since 1961

Baltica

BALTICA Volume 27 Number 1 June 2014 : 1–14
doi: 10.5200/baltica.2014.27.01

New data on the palaeo-incisions network of the south-eastern Baltic Sea

Dmitrij Gerok, Leonora Živilė Gelumbauskaitė, Tom Flodén, Algimantas Grigelis, Albertas Bitinas

Gerok, D., Gelumbauskaitė, L. Ž., Flodén, T., Grigelis, A., Bitinas, A., 2014. New data on the palaeo-incisions network of the south-eastern Baltic Sea. *Baltica, 27 (1), 1–14.* Vilnius. EISSN 1648-858X.

Manuscript submitted 2 February 2014 / Accepted 22 May 2014 / Published online 9 June 2014.
© Baltica 2014

Abstract The present study area is located within the south-eastern segment of the Baltic Sea framed by 55°30’–56°30’ N and 19°00’–21°15’E. The area is re-visited with the aim to describe in more detail the geologic prerequisite for development of the palaeo-incisions as well as the timing of their subsequent infillings. The channels form distinctive features in the sedimentary bedrock along the outer limits of pre-Weichselian ice sheets, on average reaching depths into the bedrock of 50 m in the nearshore zone of Lithuania to 100 m along the slope to the Gotland depression in the west. The development of palaeo-incisions system is governed by the easily eroded late Palaeozoic to Mesozoic bedrock of the present area. Only rare occurrences of channels have been reported from the middle and lower parts of the Palaeozoic further west in the Baltic. The present investigation supports a mechanism that the channels formed below the ice near the ice sheet margin by melt water erosion under high pressure. The channels start at random where a fracture in the ice develops forming outlet of water contained below the central part of the ice sheet. The channels often merge together in the direction of the ice margin, possibly gradually adapting to previous fracture systems in the bedrock. The investigated incisions were infilled prior to the advance of the Weichselian ice sheet and some have been reopened and repeatedly infilled.

Keywords *• seismoacoustic survey • seismostratigraphy • pre-Quaternary topography • palaeo-incisions network • Late Palaeozoic bedrock • Mesozoic bedrock • south-eastern Baltic Sea*

✉ *Dmitrij Gerok (dgerok@gmail.com), Albertas Bitinas, Klaipėda University, Herkaus Manto Str. 84, Klaipėda, Lithuania; Leonora Živilė Gelumbauskaitė (leonora@geo.lt), Algimantas Grigelis, Nature Research Centre, Akademijos Str. 2, Vilnius, Lithuania; Tom Flodén (tom@geo.su.se), Stockholm University, Stockholm, Sweden*

INTRODUCTION

This paper presents new details on the palaeo-incision network of the south-eastern Baltic Sea. The initial analog soundings in the area, performed in 1993–1995, were subsequently interpreted and published. These soundings, as well as a dense net of soundings performed in 1998–1999, form the basis of the present investigation. The use of modern digital techniques have greatly improved the quality of both data sets.

The present day topography of the investigated area, looking westwards from the Lithuanian nearshore zone, is subdivided into the submarine Curonian Plateau, the northern part of the Gdansk Depression with the gentle Klaipėda Slope to the north, the Klaipėda–Ventspils Plateau with the shallow Klaipėda Bank area, and the eastern slope of the Gotland Depression (Fig. 1). In general, palaeo-incisions are present within a wide zone, the outer limit of which coincides with the extensions of the Pleistocene ice sheets. The palaeo-incisions are generally infilled with till and glaciofluvial sediments of the respective ice stages, i.e. prior to the advance of the Weichselian ice sheet. In some areas, e.g. in Lithuania, Latvia and Denmark, they occur in a pattern that may indicate a relationship to river valleys or fracture systems in the pre-glacial bedrock.

Different opinions have been put forward with re-

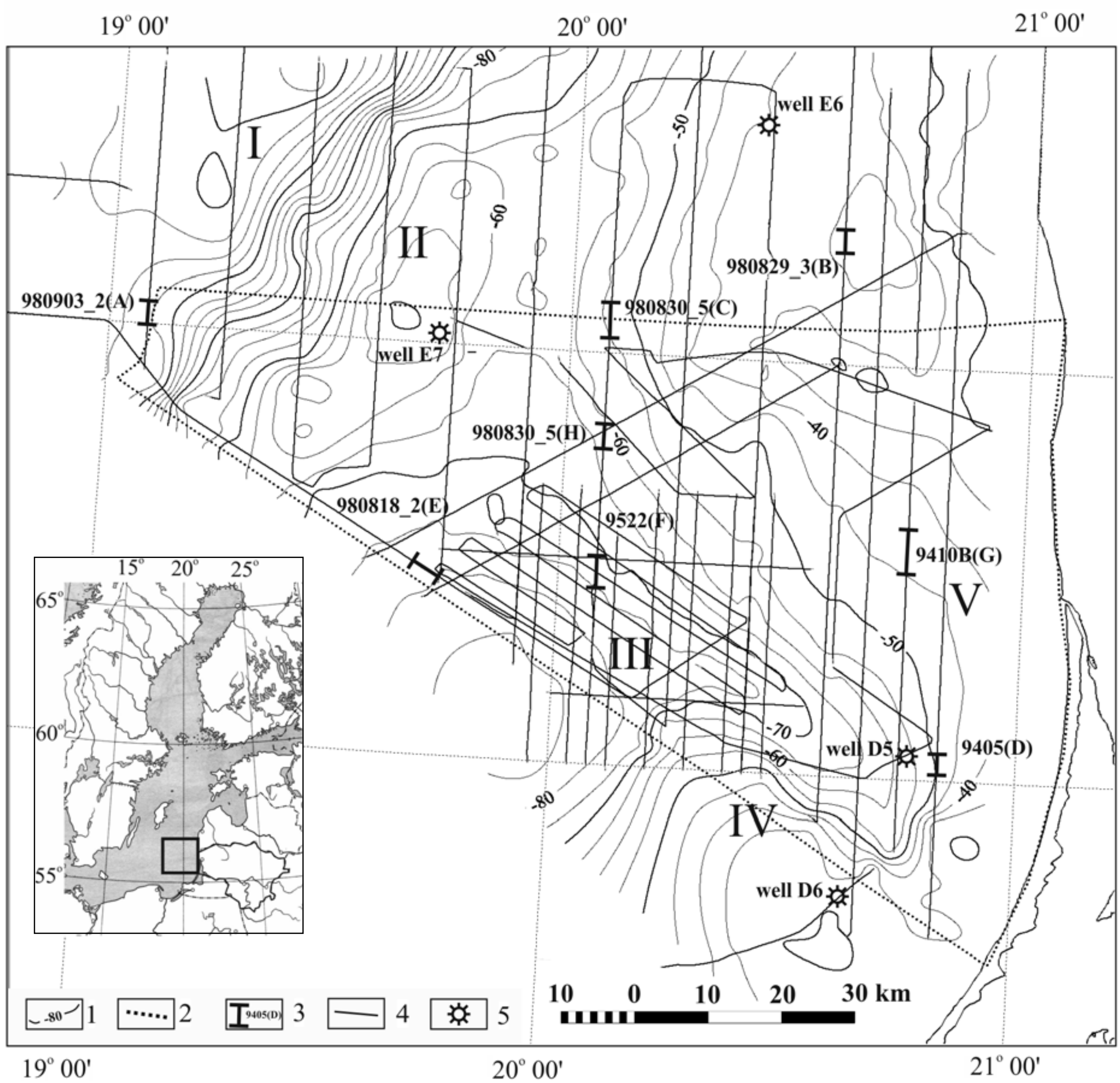

Fig. 1 Location map: 1 – contour intervals at 5 m depth are drawn after seismoacoustic data; 2 – Lithuanian Sea border; 3 – fragments of seismic lines (see Fig. 5); 4 – seismic lines; 5 – wells. Morphology: I – eastern slope of Gotland Depression; II – Klaipėda–Ventspils Plateau (Klaipėda Bank and Liepaja Bank); III – northern part of Gdansk Depression and it Klaipėda Slope; IV – Curonian Plateau; V – near shore zone.

gard to the genesis of palaeo-incisions in the sub-Quaternary surface. Numerous studies favour an idea of a complex stepwise periglacial, subglacial-glaciofluvial, postglacial-fluvial origin of the palaeo-incisions that were then even further reshaped by the next generation of Pleistocene glaciers (Timofeev *et al.* 1974; Gaigalas 1976; Sviridov *et al.* 1976; Gudelis *et al.* 1977; Blazhchishin *et al.* 1982; Tavast, Raukas 1982; Eberhards, Miidel 1984; Sviridov 1984; Veinberga *et al.* 1986; Rozhdestvensky 1989; Repečka 1991; A. Šliaupa *et al.* 1995; Savvaitov *et al.* 1999). Initially it was noted that the zones with fragments of incisions extend clearly in the NE–SW direction, responding to the distribution of the soft sedimentary rocks of the Triassic, Jurassic and Cretaceous geological systems, respectively (Sviridov 1984, 1991). Later on, an idea was expressed on possible links between glacial-subglacial incisions and fossil cryogenic structures in the Mesozoic bedrock of the south-eastern Baltic Sea (Monkevičius 1999).

Other authors have put forward a subglacial or more precisely a subglacial-fluvioglacial hypotheses based on a mechanism that the channels were formed below the ice near its margin by melt water erosion under high pressure (Kuster, Meyer 1979; Ehlers *et al.* 1984; Wingfield 1989; Bjerkeus *et al.* 1994; Flodén *et al.* 1997; Bitinas 1999; Jurgens 1999). The original hypothesis of palaeo-incisions as channels formed beneath the ice sheets by melt water erosion under high pressure was developed by Boulton and Hidmarsh (1987). The hypothesis has since then been widely discussed (Boulton 1996).

The present data, that originate from seismo-acoustic investigations in the south-eastern segment of the Central Baltic Sea, show that the palaeo-incisions here are imprinted into the Neogene peneplain surface. They are weakly expressed as compared to the palaeo-incisions in the subsurface of the Middle Devonian terrigenous rocks along the eastern slope of the Gotland depression (Bjerkéus *et al.* 1994; Gelumbauskaitė, 1996; Flodén *et al.* 1997). Their connection to the fragmented system of late- to post-glacial channels in the Late Quaternary sequence of the study area is not yet clear. Neither is the inheritance of the palaeo-incision from the Pra-Nemunas River. The Neogene Pra-Nemunas stream was first noted in 1961 and studied in more detail in 1977 (Gudelis 1961; Gudelis *et al.* 1977). Otherwise, geophysical surveys in the central western part of the Baltic Sea, e.g. in the Hanö Bay, have not revealed any similar structures which strongly indicates that the valleys are truly of a general periglacial origin sculptured during major standstills of ice sheets (Flodén *et al.* 1997).

GEOLOGICAL SETTING

The seismostratigraphic framework

The sedimentary bedrock of the investigated area ranges from Middle Devonian to Late Cretaceous (Table 1 and Fig. 2). Simple geological schemes of the pre-Quaternary rocks of the Central Baltic Sea (CBS) were set in the mid 1960's tracing merely the boundaries of the geological systems seawards from the East Baltic mainland and from Scandinavia (Gudelis 1970).

Later on, in the last decades of 20th century, the knowledge of the bedrock geology of the CBS increased significantly through deep seismic survey, hydrocarbon prospective drilling and tectonic analyses ranging over an internal structure of entrails. Studies of marine drilling cores using mainly micropalaeontological methods allowed the exploration of the pre-Quaternary stratigraphic sequence in the eastern segment of the CBS (Grigelis 1995).

Moreover, continuous seismic profiling (CSP) data (close to 8,500 km of profiles) shot during Lithuanian-Swedish marine geological–geophysical expeditions in 1993–1995 provided a reliable source for detailed investigations of the upper parts of the sub-Quaternary bedrock of CBS (Grigelis 1999). An idea was developed about the presence of sub-Permian and sub-Quaternary peneplains in the south-eastern Baltic Sea. This facilitated the construction of a modern geological map (Grigelis 1995). The next step was to establish the seismo-stratigraphic units and boundaries of the

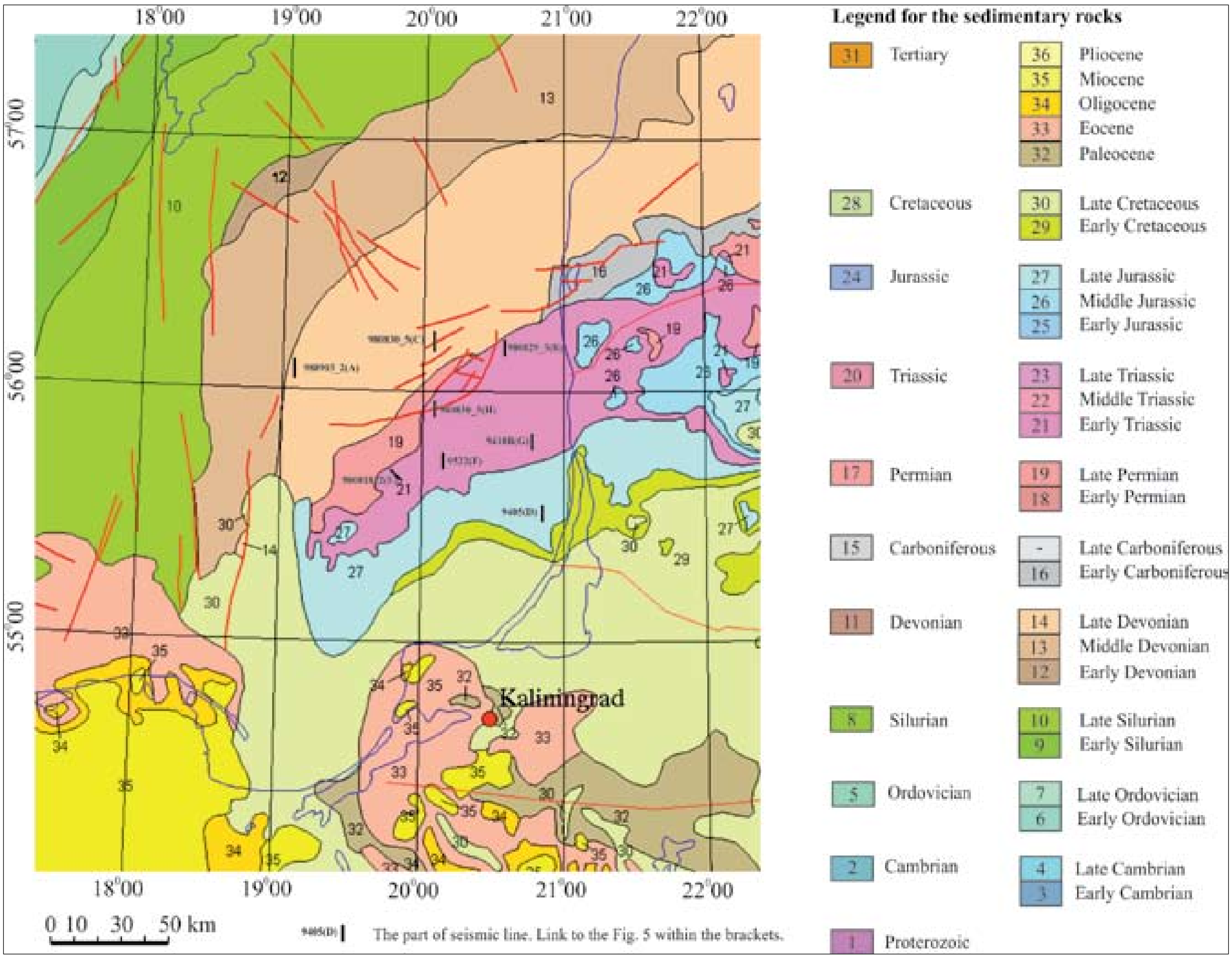

Fig. 2 Basic geological map of the south-eastern segment of the Baltic Sea (after Grigelis 2009, modified in 2012).

Late Palaeozoic (Permian) and Mesozoic bedrock of the south-eastern segment of the Baltic Sea (Grigelis 1999) that supplemented the seismo-stratigraphy of the Palaeozoic of the CBS defined in the late 1970's (Flodén 1980).

Several geological maps of the CBS, and of the entire Baltic Sea, have been compiled since 1980 based on more or less relevant geological-geophysical data (see Grigelis *et al.* 1993; Grigelis 2011). A basic geological map of the CBS, the original version at a scale of 1:500 000, was compiled by A. Grigelis in 1998 (Fig. 2), and later integrated into the geological map of Northern Europe (Sigmond, Ed. 2002) and in the International geological map of Europe (IGME-5000; Asch, Ed. 2005). The latest one is used in the digital version of "One Geology Europe" elaborated in 2011–2012 (Stevenson 2012).

The pre-Quaternary rock surface

The present Curonian Plateau and the Gdansk Depression are located on the peneplain formed in the Late Permian and Mesozoic rocks. The Klaipėda–Ventspils Plateau, with its steep eastern slope to the Gotland Depression, is located on the peneplain formed in the Devonian rocks. The sub-Quaternary surface was formed during the Oligocene/Neogene uplift and denudation. Based on the interpretation of the seismic profiles obtained in 1993–1994, a first version of the pre-Quaternary surface of the eastern and southern Baltic Sea with palaeo-incisions was compiled and described in 1995 (Gelumbauskaitė 1996). Later this scheme was updated using new data. The topography of the sub-Quaternary morphostructure is set off by ridges and lowerings (Gelumbauskaitė, Litvin 1986; Gelumbauskaitė, Grigelis 1997) (Fig. 3).

The palaeo-incisions of the Eastern Trough of the Gotland Depression, incised into the structural–denudational surface of the Middle–Upper Devonian rocks, were examined in seventy-three segments (Gelumbauskaitė, Grigelis 1997). The absolute depths of these incisions range from –204 to –327 m below sea level. Two groups of incisions were identified along the slope of the Klaipėda Bank structural terrace, namely U or W shaped incisions of the longitudinal direction with relative depths of 105–143–160 m, and U shaped latitudinal incisions with relative depths of 80–95–107 m. The term *relative depth* means in this case the depth into the bedrock, i.e. the erosional depth. Anomalous incisions were distinguished along the foot of the slope. Their bottoms are shaded either by multiple reflectors or discharge zone (or both), or by the extension of a deep fault.

The Upper Devonian Klaipėda–Liepaja Uplift namely the structural terraces of the banks, was formed in the Pliavinias–Pamūšis Group. The Uplift separates the East Gotland Trough from the Gdansk Depression. Its top occurs at a depth of 40–60 m. No palaeo-incisions penetrating into the sub-Quaternary surface of the Klaipėda–Liepaja Uplift have been recognized.

The northern part of the Gdansk Depression is located in Permian–Triassic–Jurassic sedimentary rocks. The depth of the depression is 100–120 m, and a foot of the Klaipėda Slope is cut by incisions with absolute depths of –116 to –168 m, this corresponds to relative depths of 50–80–90 m. The incisions are generally V shaped and extend from east to west. Some incision segments, that penetrate into the Upper Triassic surface to relative depths of 40 m, are inter-calibrated with the nearby boreholes and cores (Majore *et al.* 1997; Gelumbauskaitė 1999; Gelumbauskaitė 2000, 2009).

Table 1 Stratigraphic subdivision and boundaries of Late Paleozoic and Mesozoic strata of the south-eastern Baltic Sea (after Grigelis 1999; * after Flodén 1980).

Stratigraphy				Environment	Seismic unit
System	Series	Stage	Formation		
Cretaceous	Upper	Santonian, Coniacian, Turonian	Brasta Formation	Marine	K2
		Cenomanian	Labguva Formation	Shallow marine nearshore zone	K1
	Lower	Albian	Jiesia Formation		
Jurassic	Upper	Oxfordian	Ažuolija Formation	Marine	J4
	Middle	Callovian	Skinija Formation Paprtinė Formation	Shallow marine	J3 J2
		Bathonian	Skalviai Group (upper part)	Brackish water basin	J1
Triassic	Lower		Purmaliai Group	Continental basin	T2 T1
Permian	Upper	Z2 Werra Cycle	Naujoji Akmenė Formation	Shallow marine	P2–P3
			Sasnava Formation		P1
			Kalvarija Formation		
Devonian*	Upper	Frasnian	Gauja Beds to Amula Beds	Shallow marine	D3 – D4
	Middle	Givetian and Eifelian	Pärnu Beds to Burtnieki Beds	Shallow marine	D2

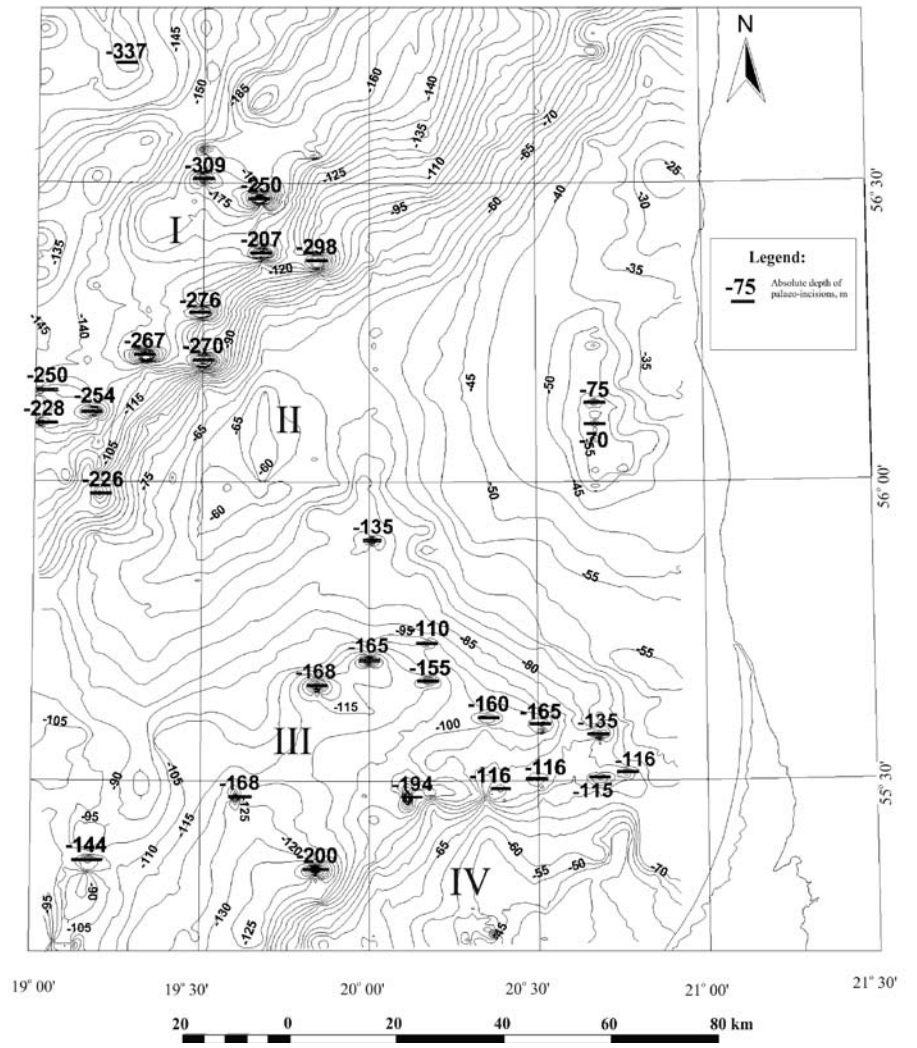

Fig. 3 Pre-Quaternary rock surface of the south-eastern Baltic Sea (after Gelumbauskaitė, 1995). Subdivision of morphostructure: I – Eastern rock Gotland Through; II – Klaipėda–Liepaja Uplift; III – Gdansk Depression; IV – Curonian structural terrace. Segments of the palaeo-incisions with absolute depth in meters are modified by L. Ž. Gelumbauskaitė, 2014.

The peneplain of the Klaipėda submarine slope in the sub-Quaternary topography is exposed by two denudational levels at 60–65 and 30–45 m respectively. The peneplain is dissected by incision segments to relative depths of approximately 40 m into the Triassic substratum. The south-eastern part of the Gdansk Depression is bordered by a klint of Cretaceous sedimentary rocks. The Curonian structural terrace at the top of the Cretaceous rocks is located at a depth of 50–60 m. In this shallow zone, the palaeo–incisions with roots in the Cretaceous substratum are less deep, approximately 30 m.

The stratigraphy of Quaternary succession

The Quaternary cover in the south-eastern Baltic Sea was evaluated interpreting seismic data from the 1993–1995 survey (Gelumbauskaitė 1996). In general, the thickness varies from 5 m to 20–25 m on the plateau and reaches 40 m on the depressions. Shorewards in the coastal zone, the thickness of the Quaternary cover increases up to 50–60 m. The lithostratigraphy is based on short drill cores that penetrate the entire Quaternary depositional complex (data from the marine geological mapping at the scale 1:500 000/1:200 000 in 1975–1978; engineering geological research of *PETROBALTIC* in 1989–1990). The depositional Pleistocene–Holocene complex varies from 10 m in the shallow zone to 48 m on the Klaipėda Slope (on E–W Klaipėda traverse) (Majore *et al.* 1999; Gelumbauskaitė 2009).

The palaeo-incisions are mainly filled in with Pleistocene sediments to their average depth of 80 m. According to the seismic profiling data, several different infilling units, i. e. tills, clays, and stratified, or unstratified, sand and gravel deposits were distinguished in the eastern part of the central Baltic Proper (Bjerkéus *et al.* 1994; Flodén *et al.* 1997). The infilling of the channels often indicate two, or sometimes three, depositional events. This might indicate that some channels were successively reopened possibly even during different glaciation periods.

Data from lithological studies of tills in the boreholes on the Klaipėda slope (Majore *et al.* 1997) show the presence of three till units representing different periods in advancing of Pleistocene glaciers. These were most probably linked with the Elsterian glaciation (MIS 12; Marine Isotope Stage), the Saalian complex of glacial advances (MIS 10–6), and the last Weichselian (MIS 2) glacial cover, respectively. Weichselian till extends across a significant part of the present Baltic Sea bottom except for plateau tops and shallow zones, where it has been eroded during different stages of the Baltic Sea formation in the Holocene. Saalian till crops out on the seafloor there (Repečka *et al.* 1991; Bitinas *et al.* 1999).

MATERIAL AND METHODS OF INTERPRETATION

Material

The data used in present investigation were collected during joint geological–geophysical surveys performed by the Lithuanian Institute of Geology (Department of Baltic Marine Geology) and Stockholm University (Department of Geology and Geochemistry) in 1993–1995 and in 1998–1999 [1], [2], [3] (see Fig. 1). The seismic lines are located every 5 km nearshore and every 10 km in the western and northern parts of the investigated area. In the central part of the area the lines are located every 2.5–5 km and a set of NW–SE lines every 2 km. The total length of the 62 seismic lines studied is 2233 km.

Equipment

A *PAR-600B* airgun, 100–1000 Hz at 14 MPa, was used as seismic source and a hydrophone eel of 20 m length as seismic recorder (Flodén *et al.* 1997). The record sweep was 0.5 s which is sufficient to obtain seismic data down to about 500 m depth (b. s. l.) in the present area. The signal processing was done on site, and both stacked and unstacked records, band pass filtered 200–500 Hz, were displayed on precision graphic recorders. An echosounder, *FURUNO-FE881 MK-II,* was used to record water depths. A *Raytheon,* and later a *NavTrackXL,* GPS navigator was used for positioning. The obtained accuracy was generally about ± 50 m. A geographical coordinate system based on the *WGS-84* geoid was chosen to fix the position of the seismic lines (see Appendix).

Baselines of interpretation

The seismic data are interpreted with *Halliburton Geographix* software. First analogous seismic data were digitized with *Mathworks Matlab*, *SegyMat* (free open software) and *IMAGE2SEGY* (Barcelona Institute of Marine Science) to *Seg-Y* file format. Next, all the seismic data were imported to the inner *Halliburton Geographix* software format. Seismic units (see Table 1) were interpreted using data from the offshore wells D5, D6, E6 and E7 (location see Fig. 1). The tops of the seismic complexes J4, J2 and T1 were connected to the well D5 (Fig. 4), complexes K1, J4, J2, T1 and P2 to the well D6. The top of the Upper Devonian complex was connected to the wells E6 and E7.

RESULTS

Description of selected profiles

The seismic lines shot in 1993–1995 have been interpreted earlier (Bjerkéus *et al.* 1994; Gelumbauskaitė 1995; Flodén *et al.* 1997; Gelumbauskaitė, Grigelis 1997; Gelumbauskaitė 1999, 2000). The earlier interpretation of the seismic lines 9302, 9404, 9405 and 9410, together with well data, provided the basis for general seismic data interpretation.

The selection of seismic horizons, and their correlation at the intersections of the lines, was realized in the time domain. The seismic boundaries of the bedrock are generally rather distinct and are easily traced along the seismic sections. In places of low reflectivity it is also possible to separate the seismic complexes by their geometric shape, amplitude and the configuration of the seismic reflections. Correlation by time between seismic sections was done using the sea bottom reflection as a seismic marker. The maximum time shift between all the seismic sections is 8 ms. The described segments of the seismic lines (Figs 5A-H) are shown on the location map (Fig. 1).

The most distinct palaeo-incisions are found within the Upper Devonian seismic complex in the north–western part of the investigated area. V-shaped incisions penetrate here into a seismically homogeneous body that is underlain by a slightly folded complex (Fig. 5 A).

The reflection from the P2 seismic complex (Fig. 2, Table 1) is very intense, easily recognized and possible to use as a seismic marker (Fig. 5 F, H).

[1] Joint Lithuanian–Swedish marine geological-geophysical expedition: Report of investigations in the Central Baltic / cruise of R/V „Vėjas" No. 6/48, June 17–July 2, 1993, No. 14/56, August 20–September 8, 1994. – Department of Baltic Marine Geology, Institute of Geology, Vilnius; Department of Geology and Geochemistry, Stockholm University / chief scientists A. Grigelis, T. Flodén; contributors M. Bjerkéus, Ž. Gelumbauskaitė, M. Repečka, K. Jokšas, P. Šimkevičius. – Vilnius–Stockholm, Institute of Geology, 1994, 23 pp.

[2] Gotland Basin Experiment (GOBEX): Final report of investigations in 1994-1996 / Science and Studies Foundation of Lithuania. – Institute of Geology / chief scientist A. Grigelis; contributors L. Ž. Gelumbauskaitė, A. Grigelis, M. Repečka, P. Šimkevičius, R. Radzevičius. – Vilnius, 1996, 35 pp.

[3] http://www.eu-seased.net/seismic and sonar/Euroseismic/metaformat

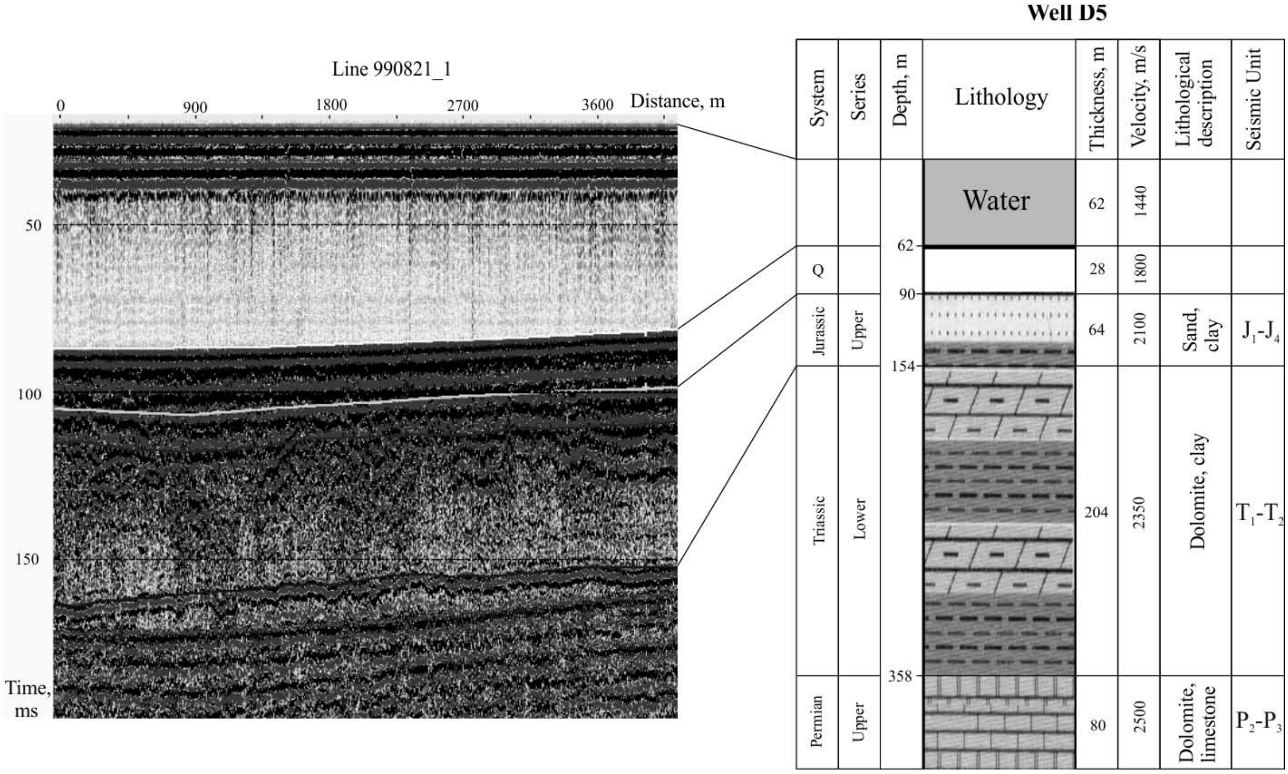

Fig. 4 Basic seismic profile of the Quaternary–Permian sequence calibrated with D5 well data.

The main feature of the palaeo-incisions in the Triassic area (see Fig. 2), as compared to the Devonian area, is the geometrical and amplitude changes of the reflections inside the incisions in relation to the surrounding bedrock areas (Fig. 5 E).

The palaeo-incisions in the nearshore zone often exhibit strong reflections with apparent angles of more than 30 degrees crossing over the reflection multiple of the sea floor (Fig. 5 B, H). Furthermore, breaks in strong and endurent bedrock reflections often facilitate the identification of palaeo-incisions here (Fig. 5 C, D, H).

The selected seismic horizons from the time domain were converted to the depth domain in accordance with the available seismic velocities (Table 2).

Table 2 Mean values of layer velocities in lithological-stratigraphic complexes of the Baltic Sea (after Grigelis 1999).

Age of complexes	Layer velocity, m/s
Water layer	1438–1446
Quaternary	1700–1850
Paleogene and Neogene	1950
Cretaceous	2000
Jurassic	2100
Triassic	2350
Permian	2200–5000
Devonian and Carboniferous	2500
Silurian	3000
Ordovician	3500
Cambrian	2750

The surface of the Quaternary relief was created using the minimum curvature method and a grid of 100 × 100 m in the Lithuanian LKS-94 coordinate system.

The main features of the palaeo-incision network

The palaeo-incision network of the investigated area is divided into three parts, namely the nearshore zone (3 in Fig. 6), the central zone (4 in Fig. 6) including the northern part of the Gdansk Depression and its Klaipėda Slope, and the deep-water zone (5 in Fig. 6) including the eastern slope of the Gotland Depression. About one hundred crossing palaeo-incisions seismic sections displaying palaeo-incisions were analysed during the present data processing. The investigated area is 67 km from north to south and 82 km from west to east. The relative depths below the bedrock surface range from 23 to 153 m. The relative depths increase from the shore to the deep-water area, approximately from 50 to 100 m into the bedrock.

The relative width of the palaeo–incisions comprises an interval of 370-7900 m. The term *relative width* means in this case the visible width of the palaeo–incision along the profile. The true angle between the seismic line and the direction of a palaeo–incision often is unknown. The angle smaller than 90 degrees makes the visible width of the palaeo–incision wider. The average relative width decreases from the nearshore zone (2210 m), through the central zone (1670 m) to the deep–water zone (1250 m).

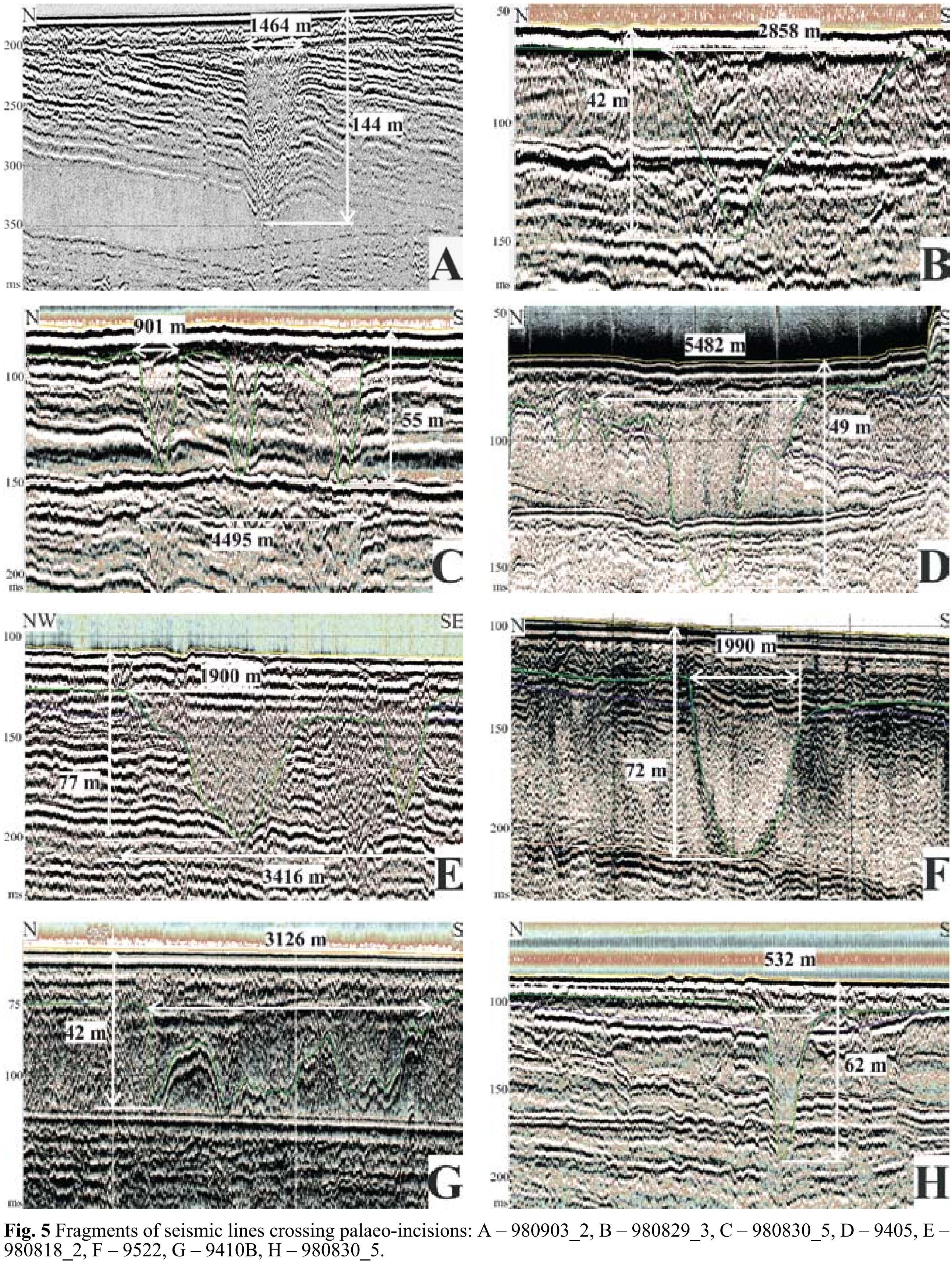

Fig. 5 Fragments of seismic lines crossing palaeo–incisions: A – 980903_2, B – 980829_3, C – 980830_5, D – 9405, E – 980818_2, F – 9522, G – 9410B, H – 980830_5.

The distribution of palaeo–incisions by shape changes from quite a few complicated W– and WW–shapes in the nearshore zone to the prevailing trivial V–shape in the deep–water zone. According to the reflectivity pattern of the palaeo–incision infillings, these may be divided into distinctly different types, namely *transparent* – without any seismic reflections inside (Fig. 5 E), *simple* – there are reflections, but no distinct seismic markers (Fig. 5 F, G, H), *layered* – there are parallel seismic markers (Fig. 5 C) and *complicated* – the internal reflections may indicate several generations of erosion/infilling (Fig. 5 A, B, D). The last type is prevailing to more than 50%. No distinct pattern has been observed regarding the infillings of the complicated type when comparing between incisions, however.

The nearshore zone

The palaeo–incisions in the nearshore zone predominantly extend in the NEE to SWW direction (Fig. 6). The visible lengths of the palaeo–incisions are about 20–25 km. Towards the NNE they simply terminate, whereas towards the SSW they generally merge together. The palaeo–incisions in this zone are generally rather shallow reaching relative depths of 23–80 m into the bedrock, their average depth is about 50 m. Wide palaeo–incisions, with relative widths of more than 2000 m, frequently occur in this zone. One specific feature of the nearshore zone is the complicated shape of the palaeo–incisions here. W– and WW–shapes are widely distributed counting for about 50% of the incisions. V– and U–shapes comprise the remainder in about equal proportions, 25% each. This zone may be described by its infillings as follows: 16 palaeo–incisions are of the complicated type, nine of the simple type, seven of the transparent type and three of the layered infilling type.

The central zone (northern part of Gdansk Depression and its Klaipėda Slope)

The incisions in the northern part of the central zone extend from northeast to southwest and from north to south (Fig. 6). The distribution of the palaeo-incisions in southern part is more complicated. The palaeo-incisions of the central zone extend to relative depths of 27–113 m into the bedrock, at an average about 80 m. Palaeo-incisions of various shapes are present in this zone. The V-shape dominates to 43%, while the U-shape is also widely distributed to 34%. The remaining incisions, 23%, demonstrate W- and WW-shapes in cross-section. The relative width of the palaeo-incisions varies widely, from 500 m to 7900 m. Regarding the types of the infillings then 29 palaeo-incisions are filled with complicated, eleven with simple, eight with transparent and five with layered types.

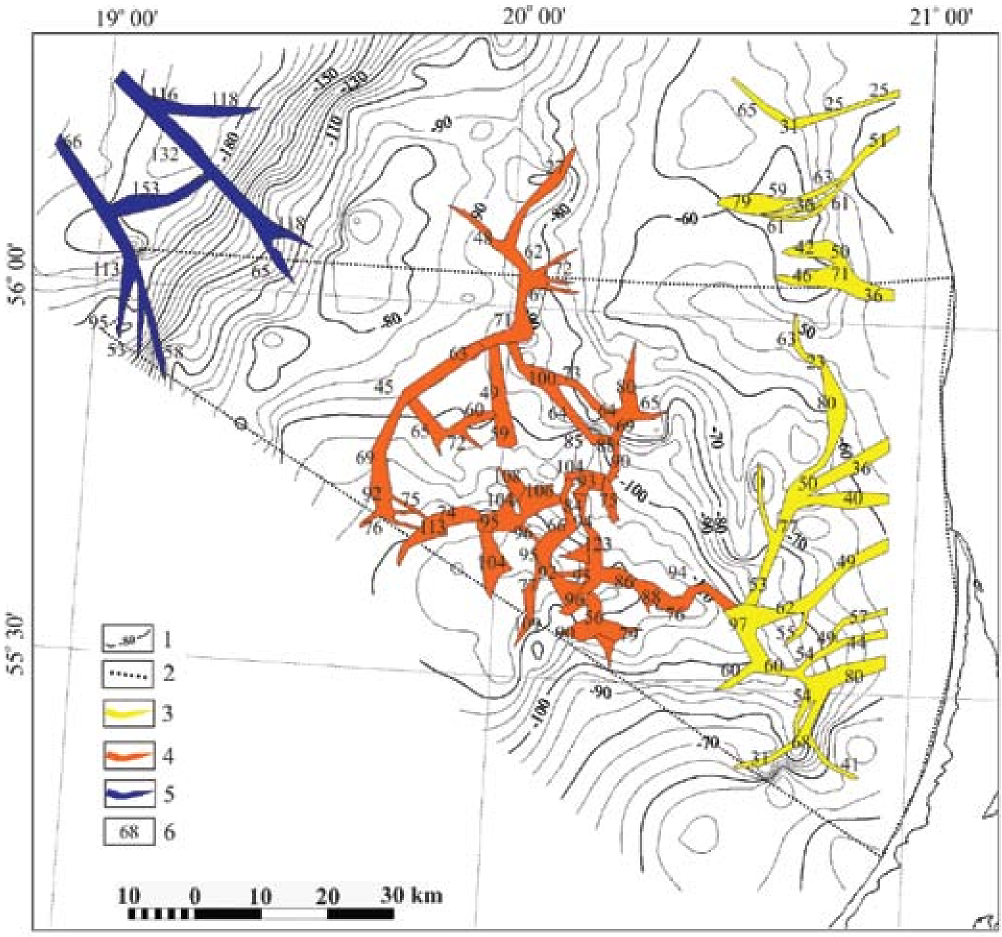

Fig. 6 The map of palaeo-incisions on the pre-Quaternary rock surface. 1 – contour lines of the sub-Quaternary surface (drawn every 5 m); 2 – Lithuanian Sea border; 3 – near shore zone rock of palaeo-incisions, 4 – central zone of palaeo-incisions, 5 – deep-sea zone of palaeo-incisions, 6 – relative depth of palaeo-incisions in meters.

The deep-water zone (eastern slope of Gotland Depression)

The palaeo-incisions of the deep-water zone mainly traverse from northwest to southeast (Fig. 6). North–westwards they continue outside the present area. The length of the two main incisions is about 42 km inside the present area. This is the zone with the deepest palaeo-incisions. Their relative depths are in the range of 53–153 m into the bedrock with an average depth of about 100 m. The V-shape dominates in the cross-sections to 73% in this zone. The relative width of the palaeo-incisions is between 600 and 2000 m. This zone is separated from the central zone by the structural high of the Klaipėda Bank. Nine of the palaeo-incisions exhibit infillings of the complicated type and two are of the transparent type.

DISCUSSION

The complexity of the present seismic interpretation involves several aspects. One limiting factor is that only a few offshore wells are accessible within the investigated area (see Fig. 1). This fact ravels the geological interpretation of the seismic complexes and due to the complicated glacial composition of the Quaternary deposits, sometimes makes it impossible. The other problem is the water depth of the investigated area. In the shallow areas, multiple reflections from the seismic boundaries most often are very intense and overprint the reflections of deeper seismic boundaries. This is the reason that shallow water part of the present area less investigated. It is possible to solve this problem using multichannel equipment and common deep point (CDP) seismic method in the shallow water.

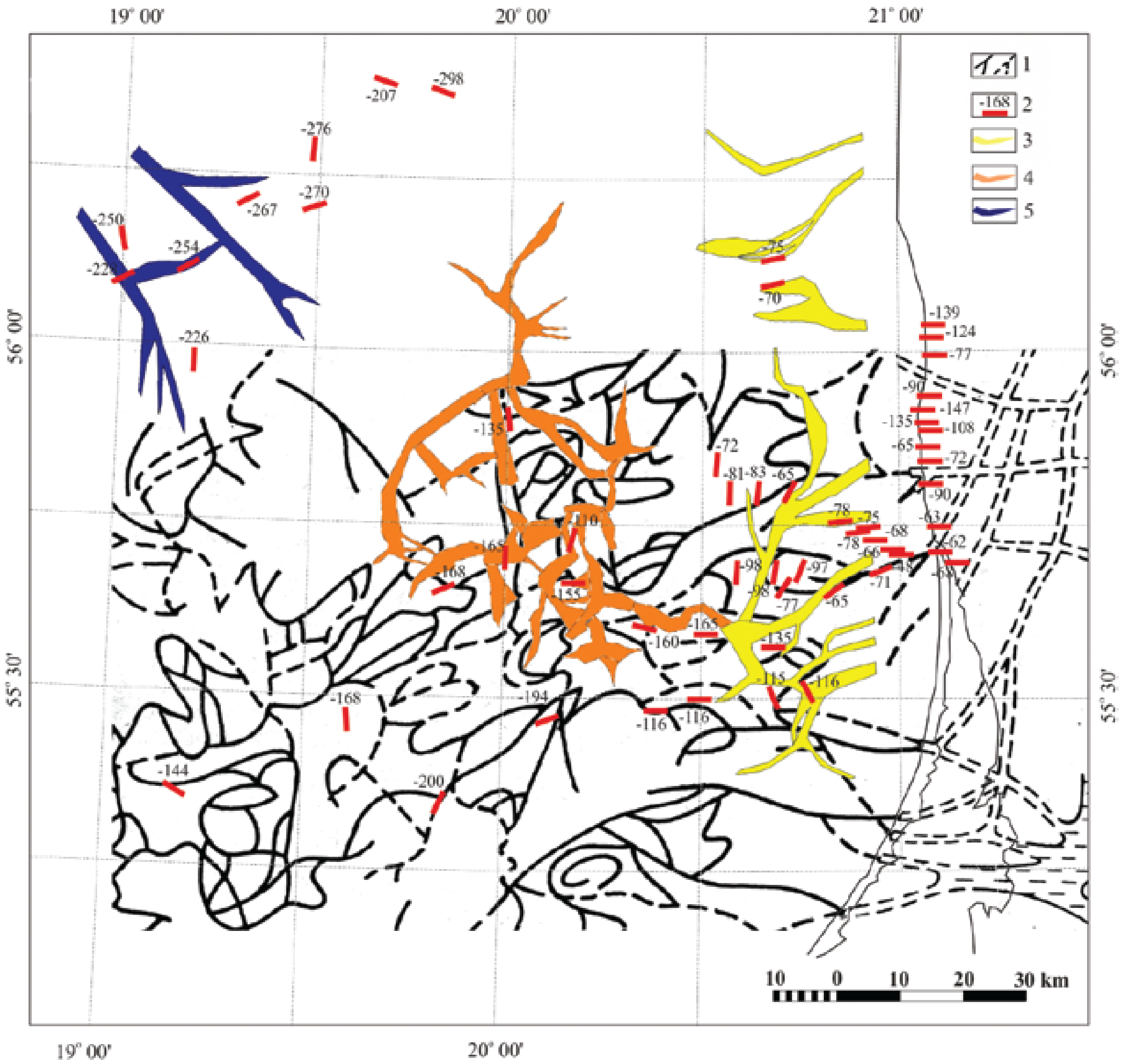

Fig. 7 Image of bearing expression of different palaeo-incision plans imprinted in the pre-Quaternary surface of the south-eastern Baltic Sea. 1 – palaeo-incisions (after Sviridov, 1984); 2 – palaeo-incisions with absolute depth in meters (after Gelumbauskaitė, 1995, 1999, 2000, modified in 2014); 3 – near shore zone of palaeo-incisions; 4 – central zone of palaeo–incisions; 5 – deep–sea zone of palaeo-incisions.

In addition, locally it is rather hard to resolve the changes of seismic facies in the seismic reflections that indicate the location of palaeo-incisions or other events such as e.g. gas-saturated rocks. Various geological facies and local irregularities in the sediments occur within the area. One more disputable question is the seismic signature of palaeo-incisions. Using the seismic data it is sometimes possible to determine more than one generation during the formation of a palaeo-incision.

The seismic reflections are often weak in the lowest parts of the palaeo-incisions, because their infillings are composed in a complicated way. Thus, to determine the depth of a palaeo-incision may become a rather tough question. The irregular distribution of the seismic lines inadvertently results in different accuracies in the shape and direction of the palaeo-incisions within the studied area.

There are three different schemes of palaeo-incisions compiled in various time of the south-eastern Baltic Sea. The oldest scheme (Sviridov 1984) is based on continuous seismic profiling, dredging, and the other geological data. It should be noted the Sviridov's scheme is positioned using the shape of coastal zone and does not contain any precision in positioning. Later the new scheme was compiled and improved by data of different sources obtained during projects *GOBEX, Inco-Copernicus Mass* and during a national geological–geophysical mapping programme at the scale 1:200 000/1:50 000 (Gelumbauskaitė 1996, 1999, 2000). The latest scheme, presented in this paper, is created by materials performed by the joint Lithuanian–Swedish data. By comparing the three different schemes of palaeo-incisions composed on to one general map (Fig. 7) it is possible to note that the general directions of the palaeo-incisions coincide and the network of palaeo-incisions is irregular.

CONCLUSIONS

The fragmented palaeo-incisions in the south-eastern segment of the Baltic Sea in general do not form a unified system similar to the present river's network. Most probably, they represent tunnel-like valleys that were formed by melt water discharges beneath continental ice sheets.

The allocation of palaeo-incisions by shape changes from the complicated W– and WW-shape forms nearshore to the simple V-shape forms on the slopes and in the deep-water zone. Within the V-shaped forms, two groups of palaeo-incisions have been identified. In the longitudinal direction, the deepest palaeo-channels are recorded on the flat even surfaces of the depressions and on the foot of its slopes. In the latitudinal direction, palaeo-incisions dissect the Klaipėda Slope and partly the nearshore zone.

According to seismic reflections *transparent, simple, layered* and *complicated* types of infilling have been differentiated. The complicated type of infilling contains indications of repeated opening and infilling of the incision, possibly during successive glaciations. No regularity has been observed in the distribution of palaeo–incisions with various infillings. Previous studies have interpreted the incision infillings as till units, clays, stratified and unstratified layers of sand and gravel sediments of the different Pleistocene stages. The palaeo-incisions seem everywhere to have been filled in prior to advance of the Late Weichselian ice sheet.

Acknowledgements

The authors are deeply indebted to Dr. Igor Tuuling (Tartu) and Dr. Sten Suuroja (Tallinn) for their comments and suggestions that allowed improving the quality of paper. The research was partly supported by a grant of national project No. VP1-3.1-ŠMM-08-K-01-019 (DG).

References

Asch, K. (Ed.), 2006 (2005). The 1:5 Million International Geological Map of Europe and Adjacent Areas – IGME5000. Geologische Bundesanstalt, Hannover, 1 map.

Bitinas, A., 1999. Some remarks on distribution and genesis of palaeo-incisions in the East Baltic area. *Geological Quarterly* 43 (2), 183–188.

Bitinas, A., Repečka, M., Kalnina, L., 1999. Correlation of tills from the south-eastern Baltic Sea bottom and near shore boreholes. *Baltica Special Publications* 12, 5–10.

Bitinas, A., Damušytė, A., Molodkov, A., 2011. Geological structure of the Quaternary sedimentary sequence in the Klaipėda Strait, south-eastern Baltic. In J. Harff et al. (eds), The Baltic Sea Basin, Springer-Verlag Berlin Heidelberg, 135–148.

Bjerkéus, M., Gelumbauskaitė, L. Ž., Sturkell, E., Flodén, T., Grigelis, A., 1994. Paleochannels in the east central part of the Baltic Proper. *Baltica* 8, 15–26.

Blazhchishin, A. I., Boldyrev, V. L., Efimov, A. N., Timofeev, I. A., 1982. Ancient shorelines and shore formations in the south-eastern part of the Baltica Sea. *Baltica* 7, 51–64. [In Russian with English summary].

Boulton, G. S., 1996. The origin of till sequences by sub–glacial sediment deformation beneath mid-latitude ice sheets. *Annals of Glaciology* 22, 75–84.

Boulton, G. S., Hindmarsh, C. A., 1987. Sediment deformations beneath the glaciers: rheology and geological consequences. *Journal of Geophysical Research 92 (B9)*, 9059–9082. http://dx.doi.org/10.1029/JB092iB09p09059

Eberhards, G., Miidel, A., 1984. Main features of the development of river valleys in the east Baltic. *Proceed-*

ings of the Academy of Sciences of the Estonian SSR, Geology 33, 136–144.

Ehlers, J., Meyer, K. D., Stephan, H. J., 1984. The pre-Weichselian glaciations in north-west Europe. *Quaternary Science Review 3*, 1–40. http://dx.doi.org/10.1016/0277-3791(84)90003-9

Flodén T., 1980. Seismic stratigraphy and bedrock geology of the Central Baltic. Stockholm Contributions Geology XXXV, 240 pp.

Flodén, T., Bjerkéus, M., Sturkell, E., Gelumbauskaitė, L. Ž., Grigelis, A., Endler, R., Lemke, W., 1997. Distribution and seismic stratigraphy of glacially incised valleys in the southern part of the Baltic. *Sveriges Geologiska Undersökning*, *Ser. Ca 86*, 43–49. [*Proceedings of the Fourth Marine Geological Conference* – the Baltic, Uppsala 1995].

Gaigalas, A., 1976. The buried palaeo-incisions of the sub–Quaternary rock surface of the south-east Baltic region. Mokslas Publishers, Vilnius, 140 pp. [In Russian with English summary].

Gelumbauskaitė, L. Ž., Litvin, V. M., 1986. Bottom geomorphology of the south-eastern Baltica Sea. (Геоморфология дна юго-восточной части Балтийского моря). *Geomorfologiya 1*, 55–61. [In Russian with English summary].

Gelumbauskaitė, L. Ž., Litvin, V. M., 1990. On development of bottom morphostructure of the Baltica Sea. (О развитии морфоструктуры дна Балтийского моря). *Geomorfologiya 2*, 66–71. [In Russian with English summary].

Gelumbauskaitė, L. Ž., 1996 (1995). Bottom relief and genesis of the Gotland depression. *Baltica* 9, 65–75.

Gelumbauskaitė, L. Ž., Grigelis, A., 1997. Paleogeomorphological reconstruction of the sub-Quaternary surface of the Central Baltic Sea. *Sveriges Geologiska Undersökning*, *Ser. Ca 86*, 51–56. [*Proceedings of the Fourth Marine Geological Conference* – the Baltic, Uppsala 1995].

Gelumbauskaitė, L. Ž., 1999. Sub-Quaternary surface of the south-eastern Baltic Sea. *Baltica 12*, 15–18. (*Proceedings of the Fifth Marine Geological Conference, Special Publication*).

Gelumbauskaitė, L. Ž., 2000. Late– and Postglacial palaeogeomorphology on the Klaipėda submarine slope, south-eastern Baltic Sea. *Baltica* 13, 36–43.

Gelumbauskaitė, L. Ž., 2009. Character of sea level changes in the subsiding south-eastern Baltic Sea during Late Quaternary. *Baltica 22 (1)*, 23–36.

Goreckiy, G. I., 1967. On the origin and age of deep valley-like lowerings in the bed of Antropogene glacial deposits. In *Lower Pleistocene of glacigenous areas of Russian Lowland*, 17–32, Nauka, Mocsow. [In Russian].

Grigelis, A., Amantov, A. A., Efimov, A. N. et al., 1993. Geological map of the Baltic Sea bottom and adjacent land areas. Scale 1:500 000. Cartography Enterprise, Sankt-Petersburg / Institute of Geology, Vilnius. 7 sheets.

Grigelis, A., 1995a. Mesozoic and Paleogene stratigraphy of the south-eastern part of the Baltic Sea. *Prace Państwowego Instytutu Geologicznego 149*, Warszawa, 43–46. (*Proceedings of the third Baltic Marine Geological Conference „The Baltic”*).

Grigelis, A, 1995b. Sub-Permian and sub-Quaternary peneplains in the south-east Baltic Proper. *Nachrichten Deutsche Geologische Gesellschaft 54*, Hannover, 76–78.

Grigelis, A., 1999. Stratigraphic units of Late Paleozoic and Mesozoic bedrock of the Baltic Sea. *Baltica 12*, 19–27. (*Proceedings of the Fifth Marine Geological Conference, Special Publication*).

Grigelis, A., 2011. Research of the bedrock geology of the Central Baltic Sea. *Baltica* 24 (1), 1–12.

Grigelis, A., Monkevičius, A., 1995. Continuous seismic profiling in the Baltic Sea. *Geologijos akiračiai 3*, 29–37. [*Geological Horizons*, Vilnius].

Gudelis, V., 1961. General features of the sea coast development of the Eastern Baltic mainland in late- and postglacial time. *Proceedings of the Institute of Geology of the estonian Academy of Sciences VIII*. [In Russian with English summary].

Gudelis, V., 1970. General features of geology and geomorphology of the sea bottom at the central sector of the Baltic Sea. *Baltica 4*, 103–113. [In Russian with English summary].

Gudelis, V., Lukoševičius, L., Kleymenova, G. J., Vyshnevskaya, E. M., 1977. Geomorphology and late– and postglacial bottom deposits of the south-eastern Baltic. *Baltica 6*, 245–256. [In Russian with English summary].

Jurgens, U., 1999. Burried Quaternary channels in the southern Baltic Sea north of Rügen Island, Germany: distribution and genesis. *Baltica 12*, 43–47. (*Proceedings of the Fifth Marine Geological Conference, Special Publication*).

Kuster, H., Meyer, K. D., 1979. Glaziäle Rinnen im mittleren und nordöstlischen Niedersachsen. *Eiszeithalter und Gegenwart 29*, 135–156.

Majore, J., Rinke, R., Savvaitov, A., Veinbergs, I., 1997. Lithostratigraphical identification of tills in the south-eastern part of the Baltic Sea by the method of the rounded hornblend grains. *Baltica* 10, 9–12. [In Russian with English summary].

Molodkov, A., Bitinas, A., Damušytė, A., 2010. IR-OSL studies of till and inter-till deposits from the Lithuanian Maritime Region. *Quaternary Geochronology* 5, 263–268. http://dx.doi.org/10.1016/j.quageo.2009.04.004

Monkevičius, A., 1999. Glacial incisions and fossil cryogenic structures in the Mesozoic deposits of the SE Baltic Sea. *GFF* 121, 1–12. http://dx.doi.org/10.1080/11035899901211001

Repečka, M., Rybalko, A., Malkov, B., Blazhchishin, A., Emelyanov, E., Efimov, A., Isachenko, S., Spiridonov, M., Juškevičs, V., 1991. Quaternary. In A. Grigelis (Ed.), *Geology and geomorfology of the Baltic Sea*, 229–256, Leningrad, Nedra. [In Russian].

Rozhdestvensky, D. S., 1989. Buried lower Cenozoic valleys in the south-eastern Baltic Sea (according to the data of seismoacoustic profiling). *Bulletin of MOIP, Geological Section*, Vol. 54 (5), 41-45. [In Russian].

Savvaitov, A., Veinbergs, I., Goldfarb, Yu., 1999. General features of the sub-Quaternary relief of the Baltic Sea in the Latvian Economic Zone. *Baltica* 12, 99–102. (*Proceedings of the Fifth Marine Geological Conference, Special Publication*).

Sigmond, E. M. O. (Ed.), 2007 (2002). Geology of the land and seas of Northern Europe. *NGU, Special Publication* 10, Trondheim, Norway.

Stevenson, A., 2012. The European marine observation and data network – geological data. *Baltica* 25 (1), 87–90. http://dx.doi.org/10.5200/baltica.2012.25.08

Sviridov, N. I., Litvin, V. M., Gaigalas, A. J., Repečka, M. A., 1976. Relief of the sub-Quaternary surface of the Baltic region. *Sovetskaya Geologiya* 5, 60–69. [In Russian].

Sviridov, N. I., Litvin, V. M., 1983. Structure of the sedimentary cover of the south-eastern areas of the Baltic Sea. *Sovetskaya Geologiya* 4, 86–94. [In Russian].

Sviridov, N. I., 1984. The origin of faults in the upper part of the sedimentary cover of the Baltic Sea. *Sovietskaya Geologiya* 6, 72–79. [In Russian].

Sviridov, N. I., 1991. Seismostratigraphic subdivision of the sedimentary cover. In A. Grigelis (Ed.), *Geology and geomorphology of the Baltic Sea*, Nedra, Leningrad, 50–66. [In Russian].

Šliaupa, A., Gelumbauskaitė, Ž., Straume, J., Šliaupa, S., 1995. Neotectonic structure of eastern part of the Baltic Sea and adjacent land area. *Technika Poszukiwań Geologicznych, Geosynoptika i Geotermia* 3, 63–65.

Tavast, E., Raukas, A., 1982. Relief of bedrock in Estonia. Tallinn, Valgus, 194 pp. [In Russian with English summary].

Timofeev, I., Bergman, V., Efimov, A., Namestnikov, A., Gorban, L., 1974. Quaternary deposits of the Baltic Sea bottom within the limits of the sector Liepaja–Klaipėda. *Problems of Quaternary Geology* 7, Zinaatne, Riga, 33–37. [In Russian with English summary]. PMid:4461935

Veinberga, A. F., Veinbergs, I. G., Klavinš, I. R., 1986. Geomorphology of the bottom in the south-eastern part of the Baltic Sea and the features of retreat the Last ice sheet from this region. *Morphogenesis of the relief and palaeogeography of Latvia*, Riga, 130–144. [In Russian with English summary].

Wingfield, R. T. R., 1989. Glacial incisions indicating Middle and Upper Pleistocene ice limits of Britain. *Terra Nova* 1, 538–548. http://dx.doi.org/10.1111/j.1365-3121.1989.tb00430.x

APPENDIX. The coordinates of seismic lines.

Line	Start of line		End of line		Length, km
	Lat N	Long E	Lat N	Long E	
9302B	55° 15.9′	20° 21.0′	55° 23.3′	20° 42.2′	26.4
9404	56° 20.0′	20° 40.0′	55° 18.5′	20° 39.7′	114.2
9405	55° 18.7′	20° 49.9′	56° 21.7′	20° 50.1′	116.9
9410A	56° 22.9′	20° 45.0′	56° 00.9′	20° 45.1′	40.8
9410B	55° 57.3′	20° 45.0′	55° 24.9′	20° 45.0′	60.0
9513	56° 09.9′	20° 50.5′	55° 44.1′	19° 35.3′	91.8
9514	55° 41.5′	19° 43.0′	55° 60.0′	20° 35.0′	64.2
9515	55° 50.0′	20° 27.5′	55° 30.0′	20° 27.5′	37.0
9516	55° 30.0′	20° 25.0′	55° 50.0′	20° 25.0′	37.1
9517	55° 50.0′	20° 22.6′	55° 30.0′	20° 22.5′	37.2
9518	55° 30.1′	20° 17.5′	55° 50.0′	20° 17.5′	37.0
9520	55° 30.0′	20° 12.5′	55° 50.0′	20° 12.5′	37.0
9521	55° 46.6′	20° 07.5′	55° 30.0′	20° 07.5′	30.8
9522	55° 30.0′	20° 05.0′	55° 50.0′	20° 05.0′	37.1
9523	55° 50.0′	20° 02.5′	55° 30.0′	20° 02.5′	37.0
9524	55° 30.0′	19° 57.5′	55° 50.0′	19° 57.5′	37.1
9525	55° 50.0′	19° 55.0′	55° 37.0′	19° 55.0′	24.2
9526A	55° 35.0′	19° 59.9′	55° 35.0′	20° 32.5′	34.2
9526B	55° 45.0′	20° 32.5′	55° 45.0′	19° 45.0′	49.7
980829_3	56° 22.7′	20° 35.0′	55° 40.0′	20° 35.0′	79.3
980829_4	55° 40.0′	20° 35.0′	55° 26.9′	20° 34.5′	24.4

Line	Start of line		End of line		Length, km
	Lat N	Long E	Lat N	Long E	
980830_1	55° 30.4′	20° 25.0′	56° 05.9′	20° 25.0′	65.8
980830_3A	56° 07.8′	20° 25.4′	56° 08.2′	20° 25.0′	0.9
980830_3B	56° 08.9′	20° 25.0′	56° 10.0′	20° 25.0′	2.0
980830_5A	56° 10.3′	20° 25.0′	56° 18.9′	20° 25.0′	15.9
980830_5B	56° 20.0′	20° 21.9′	56° 20.1′	20° 10.2′	12.1
980830_5C	56° 18.2′	20° 05.1′	55° 43.7′	20° 05.0′	64.0
980830_6A	55° 42.0′	20° 04.7′	55° 38.0′	20° 05.0′	7.3
980830_6B	55° 36.7′	20° 06.0′	55° 33.5′	20° 13.8′	10.2
980830_6C	55° 33.8′	20° 15.0′	56° 22.4′	20° 15.0′	90.2
980901_1	56° 21.9′	19° 55.0′	56° 04.7′	19° 54.9′	31.9
980901_2A	56° 04.4′	19° 54.7′	55° 40.5′	19° 55.0′	44.5
980901_2B	55° 40.3′	19° 54.0′	55° 41.7′	19° 49.1′	5.8
980901_3	55° 44.3′	19° 45.0′	56° 19.5′	19° 45.0′	65.3
980901_4A	56° 19.7′	19° 25.0′	55° 49.1′	19° 26.6′	56.8
980901_4B	55° 52.0′	19° 35.0′	56° 19.9′	19° 35.0′	51.8
980901_6	56° 18.7′	19° 15.1′	55° 56.0′	19° 15.0′	42.1
980903_1	55° 57.0′	19° 05.0′	55° 58.7′	19° 05.0′	3.2
980903_2	55° 58.9′	19° 05.0′	56° 17.5′	19° 05.0′	34.5
990818_2	56° 00.0′	18° 49.3′	55° 37.1′	20° 03.2′	88.2
990818_3A	55° 37.1′	20° 03.3′	55° 40.1′	20° 22.6′	21.1
990818_3B	55° 41.4′	20° 23.8′	55° 49.9′	19° 58.6′	30.7
990818_3C	55° 48.8′	19° 56.0′	55° 38.6′	20° 25.4′	36.1
990819_1A	55° 38.0′	20° 27.3′	55° 37.4′	20° 28.8′	1.8
990819_1B	55° 36.0′	20° 29.8′	55° 47.4′	19° 54.3′	42.7
990819_2	55° 46.6′	19° 51.8′	55° 38.9′	20° 15.0′	28.2
990820_1A	55° 37.5′	20° 19.2′	55° 35.7′	20° 24.5′	6.5
990820_1B	55° 34.3′	20° 24.0′	55° 45.8′	19° 49.1′	42.3
990820_1C	55° 44.9′	19° 47.5′	55° 39.8′	20° 03.1′	18.9
990821_1A	55° 39.4′	19° 59.3′	55° 43.9′	19° 44.9′	17.3
990821_1B	55° 43.4′	19° 44.6′	55° 32.1′	20° 47.0′	68.9
990821_1C	55° 34.1′	20° 46.8′	55° 37.7′	20° 36.9′	12.3
990821_2D	55° 37.7′	20° 36.9′	55° 38.0′	20° 36.1′	1.0
990821_3A	55° 38.6′	20° 36.0′	55° 48.2′	20° 36.0′	17.8
990821_3B	55° 49.3′	20° 36.6′	55° 55.5′	20° 53.6′	21.2
990821_3C	55° 56.2′	20° 54.1′	55° 59.6′	20° 12.5′	43.8
990821_3D	56° 00.3′	20° 09.4′	56° 00.1′	20° 04.9′	4.7
990821_4A	56° 00.0′	20° 05.0′	55° 50.8′	20° 23.5′	25.8
990821_4B	55° 50.0′	20° 23.4′	55° 50.0′	20° 17.5′	6.2
990821_4C	55° 50.5′	20° 14.1′	55° 58.7′	19° 59.4′	21.5
990822_1	56° 00.0′	19° 54.0′	56° 01.5′	19° 45.7′	9.0
990822_2	56° 09.7′	19° 01.0′	56° 10.0′	18° 51.9′	9.5
					2233.1