire Ordovician-Silurian boundary unit $O_{4–5}$–S_2.

THE $O_{4–5}$–S_1 UNIT (PIRGU AND PORKUNI STAGES)

The thickness of the $O_{4–5}$–S_1 unit between Saaremaa and Gotland reveals no unequivocal trans-Baltic trends (Fig. 10). Offshore Saaremaa, close to the Silurian Klint, this unit is everywhere about 40 m thick. Offshore Gotland, however, its value is influenced by the carbonate mounds and erosional features. It varies between 35 and 55 m there. The maximum thicknesses are connected with the large, often outsculptured by erosion, mound structures and the minimum values occur between the mounds (Fig. 9). In the middle of the Baltic, thickness values between the 40–50 m prevail. Due to the limited visibility it is hard to decide about any northsoutherly submarine thickness trends in the $O_{4–5}$–S_1 unit, although slight southerly thicknesses decrease is perceptible offshore Gotland (Fig. 10).

THE S_1–S_2 UNIT (PRE-ADAVERE SILURIAN PORTION)

The greatest thicknesses of the S_1–S_2 unit, about 40 m, occurs just offshore from Saaremaa (Fig. 10). Further south-west along the Silurian Klint, a slightly decreased thickness of this unit occurs. Midway through the Baltic, in the area void of obscuring shallow water multiples, a southerly thickness reduction appears in this unit. Between the profiles S9312 and 2004-2 (Fig. 2) the S_1 and S_2 reflectors are indistinguishable along many approximately N–S trending lines and the thickness of the unit approaches to zero (e.g. 2004-5 in Fig. 5). Offshore from Gotland north-east, the pre-Adavere Silurian portion is normally about 10–15 m thick. However, it can wedge out above the large carbonate mounds (Fig. 9).

THE $O_{4–5}$–S_2 UNIT (ORDOVICIAN-SILURIAN BOUNDARY BEDS)

The maximum thickness of the $O_{4–5}$–S_2 unit (>80 m) occurs just offshore from Saaremaa. The minimum values, about 45–50 m, appear in many places within the western half of the area investigated (Fig. 10). There occurs a slight southwesterly and southerly thickness diminution of this unit offshore from Saaremaa and from Gotland, respectively. In general, the thickness changes in this unit are mainly dependent on the thickness alternations in the pre-Adavere Silurian portion (S_1–S_2 unit).

THE THICKNESS OF THE PORKUNI STAGE (or_2–S_1 UNIT)

The Porkuni Stage is indistinguishable in most of the seismic lines due to its negligible thickness or lack of equivalent layers between Saaremaa and Gotland. The unit is identified only in the erosional cuts along the occasional or_2 reflector offshore from Gotland. Values of 12–16 m (Fig. 10) are in good accordance with the core sections (Puikule, Holdre, Ruhnu *etc.*) from Southern Estonia and Northern Latvia. Here, in the transitional belt between the Estonian Shelf and the Livonian Tongue (Fig. 1) the thickness of Porkuni Stage varies around 14–18 m (see Hints and Meidla, 1997*b*, figs. 61, 62).

COMPARISION BETWEEN OFF- AND ONSHORE THICKNESSES AND TRENDS

UPPERMOST ORDOVICIAN

The thickness of the O_{4-5}–S_1 unit offshore from northwestern Saaremaa (40–45 m) matches well with its values in the nearest Emmaste 49.8 m, Undva 41.6 m and Viki 45.8 cores onshore (Figs. 2 and 10). A striking thickness change onshore occurs in southwestern Saaremaa. The 44.1 m thick O_{4-5}–S_1 unit, mainly of Pirgu age (41.4 m) in the Kaugatuma core vanishes entirely in the Ohessaare core some 20 km southwards (Fig. 10; Hints and Meidla, 1977*a*, *b*). The Porkuni and Pirgu rocks, respectively 2.5 and 7.7 m in thickness, appear again in the Kolka core in Northern Latvia (Kaljo *et al*., 1988; Fig. 2). The thickness of the layers increases towards Southern Latvia. Due to the shallow-water multiples we were not able to assess the thickness of the O_{4-5}–S_1 unit along the western coast offshore from Saaremaa.

On Gotland, the thickness of the O_{4-5}–S_1 unit is available only from the File Haidar (37 m) and Grötlingbo (16.7 m) cores (Nõlvak and Grahn, unpubl. data), located in the northern and southern part of island, respectively (Fig. 2). In the File Haidar core, the entire O_{4-5}–S_1 unit (37 m) corresponds to the lower half of the Pirgu Stage. In the Grötlingbo core, the uppermost 6.7 m from this unit corresponds to the Porkuni strata, whereas the remaining 10 m is correlated with the from the lowermost part of the Pirgu Stage (Nõlvak and Grahn, unpubl. data). Thus, on Gotland this unit reveals considerable inconsistency both in stratigraphy and in thicknesses.

The closest thickness data of the O_{4-5}–S_1 unit offshore north-east of Gotland (about 35–45 m) matches well with the value in the File Haidar core (Fig. 10). However, offshore, in the erosional cut(s) along the or_2 reflector, this unit obviously includes also some 12–15 m of Porkuni strata (Fig. 10), which onshore were identified only further south in the Grötlingbo core (Fig. 2). This fact points towards a highly irregular occurrence and unpredictable thickness of the Porkuni strata around Gotland, which is obviously due to the combination of three erosional events. The erosion at the Ordovician-Silurian boundary and obviously also at the boundary of the Raikküla and Adavere stages have reduced the thickness of the Porkuni strata around Gotland. However, the erosional incisions along the Pirgu and Porkuni stages, which first got infilled with the Porkuni strata and protected these layers from the later erosions, represent the thickest parts of this unit.

Although the thickness of the O_{4-5}–S_1 unit varies locally both on the Estonian mainland and in the submarine area, regionally it undergoes a slight reduction in thickness southwestwards. This is clear onshore, where the Pirgu and Porkuni stages both have a slightly decreased thickness on southwestern Saaremaa compared to that in Central Estonia (Hints and Meidla, 1997*a*, *b*). The thickness variation of the O_{4-5}–S_1 unit offshore from Gotland is obviously due to the numerous carbonate buildups (Figs. 6 and 9), which is well known (40–65 m) also from Central-Southern Estonia (Hints and Meidla, 1997*a*).

LOWERMOST SILURIAN

The about 40 m-thick S_1–S_2 unit offshore from northwestern Saaremaa is in good agreement with the total thickness of the Juuru and Raikküla stages in the nearest onshore borehole core (Undva 43.8 m; Fig.10). On Saaremaa, the total thickness of these stages gradually increases southwards, being 51.6, 59.2 and 65.2 m in the Viki, Kaugatuma and Ohessaare borehole cores (Fig. 10), respectively. However, the first N–S thickness trend of this unit offshore from Saaremaa, first visible midway through the Baltic, reveals in, opposition to the mainland, a southerly thinning of the S_1–S_2 unit.

The rarely observed thickness values of the S_1–S_2 unit from Gotland (Grahn, 1995) show a southwards thinning trend in the northern part of the island, but a southwards thickening trend in the southern part. Namely, in the File Haidar core (Fig. 2) the thickness of pre-Adavere Silurian unit is about 8 m, in central and southern Gotland, in the Rosendal and När cores respectively (Fig. 2), the corresponding values are 0 and 17 m (Grahn, 1995).

In an east-west direction, a slight thickness reduction of the S_1–S_2 unit is traced on the Estonian mainland (Nestor, 1997). This reduction continues offshore from Saaremaa. Midway through the Baltic this trend disappears, as varying thickness values of this unit offshore from Gotland reveal no clear trends in thickness changes.

DISCUSSION AND CONCLUSIONS

HIATUSES IN THE ORDOVICIAN-SILURIAN BOUNDARY SEQUENCES AROUND GOTLAND

Since the discovery of the discontinuous Ordovician-Silurian boundary in the File Haidar core below Gotland (Thorslund and Westergård, 1938), the stratigraphic span of the missing Ordovician-Silurian boundary beds around Gotland has been a subject of heated discussion (Martinsson, 1967, 1968; Thorslund, 1968). Due to the scarce data, the nature of this hiatus has been treated very cautiously. According to Männil (1966), the reduced influx of sediments, or even non-deposition around Gotland since Pirgu time, was caused by a progressive uplift and shallowing of the Gotland Elevation. He sketched a large land area just north of Gotland by the end of the Ordovician (see fig. 68 in Männil, 1966); however, he never included Gotland in this area, and neither mentioned erosion to explain the Ordovician-Silurian boundary hiatus below Gotland. Although Thorslund (1968) did not exclude the possibility that Gotland was a mainland resembling to Northern Estonia at the Ordovician-Silurian transition, he avoided the term "erosion" due to the lack of clear evidence.

The seismic data support the rare onshore data from chitinozoans (Nõlvak and Grahn, 1993, unpubl. data; Grahn, 1995), both showing that the completeness of the Ordovician-Silurian boundary beds around Gotland is dependent on three hiatuses with considerably varying time spans. The seismic recordings have furthermore revealed distinct evidence of erosion along all three discontinuity surfaces, which according to the latest data from Estonia (Harris *et al*., 2004, 2005) are largely of submarine origin. Thus, the extent of the eroded rocks at the boundaries of the Pirgu and Porkuni stages (or_2), Ordovician and Silurian systems (S_1) and Raikküla and Adavere stages (S_2) determine the stratigraphy and thickness of the O_{4-5}–S_2 unit around Gotland. The distribution, the vertical extent and the locations of maximum erosion at these boundaries are laterally highly variable. As a result, the younger erosional surfaces higher up in the section can reach the older ones underneath, and thus the thickness and stratigraphy of the Ordovician-Silurian transitional beds around Gotland can change considerably across short distances.

HIATUSES IN THE ORDOVICIAN-SILURIAN BOUNDARY SEQUENCES IN ESTONIA AND NORTHERN LATVIA

All the discontinuities discussed above, with notable hiatuses, are also well known in Estonia (Einasto, 1986; Kaljo *et al*., 1988; Nestor, 1997; Nõlvak, 1997; Harris *et al*., 2004, 2005; Hints *et al*., 2005). They definitely reflect widely spread stratigraphic gaps along the Estonian Shelf to the Livonian Tongue transect (Fig. 1). The erosional nature of these hiatuses in Estonia, either subaerial or submarine in origin, has been established by many authors (Ainsaar, 1995; Perens, 1995; Nestor, 1997; Harris *et al*., 2004, 2005; Hints *et al*., 2005).

Subaerial erosion was induced by two rapid sea level falls during the Hirnantian Glaciation in the latest Ordovician (Brenchley *et al*., 2003), which in the Baltic Basin exposed the large shallow shelf and slope areas and produced unconformities that bracket Porkuni strata on the shelf (Harris *et al*., 2004). In both cases, extensive channelling developed at the shelf-slope transition (Ainsaar, 1995; Perens, 1995). The shelf areas of the Baltic Basin were probably also exposed at the transition between Raikküla and Adavere times, which in Estonia is marked by an extensive, northwesterly increasing erosional hiatus (Nestor, 1997).

The structural setting, the shelf and deep-basin edge location along the flank of the Livonian Tongue favoured submarine erosion and slumping of muddy sediments at the boundary of the Pirgu and Porkuni stages (Harris *et al*., 2004). This structural background and thus similar submarine erosional processes probably characterizes also the Ordovician-Silurian boundary. As will be discussed below, submarine slope processes on the shelf deep-basin transect most likely played an important role also in the formation of the erosional disconformity at the boundary of the Raikküla and Adavere stages.

COMPARISON OF EROSIONAL SURFACES AND TRENDS BETWEEN ESTONIA AND GOTLAND

The style and amount of erosion at the boundary of the Pirgu and Porkuni stages around northern Gotland differs considerably from that of the Estonian Shelf, being more similar to the erosional features revealed between the Estonian Shelf and Livonian Tongue transect in Central-Southern Estonia and Northern Latvia (Fig. 1). First, the channel-like incisions in the Pirgu strata between the carbonate mounds are well documented features both offshore from northern Gotland (Tuuling *et al*., 1995; Tuuling and Flodén, 2000) and in Central-Southern Estonia (Ainsaar, 1995; Perens, 1995; Hints *et al*., 2005). Secondly, a zone of abruptly southwards reducing thicknesses in the Pirgu strata that occurs around the Estonian and Latvian border (see Hints and Meidla, 1997*a*, fig. 58; Harris *et al*., 2004) is also established in the seismic lines and borehole cores around northern Gotland.

The channelling and slightly southerly increasing erosional cut along the Ordovician-Silurian boundary are common features on- and offshore Gotland and in Estonia (Perens, 1995; Hints and Meidla, 1997*b*; Nõlvak, 1997; Harris *et al*., 2004). The area of maximum erosion along the Ordovician-Silurian boundary more or less coincides with the abrupt erosional cut along the Pirgu and Porkuni stages both in Estonia (see Hints and Meidla, 1997*b*, fig. 61) and around Gotland. The missing Porkuni rocks in some borehole cores in Southern Estonia (see Hints and Meidla, 1997*b*, fig. 61) and in the File Haidar core on Gotland corroborate the seismic data, showing that in places the erosional cut along the Ordovician-Silurian boundary can reach the underlying erosional boundary of the Pirgu and Porkuni stages.

Thus, the changes in the O_{4-5}–S_1 interval in the area between northwestern Saaremaa and northern Gotland are similar to a north-south gradient that appears in the same interval in the Estonian mainland. This suggests that they have been caused by the common structural and facies changes in the Baltic Basin. The slightly varying thickness and constant internal structure of this unit, typical of a shallow shelf setting, stretches from Northern-Central Estonia across southern Hiiumaa/northern Saaremaa and continues offshore up to midway between Saaremaa and Gotland. Considerable thickness variations, numerous carbonate mounds, the channel-like incisions and southwards dipping surfaces of erosional origin in the O_{4-5}–S_1 unit are typical features for the transitional belt (Fig. 1). West of Estonia, the latter features appear only faintly midway between Saaremaa and Gotland, and gradually get stronger towards Gotland.

The erosional cuts at the boundary of the Raikküla and Adavere stages around northern Gotland and east of the Baltic show opposite trends. In Estonia, the amount of the missing Raikküla Stage, and thus the erosional cut along its upper boundary, diminish southeastwards (see Nestor, 1997, fig. 66 and table 8). Offshore from northeastern Gotland, however, the S_1–S_2 unit wedges out southwards along the erosional S_2 reflector in many seismic profiles (Figs. 5 and 10). The southerly reducing thickness of this unit appears also in the northern half of Gotland. The 8 m thick S_1–S_2 unit in the File Haidar core is entirely missing in the Rosendal core (Fig. 2; Grahn, 1995). However, the 17 m-thick S_1–S_2 unit in the När core further south (Fig. 2; Grahn, 1995) proves that on southern Gotland this unit has a southerly increasing thickness as in Estonia.

Based on these trends we may assume that a wide, north-east to south-west oriented valley-like erosional incision once extended along the boundary of the Raikküla and Adavere stages across the Baltic. The valley connected the areas north of the presently outcropping Raikküla rocks in Estonia with central Gotland. In Estonia, only the southeastern slope of this incision has been preserved. Its northwestern slope with the south to southeasterly reducing thickness of the S_1–S_2 unit has probably been removed by pre-Devonian and modern erosional events.

Thus, the analogous erosional patterns and features in Central-Southern Estonia and around Gotland at the end of the Ordovician period are mostly due to the fact that both of these areas were structurally placed at the shallow shelf to deep basinal transect. This distally steepening slope area was liable to submarine slumping of muddy sediments and subaerial channelling during the abrupt sea level falls.

In the Early Silurian, the progressing Caledonian Orogeny and tectonic movements on the southern slope of the Baltic Shield gradually rearranged the bottom morphology of the Baltic Basin between Estonia and Gotland. Due to the general subsidence of the areas south/south-west of Estonia, the deep-water central depression of the Baltic Basin, namely the Livonian Tongue, became most accentuated at the transition of the Raikküla and Adavere times (Nestor, 1990). West of Estonia, subsidence of the Baltic Basin was probably also induced by an active deep crustal structure, the Bothnian-Baltic mobile zone (Puura and Flodén, 1997), which has influenced the palaeogeography in Baltoscandia repeatedly since the Middle Proterozoic (Tuuling and Flodén, 2000*b*). These events also involved the areas around Gotland and the eastwesterly oriented facies belts between Estonia and Gotland, typical during the Ordovician, gradually assumed a north-west to south-east orientation in Early Silurian (see Basset *et al*., 1989, fig. 119).

This new structural setting, however, may be a clue towards explaining the north-east to south-west directed erosional incision, described above, at the boundary of the Raikküla and Adavere stages, as well as towards understanding the nature of the missing Llandovery rocks around Gotland. This incision, that crosses the facies belts, may reflect a large submarine erosional channel, which formed on a steep shelf to deep-basin transect. Along this channel, the instable muddy slope sediments were, during the Early Silurian, repeatedly transported to deeper parts of the Baltic Basin. As the stratigraphic gap in the Llandovery rocks around Gotland includes also the lowermost part of the Adavere Stage (Grahn, 1995), these submarine slope processes must have still been active during Adavere time. The latter fact is also supported by the seismic data. The clear thickness reduction in the seismic unit overlying the S_1–S_2 unit appears in the seismic lines east of Gotland (Tuuling and Flodén, 2006).

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