

Research Paper

IR-OSL studies of till and inter-till deposits from the Lithuanian Maritime Region

Anatoly Molodkov^{a,*}, Albertas Bitinas^b, Aldona Damušytė^c^a Research Laboratory for Quaternary Geochronology, Institute of Geology, Tallinn University of Technology, 5 Ehitajate Rd, Tallinn 19086, Estonia^b Department of Geology and Mineralogy, Faculty of Natural Sciences, Vilnius University, 21/27 M.K. Ciurlionio Str., Vilnius LT-03101, Lithuania^c Lithuanian Geological Survey, 35 S. Konarskio Str., Vilnius LT-03123, Lithuania

ARTICLE INFO

Article history:

Received 20 October 2008

Received in revised form

16 April 2009

Accepted 20 April 2009

Available online 3 May 2009

Keywords:

IR-OSL dating

K-feldspar

Glacial tills

Lithuanian Maritime Region

Stratigraphy

MIS 4

ABSTRACT

Glacial till and inter-till deposits exposed in the Lithuanian coastal region are evidence for multiple glacial advances during the Pleistocene. Stratigraphically, tills are the most important, prominent and well preserved deposits. However, despite the importance of these deposits, there is limited chronological control and it is widely debated whether they belong to one or another Pleistocene glaciation. The aim of the present study was to find features of the glacial tills, which allow us to temporally constrain these deposits, which are usually deemed to be undatable by luminescence methods. To achieve the goal, 15 samples from five different till beds and 12 samples from underlying sandy inter-till deposits from the same area were taken for analysis by feldspar-based IR-OSL technique. This paper presents the results, which suggest that the studied deposits, including glacial tills, are mostly of late Pleistocene age (MIS 5 and 4). We discuss analytical data obtained for these materials and implications for stratigraphic subdivision of the till-bearing deposits in the Lithuanian Maritime Region.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

The stratigraphy of Pleistocene deposits in the Lithuanian coastal region is still unsolved. This is so in spite of the fact that the stratigraphically most important Pleistocene deposits, glacial tills, which are associated with numerous advances of the Scandinavian ice sheet over the north-eastern part of Europe, are widely distributed in Lithuania. However, notwithstanding many investigations, the exact number of glacial advances as well as their stratigraphic order is still controversial (Baltrūnas and Bitinas, 1994; Satkūnas and Bitinas, 1994; Gaigalas, 1995; Kondratienė, 1996).

Each glaciation left behind characteristic deposits, i.e., till and a series of glaciofluvial and glaciolacustrine sediments, but stratigraphic correlation of glacial tills and reconstruction of palaeogeographic conditions during a particular glacial or interglacial period is rather hypothetical.

Although till is the most frequent deposit of each ice advance, stratigraphic subdivision and correlation of this deposit is complicated due to glaciotectionic disturbances, variable lithological composition and colour, etc.

Besides, there are no type sections with this till in the Lithuanian coastal region, which in combination with interglacial sediments would serve as a base for stratigraphic subdivision of the Pleistocene sediment sequence. Absolute ages of those sediments, especially of glacial tills, are poorly defined here as well. This is caused mainly by the lack of dating methods applicable to glacial tills.

Till is a problematic deposit for luminescence dating. As luminescence dating methods can be used to estimate the age of the sediments that have been sufficiently bleached before deposition they have the potential to date some kind of waterlaid glacial deposits such as glaciofluvial and glaciolacustrine sediments formed adjacent to melting ice. The use of this sorted and stratified material laid down by glacial meltwater, especially if it was deposited quite far from the ice margin, is preferable for luminescence dating because these sediments are more likely to have been bleached before deposition, rather than tills.

Tills are the unsorted and unstratified rock material – a heterogeneous mixture of all shapes and sizes of particles, without layering or strata – that has been transported and deposited by a glacier during its flow. Most likely, this material was not exposed to sunlight and hence was not sufficiently, if at all, bleached. Therefore, its dating by luminescence methods is likely to be unsuccessful.

* Corresponding author. Tel.: +372 620 3062; fax: +372 620 3011.

E-mail address: molodkov@gi.ee (A. Molodkov).

Appendix A
Supplemental material

In the present study, sampling for infrared optically stimulated luminescence (IR-OSL) analysis of the till deposits together with inter-till sandy sediments was conducted to find any features of the glacial tills which potentially could allow us to temporally constrain these stratigraphically important Pleistocene deposits, and to at least associate them with one or another known glaciation that occurred in this region during the middle or late Pleistocene.

The investigations were carried out on the outcrop of Olando Kepurė Cliff, which is one of the main key sections of Pleistocene deposits in western Lithuania, and also on the four borehole sections located along the Klaipėda Strait (Fig. 1).

Based on previous geological investigations and observed stratigraphical relationships, we expected data to yield Baltija and Grūda (late Weichselian, MIS 2) and Medininkai/Warthanian (MIS 6) ages. This paper (a) describes the unexpected dating results we obtained in our attempts to constrain ages of these glacial sediments and (b) discusses analytical data obtained for glacial till and inter-till deposits and implications of our results for stratigraphic subdivision of the till-bearing deposits in the Lithuanian Maritime Region.

2. Geological setting

The thickness of the Quaternary sedimentary sequence in the Klaipėda Strait region varies from 60 to 90 m overlying Upper Jurassic and lower Cretaceous deposits (Bitinas et al., 2009). The Pleistocene sequence is generally composed of alternated till and inter-till deposits. According to the results of previous geological investigations, the sediments of four different glaciations are present in this sequence (unpublished data, archive of the Lithuanian Geological Survey). Its uppermost part is at the Baltic Sea coast covered by sediments of the Baltic Ice Lake, Ancylus Lake, Litorina and Post-Litorina Seas and also by recent aeolian sediments (Gelumbauskaitė and Šečkus, 2005; Kabailienė et al., 2009).

Three complexes of till were identified in the field. The lowermost till complex (complex I, Fig. 2 and Supplementary Fig. S1 available online) is represented by grey till with clods of grey-brown and yellowish-brown till (i.e., with rafts of glacial deposits interrupted due to glaciotectionic processes). According to the till fabric measurements, the glacier lobe responsible for the formation of this till advanced from the north. Compared to the following two till complexes this one is dominated by gravels from crystalline rocks with minor contribution from dolomites (Bitinas, 1997). The second (II) till complex is composed of two grey-brown till layers separated by a thin layer of silt and in some places by sand or sandy gravel. Both tills are very similar in colour and lithological

composition (the gravel part is enriched by Silurian limestones); glaciotectionic features (disturbed floes of Pleistocene sand and gravel) were observed in the uppermost layer. The fabric (i.e., orientation of long axis of gravel in the till), textural properties of the sediments and structural elements of glaciotectionic features suggest a NW–SE direction of ice advance during the formation of both these till layers. The third (III), uppermost till complex is represented by a single yellowish-brown and brown till layer that was formed by a glacier lobe advancing from the west (Bitinas, 1997). Post-glacial glaciolacustrine clay and recent aeolian sediments are lying on the top of the Olando Kepurė outcrop.

The boreholes along the Klaipėda Strait recovered only the upper part of the Quaternary sequence (Fig. 2). The inter-till sediments composed of laminated silt or sandy silt and fine-grained sand alternating with gyttja form the lower part in all boreholes. Traces of glaciotectionic disturbance (microfolds, thrust-faults, micro-rafts, etc.) were observed within laminated sediments. Two types of till layer were identified: brown-grey or grey-brown till and dark grey till (occasionally with a greenish tinge). The upper part of the borehole sections (to the depth of 2–8 m b.s.l.) is composed of sandy sediments (with rare interlayers of gyttja and silt) of Litorina and Post-Litorina Seas (Kabailienė et al., 2009).

3. Methods

3.1. Sampling and sediment description

The till samples for IR-OSL analysis were taken in the Olando Kepurė outcrop from the three different till complexes – three samples from each complex (Fig. 2, Supplementary Fig. S1). In the lowermost till complex (I) the samples were taken from every lithological variety of till: one sample from predominating grey till and two samples from tills of different colour. In the second (II) till complex the samples were taken from the lowermost, glaciotectionically undisturbed, part. Three till samples were taken from the upper till complex (III) represented by a homogenous single till layer.

In the borehole sections two lithologically different types of till were sampled: in borehole 62 three samples were taken from dark grey till and three samples from greyish-brown till in borehole 84 (Fig. 2, Supplementary Figs. S2–S5). Fine-grained inter-till sand with minor inclusions of tiny particles of organic matter (limnic sediments) was sampled in three borehole sections. As it was very important to estimate the age of embedded organic (gyttja) sediments, three samples beneath and above these sediments were taken in borehole 62. Sampling of the sand layer above the organic sediments was available in borehole 94. The inter-till sandy sediments sampled in borehole 103 and the sandy sediments sampled



Fig. 1. Location of the study area and of the study sites.

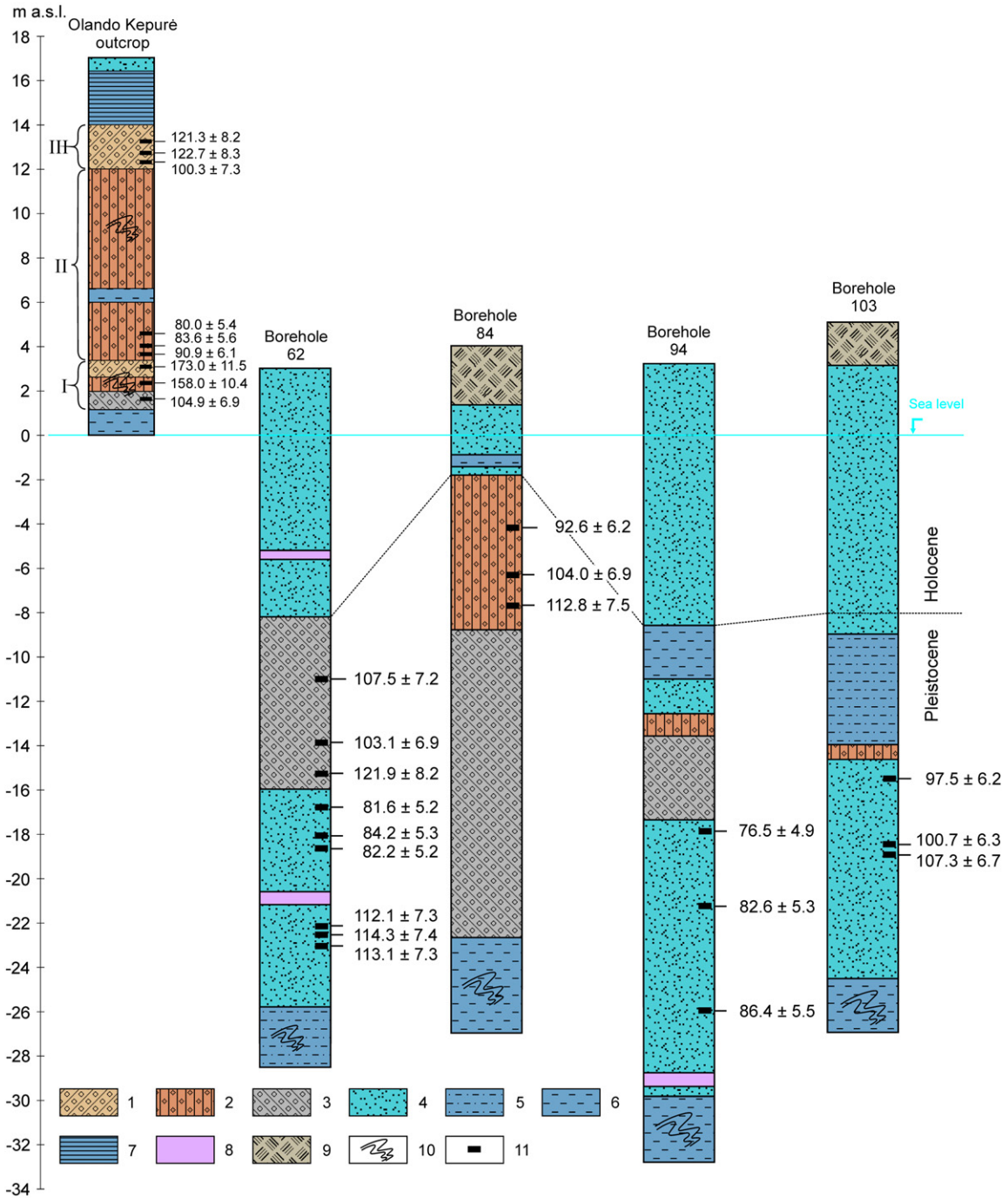


Fig. 2. Schematic cross-sections of the Olando Kepurė outcrop and boreholes along the Klaipėda Strait showing the location of the IR-OSL sampling points and luminescence ages for the samples from the till and inter-till deposits; (1) brown or yellowish-brown till; (2) grey-brown or brown-grey till; (3) dark grey (or grey with a greenish tinge) till; (4) sand; (5) sandy silt; (6) silt; (7) clay; (8) gyttja; (9) anthropogenic deposits; (10) glaciotectionized sediments; (11) IR-OSL sampling points; number indicates an absolute age of sediment (in ka). Roman numbers in the Olando Kepurė outcrop mark the till complexes described in the text.

in boreholes 62 and 94 are very similar in terms of geological setting and lithological composition.

3.2. Laboratory procedures

Feldspar grains were prepared using our standard laboratory procedures (see, e.g., Molodkov and Bitinas, 2006 for details). Briefly, alkali feldspar grains of 100–150 μm size were extracted from the sediment under subdued filtered light in the laboratory by a procedure including wet sieving, heavy liquid flotation (collecting

2.54–2.58 g cm⁻³ fraction), treatment by 10% HF for 15 min and finally etching by 20–40% HCl. The IR-OSL measurements were carried out at room temperature with the Ingrid-Type SLM-1 reader using 860 nm stimulation by short 3 s laser pulses. Detection was in the 380–430 nm wavelength range using a combination of 3 mm SZS-22 (blue-green), 3 mm PS-11 (purple) and 2 mm FS-1 (violet) colour glass filters manufactured by the LZOS, JSC (Lytkarino Optical Glass Factory), Russian Federation. For laboratory irradiation a calibrated ⁶⁰Co source delivering 6.5 × 10⁻² Gy s⁻¹ of gamma radiation was used. After irradiation samples were kept at room

temperature for at least 4 weeks to decrease the phosphorescence and to eliminate anomalous fading-like effects after irradiation.

It was found in our recent studies (Vasilchenko et al., 2005; Jaek et al., 2007a,b, 2008; Molodkov et al., 2007) that the probability of tunnelling in just-irradiated samples quickly goes down and after 1-month storage at room temperature the tunnel luminescence is typically a fraction of the total IR-OSL signal (see, e.g., Fig. 5 of Molodkov, 2007). This circumstance allowed us to avoid the long-term procedure of testing samples for anomalous fading.

The dose dependence of the IR-OSL signal is well described by exponential function in the range of the doses applied. It allows the use of exponential fitting to determine the equivalent dose, D_e , by extrapolation of the dose dependence to zero IR-OSL intensities using the multiple-aliquot additive-dose (MAAD) technique (up to 66 aliquots, 15 mg per aliquot, 11 dose points). None of the samples showed an onset of saturation even at doses as high as 1000–1500 Gy. In general, all samples are characterized by relatively small dispersion of the data points around the regression line even for samples of till deposits.

Dose-rate data is based on laboratory NaI(Tl) gamma spectrometry (for details see, e.g., Molodkov and Bitinas, 2006) taking into account the *in-situ* water content and the contribution from cosmic rays. The internal beta dose from the decay of potassium and rubidium within K-feldspar grains was obtained from the concentration estimates reported by Huntley and Baril (1997) and Huntley and Hancock (2001).

4. Results

The IR-OSL ages of samples from three successive till beds outcropping on the Olando Kepurė Cliff (55°47.4' N; 21°04.1' E, Fig. 1) fall into three groups (Fig. 2) with averages (from the bottom upwards) of 165.5 ± 11.0 ka, 84.8 ± 5.7 ka and 114.8 ± 7.9 ka. A single date of the sample from the lowermost till layer, which differs from the overlying one in colour and in some other geotechnical properties, has an IR-OSL age of 104.9 ± 6.9 ka.

The ages of the samples taken from two till beds penetrated by boreholes drilled in the Klaipėda Strait area (55°40.8'–55°38.5' N; 21°10.4'–21°8.0' E) fall into two groups with averages of 110.8 ± 7.4 ka (borehole 62) and 103.1 ± 6.9 ka (borehole 84).

The average ages of 113.2 ± 7.3 ka and 82.7 ± 5.2 ka from the bottom upwards, respectively, were obtained for the sand samples from two successive inter-till layers penetrated by borehole 62, and the average ages of 81.8 ± 5.2 ka and 101.8 ± 6.4 ka – from granulometrically identical sediments penetrated by boreholes 94 and 103, respectively.

Details of dose rates, D_e estimates and calculated IR-OSL ages are shown in Supplementary Table S1 online.

5. Discussion

5.1. Data interpretation

All samples studied showed a significant growth in the luminescence signal in response to laboratory irradiation and high luminescence sensitivity in feldspar from both glacial and nonglacial deposits.

It was expected in the present study that feldspar MAAD data points for the till samples would be highly scattered, and ages would be overestimated due to poor bleaching.

Due to a potentially wide variety of source materials the luminescence properties of the feldspars extracted from different or even the same till bodies should also have been quite different.

However, in contrast, the ages of each group of till samples agreed well with each other (Fig. 2) taking into consideration that

the given material should have characteristics incompatible with those required for luminescence dating.

It is also remarkable that feldspar additive-dose data points (Fig. 3) and ages obtained from the till deposits (Fig. 2) are characterized, against expectations, by relatively small dispersion. This is rather surprising considering the potentially highly heterogeneous nature of the till deposits in terms of both the source material composition and a mixed distribution of differently bleached mineral grains.

The agreement of IR-OSL ages between and within each of the four groups of the samples taken from the tills penetrated by

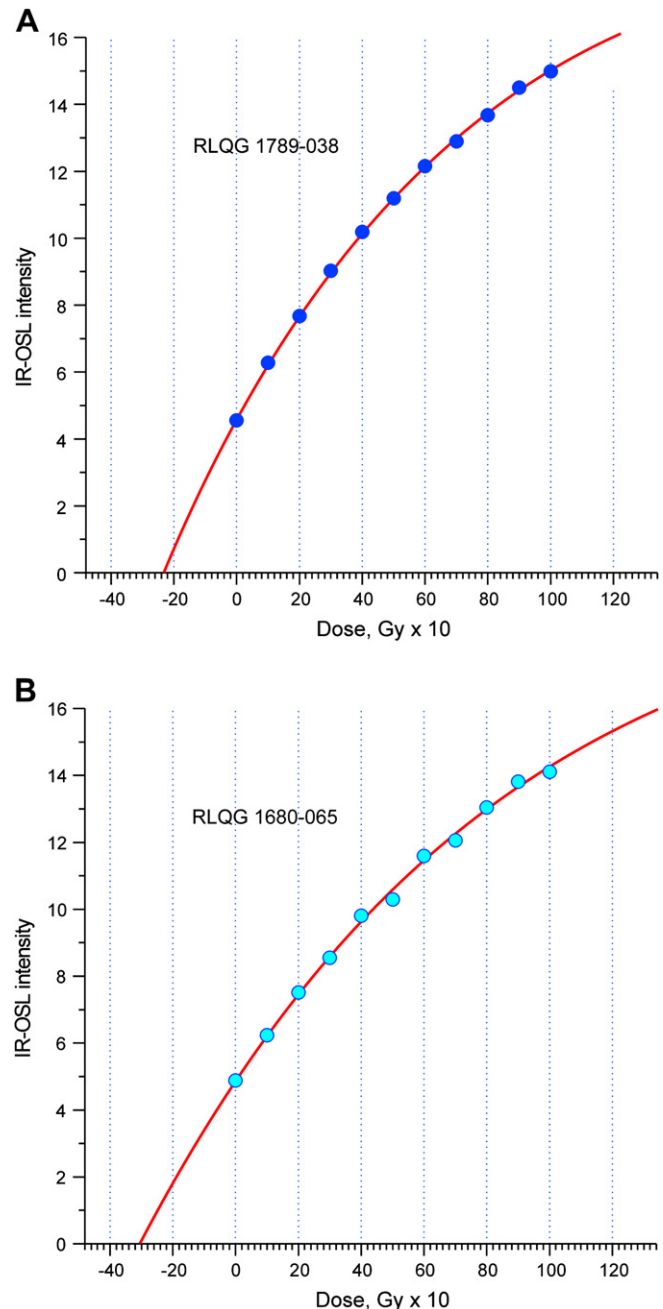


Fig. 3. Multiple-aliquot additive-dose–response curves for samples taken from typical lacustrine sand (upper) and till (lower) deposits. Sample RLQG 1789-038 is taken from borehole 62 at a depth of 22.1 m (112.1 ± 7.3 ka), and sample RLQG 1680-065 from the Olando Kepurė outcrop at a depth of 13.4 m (90.9 ± 6.1 ka). Each point in the dose–response curves is the average from six aliquots.

boreholes and those from II and III till complexes of the Olando Kepurė outcrop (Fig. 2, Supplementary Fig. S1) as well as relatively small dispersion of the additive-dose data points for the till samples (Fig. 3) indicate that feldspar grains in the glacial till samples were sufficiently bleached at deposition, i.e., during a period older than the corresponding glaciation(s). It could be the case if entrainment of underlying bleached material into a glacier was accomplished by plucking. Plucking, or catching the blocks of underlying deposits can be one of the mechanisms by which the underlying deposits can be carried by the ice and then deposited at the base of a glacier wherever the ice melts. Therefore, taking into consideration MIS 5 ages of the till samples, it can be assumed with a rather high degree of probability that the underlying deposits caught by the glacier belong to an ice-free interval, which according to Satkūnas (1999) and Baltrūnas et al. (2005) spans in Lithuania the whole MIS 5. This assumption does not conflict with some slight age inversion observed between II and III till complexes of the Olando Kepurė outcrop. This inversion can be interpreted as a result of two successive passages of a glacier over one and the same area. During the first passage of the glacier the (younger) surface of the underlying rock was caught and carried by the ice. During the second ice advance, older material was caught and then deposited on the underlying surface of till complex II.

It is worth noting here that the analysed samples from II and III till complexes in the Olando Kepurė outcrop and the tills from boreholes 62 and 84 are similar in U, Th and K content as well as in their ratios (see Supplementary Table S1). This implies that till complex I is quite different from the overlying ones and stands clearly apart from the “borehole tills” as well. This interpretation is supported by the geotechnical properties of the till complexes according to which till complex I was formed significantly earlier than overlying relief-forming till beds (for more details see Gadeikis, 1998; Bitinas et al., 2009).

Inter-till deposits studied in the present work correlate well with each other having similar age, U-Th-K content and Th/U, K/U ratios. The most similar are upper inter-till sands from borehole 62 (samples 1786–1788) and those from borehole 94 (samples 1792–1794) (see Fig. 2 and Supplementary Table S1). Lower sands from borehole 62 (samples 1789–1791) can be approximately compared with sands from borehole 103 (samples 1783–1785). All these sands seem to be deposited during MIS 5. Radioactivity data on the samples from the sands are also quite similar implying that these sands were transported from the same source area.

5.2. Stratigraphic implications of the data

The results obtained in the present study show that we dealt with well bleached (limnic, marine, etc.) sediments captured by a glacier during its advance. Limnic and/or marine sediments were probably widespread in the Baltic Sea depression during every interglacial and interstadial. Thus, based on the results of IR-OSL dating of till samples showing early Nemunas/early Weichselian (MIS 5d–5a) age, all studied tills may have been deposited during the following Weichselian pleniglacial (MIS 4–2).

The lowermost till complex in the Olando Kepurė outcrop (Fig. 2) contains a couple of older beds of till (158 and 173 ka) ascribed to MIS 6. Such incorporation can be logically explained considering the mechanism of glacioidislocation: these till beds are the glacial rafts of Medininkai/Warthanian (MIS 6) age that were captured during a later glacial advance.

According to IR-OSL dating results, the inter-till deposits together with the embedded organic sediments were formed during early Nemunas/early Weichselian (MIS 5d–5a). At the same time, on the basis of palynological data, these sediments are ascribed to the Snaigupė (Drenthe-Warthe, MIS 7) interglacial

(Kondratienė and Damušytė, 2009). However, it is noteworthy here that according to our recent results of palynological and ESR climato-chronostratigraphical studies in northern Eurasia (see, e.g., Molodkov and Bolikhovskaya, 2009) at least two parts of this (MIS 5d–5a) interval may also be correlated with the climatic ameliorations of interglacial rank.

Based on the above-presented interpretations and considering the general geological situation in the Klaipėda city region, it can be maintained that the till layer (104.9 ± 6.9 ka) from the lowermost till complex in the Olando Kepurė outcrop and all till layers in boreholes along the Klaipėda Strait associate with one and the same geological body, which was most probably formed by a glacier advance during MIS 4. This is in good agreement with a reconstruction made by Svendsen et al. (2004) according to which part of the south–western margin of the Eurasian ice sheet could have been situated in the Lithuanian Maritime Region or in the whole Western Lithuania during the Weichselian early pleniglacial maximum (MIS 4).

The upper (II and III) till complexes in the Olando Kepurė outcrop, notwithstanding that these till layers contain the same early Nemunas/early Weichselian (MIS 5d–5a) sediments (i.e., the glacier eroded the same sediments in the Baltic Sea depression), should be attributed to the late Nemunas/late Weichselian ice sheet advance (MIS 2) taking into account geotechnical properties of these tills (Gadeikis, 1998; Bitinas et al., 2009). Thus, the results of presented investigations contradict the previous opinion (Bitinas, 1997) that the lowermost till complex in the Olando Kepurė outcrop as well as the upper till layers in the boreholes in the Klaipėda Strait area could have been formed during the Medininkai/Warthanian, glaciation, i.e., during MIS 6.

6. Conclusions

The results obtained in the present study show that:

- Sediments constituting the studied till deposits were well bleached before they were captured by the ice sheets.
- Most of the IR-OSL ages from both till and inter-till deposits fall in the time interval of MIS 5d–5a.
- Plucking or catching the blocks of underlying deposits can be one of the mechanisms by which these deposits were carried away by the ice and then deposited at the base of a glacier. Therefore, taking into consideration the ages obtained for most of the till samples (between about 80 and 123 ka) it can be assumed that the underlying deposits caught by Weichselian glaciers belong to the ice-free MIS 5d–5a interval.
- At least part of these till deposits can most probably be associated with the ice movement during MIS 4.
- Part of the south–western margin of the Eurasian ice sheet could have been situated in the Lithuanian coastal region or in the whole Western Lithuania during the Weichselian early pleniglacial maximum (MIS 4).
- Two upper till layers from the lowermost till complex I of the Olando Kepurė outcrop dated at 173 and 158 ka can most probably be attributed to the glacier advance during the Medininkai/Warthanian glaciation (MIS 6); as rafts they were later incorporated into the younger till formed most likely during MIS 4.
- According to the luminescence dates obtained on two upper (II and III) till complexes in the Olando Kepurė outcrop (with averages of 84.7 and 115.7 ka, respectively) and taking into account geotechnical properties of these tills they can most likely be attributed to the late Nemunas/late Weichselian ice sheet advance (MIS 2).

- The evidence presented in this study does not support the formation of the lowermost till complex in the Olando Kepurė outcrop as well as the upper till layers in the boreholes of the Klaipėda Strait area during the Medininkai/Warthanian (MIS 6) glaciation.
- Although the luminescence results obtained in this study on the samples from glacial till deposits are unexpectedly good, the suitability of tills for luminescence dating still remains a problem.

Acknowledgements

We are grateful to colleagues Tatyana Balakhnichova and Marina Osipova for their contribution to the laboratory work reported here, to Helle Kukk for checking the English text and to Alytė Mikelaitytė for help in preparing the illustrations. Special thanks go to the anonymous referees for their valuable comments on the paper. This research was supported by grant no. 6112 from the Estonian Science Foundation, by Estonian State Target Funding Project No. 0320080s07, by Klaipėda State Seaport and Lithuanian Geological Survey.

Appendix A. Supplemental material

Supplementary information for this manuscript can be downloaded at [doi:10.1016/j.quageo.2009.04.004](https://doi.org/10.1016/j.quageo.2009.04.004).

Editorial handling by: R. Grün

References

- Baltrūnas, V., Bitinas, A., 1994. The polyvariance in stratigraphic correlation as a significant problem of the Lithuanian Pleistocene studies. *Geologija* 17, 144–151.
- Baltrūnas, V., Karmaza, B., Karmazienė, D., 2005. Structure and formation peculiarities of Pleistocene deposits in northern Lithuania. *Geologija* 52, 22–33 (in Lithuanian with English summary).
- Bitinas, A., 1997. Quaternary deposits on the outcrop Olando Kepurė. The Fifth Marine Geological Conference “The Baltic”. Abstracts. Excursion Guide. Vilnius, Lithuania, pp. 109–110.
- Bitinas, A., Damušytė, A., Molodkov, A., 2009. Geological structure of the Quaternary sedimentary sequence in the Klaipėda Strait, southeastern Baltic, in: Springer, monograph (submitted for publication).
- Gadeikis, S., 1998. Engineering geological conditions of Klaipėda City. Doctoral thesis, Vilnius University, Vilnius, Lithuania.
- Gaigalas, A., 1995. Glacial history of Lithuania. In: Ehlers, J., Kozarski, S., Gibbard, P. (Eds.), *Glacial Deposits in north-eastern Europe*. A.A. Balkema, Rotterdam, Brookfield, pp. 127–135.
- Gelumbauskaitė, L.Ž., Sečkus, J., 2005. Late Quaternary shore formations of the Baltic basins in the Lithuanian sector. *Geologija* 52, 34–45.
- Huntley, D.J., Baril, M.R., 1997. The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. *Ancient TL* 15, 11–13.
- Huntley, D.J., Hancock, R.G.V., 2001. The Rb contents of the K-feldspar grains being measured in optical dating. *Ancient TL* 19, 43–46.
- Jaek, I., Molodkov, A., Vasilchenko, V., 2007a. On the possible reasons of anomalous fading in alkaline feldspars used for luminescence dating of Quaternary deposits. *Estonian Journal of Earth Sciences* 56 (3), 167–178.
- Jaek, I., Molodkov, A., Vasilchenko, V., 2007b. Luminescent manifestation of tunnel and ionic processes in alkali feldspars. *Journal of Applied Spectroscopy* 74 (3), 357–363.
- Jaek, I., Molodkov, A., Vasilchenko, V., 2008. Instability of luminescence responses in feldspar- and quartz-based palaeodosimeters. *Journal of Applied Spectroscopy* 75 (6), 824–829.
- Kabailienė, M., Vaikutienė, G., Damušytė, A., Rudnickaitė, E., 2009. Post-Glacial stratigraphy and paleoenvironment of the northern part of the Curonian Spit, Western Lithuania. *Quaternary International* (in press).
- Kondratienė, O., 1996. The Quaternary Stratigraphy and Paleogeography of Lithuania Based on the Palaeobotanic Studies. *Academia*, Vilnius (in Russian with English summary).
- Kondratienė, O., Damušytė, A., 2009. Pollen biostratigraphy and environmental pattern of Snaigupėlė Interglacial, Late Middle Pleistocene, western Lithuania. *Quaternary International* (in press).
- Molodkov, A., 2007. IR-OSL dating of uranium-rich deposits from the new late Pleistocene section at the Voka site, north-eastern Estonia. *Quaternary Geochronology* 2, 208–215.
- Molodkov, A., Bitinas, A., 2006. Sedimentary record and luminescence chronology of the Lateglacial and Holocene aeolian sediments in Lithuania. *Boreas* 35 (2), 244–254.
- Molodkov, A., Bolikhovskaya, N., 2009. Climate change dynamics in northern Eurasia over the last 200 ka: Evidence from mollusc-based ESR-chronostratigraphy and vegetation successions of the loess-palaeosol records. *Quaternary International* ([dx.doi.org/10.1016/j.quaint.2008.05.028](https://doi.org/10.1016/j.quaint.2008.05.028)).
- Molodkov, A., Jaek, I., Vasilchenko, V., 2007. Anomalous fading of IR-stimulated luminescence from feldspar minerals: some results of the study. *Geochronometria* 26, 11–17.
- Satkūnas, J., 1999. The Upper Pleistocene stratigraphy and geochronology in Lithuania. *Litosfera* 3, 43–57.
- Satkūnas, J., Bitinas, A., 1994. The lithological composition of Saalian tills in Lithuania as a criterion for lithostratigraphical subdivision. *Acta Geographica Lodzienska* 68, 173–180.
- Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfson, Ó., Jakobsson, M., Kjær, K., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R., Stein, R., 2004. The Late Quaternary ice sheet history of northern Eurasia. *Quaternary Science Reviews* 23, 1229–1271.
- Vasilchenko, V., Molodkov, A., Jaek, I., 2005. Tunneling processes and anomalous fading in natural feldspars extracted from quaternary deposits. *Journal of Applied Spectroscopy* 72 (2), 218–223.

Appendix A
Supplemental material

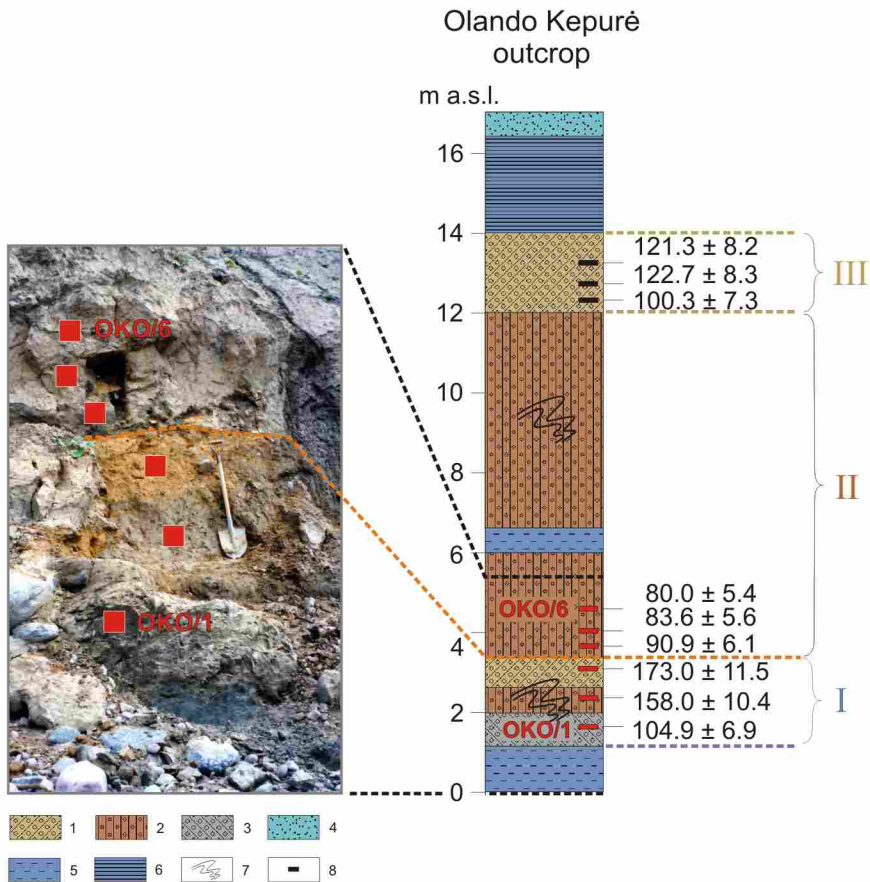


Fig. S1. Photograph and scheme of the lower part of the Olando Kepurè outcrop showing the contact between till complexes I and II. IR-OSL sampling points on the photograph are indicated by red squares; 1—brown or yellowish-brown till; 2—grey-brown or brown-grey till; 3—dark grey (or grey with a greenish tinge) till; 4—sand; 5—silt; 6—clay; 7—glaciotectionized sediments; 8—IR-OSL sampling points; number indicates an absolute age of sediment (in kyr). Roman numbers in the Olando Kepurè outcrop mark the till complexes described in the text.



Fig. S3. Detailed contact between till and inter-till sediments (fragment from the picture Fig. S2)



Fig. S2. Contact of grey till and lower-lying inter-till sediments in the core of borehole 62. IR-OSL sampling places indicated by a corresponding mark with arrow.



Fig. S4. Core of sampled grey-brown till in borehole 84.

