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OSL dating of Middle Weichselian age shallow basin sediments in Western Latvia, Eastern Baltic

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ABSTRACT

This paper presents the results of the first attempt to date the Quaternary sediments of western Latvia in the southeast Baltic region, using luminescence. The analyses have been carried out on sandy sediments of the Jurkalne Formation that are located between upper and lower Scandinavian sourced tills. Previous publications on the origin of the Quaternary sediments in the region are reviewed and it is found that there are a wide range of explanations for their processes of formation and their age of formation. It is concluded that although the sandy sediments were deposited in freshwater environment although they contain both marine and freshwater fauna and flora, a property that is explained by derivation and glaciotectonic deformation and mixing.

The samples used for dating were collected from surface exposures and boreholes and yield results that range in age from 52 ± 10 ka BP to 26 ± 4.1 ka BP. As a result of this study it is suggested that the dated sediments were deposited in a freshwater basin during MIS 3 and are overlain by a till deposited by Scandinavian Ice during the Late Weichselian (MIS 2/LGM). The underlying till is attributed to a Middle Weichselian glaciation and tentative suggestions are presented for the age of other deposits that underlie the dated sediment.

1. Introduction

The palaeogeography of northern Europe before the Last Glacial Maximum (LGM) of the Late Weichselian is not well documented because subsequent glaciation has destroyed much of the unconsolidated sediments. Despite this, recent attention has been drawn to the possibility of a Middle Weichselian glacial advance (Mangerud, 2004; Kalm, 2006) and Nenonen (1995) and Salonen et al. (2008) have proposed a glacial event between 79 ka and 62/55 ka BP, although in both cases evidence for timing and extent is sparse. Evidence for Middle Weichselian glaciation has also been reported from the southeastern side of the Baltic Sea in Estonia (Liivrand, 1991) and Poland (Marks, 1998, 2004). Zelcs and Markots (2004) have presented TL dates on glaciotectonically disturbed glaciofluvial sediments from the NW part of Latvia and proposed a possible ice advance in the area between 74 and 60 ka BP (Talsi Stadial), although these results are under debate, as recent attempts to date the same sediments using OSL are inconclusive (K.O. Eskola, pers. comm., 2008). Lacustrine sediments from NW Lithuania, dated to around 33 ka BP, have been attributed to the Middle Weichselian (Satkunas et al., 2009) at a site that is only 100 km south of the study area reported in this paper and a Middle Weichselian age has also been reported by Gaigalas (2000) who presented OSL dates on 19 samples from the Middle Nemunas lake and alluvial deposits that range from 63 ± 6 to 32 ± 4 ka BP.

Here we present the results of a study of glacial and basin sediments in western Latvia (Figs. 1, 2 and 4). These deposits are an extension of the thick Pleistocene sediments that occur beneath the Baltic Sea and provide a rare opportunity for investigating the Pleistocene history of the SE Baltic region prior to LGM. The sections consist of coastal bluffs that reach heights of about 10–18 m between the towns of Ventspils and Pavilosta (Fig. 2). Dreimanis (1936) was the first to study these sections along their entire length of more than 40 km, focusing on lithology of tills and the orientation of the glaciotectonic deformation structures. He identified a grey and a bluish grey till interbedded with, and underlain by, stratified sand, silt, clay or gravel, and assigned the upper till to the penultimate glaciation. Since then, the region has been revisited by numerous researchers (Dreimanis, 1936; Ulsts and Majore, 1964; Konshin et al., 1970; Veinbergs and Savvaitov, 1970; Danilans, 1973; Meirons and Straume, 1979; Segliņš, 1987; Kalnina et al., 2000; Kalnina, 2001), but this paper is the first to examine the sequence using OSL dating. The present results are

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Fig. 1. The southeastern Baltic region with the location of the study area in eastern Latvia.

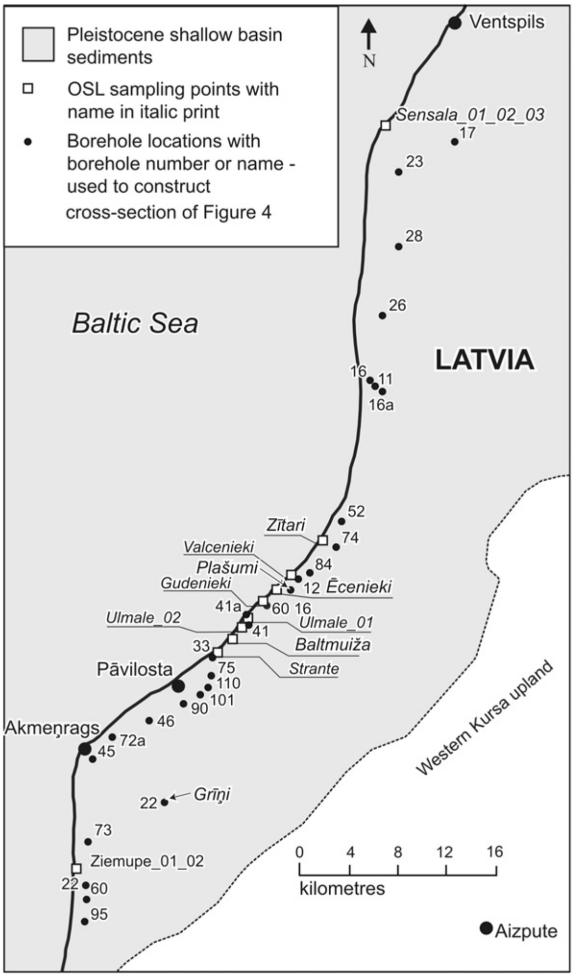


Fig. 2. Location of sites referred to in the text and to the OSL sampling points and location of boreholes used to construct the cross-sections in Fig. 4. The position of the cross-sections is shown with a dashed line. This figure also shows the extent of the Pleistocene shallow basin sediments in the region.

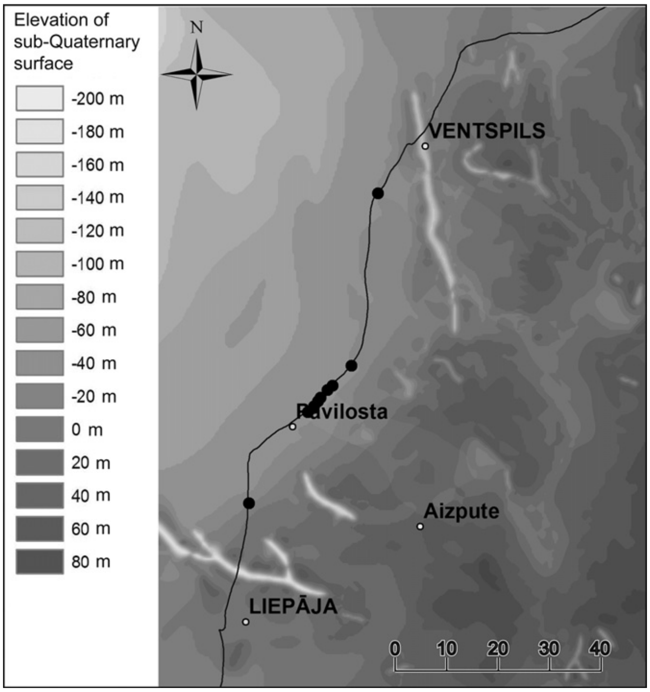


Fig. 3. The sub-Quaternary relief of western Latvia, showing also palaeo-incisions within this sub-Quaternary landscape.

part of an ongoing research programme into the chronology of the Pleistocene sedimentary sequence and dynamics of the ice sheets in western Latvia.

During several campaigns of geological mapping in western Latvia, numerous boreholes have been drilled and logged, revealing a complex succession of glacial and interglacial sediments as summarised in Figs. 3 and 4. The Pleistocene sequence in the coastal area, according to borehole logs, is up to 80 m thick (Fig. 3), being the eastern margin of a stack of Pleistocene and Holocene sediments that reach up to 200 m further west in the Baltic Sea near the Irbe Strait (Juškevics et al., 1998). The study area is located on the NE slope of the Baltic bedrock depression. The bedrock surface is 20 m below sea level in the southeast and extends down to 60 m below sea level in the NW with regional inclination of 3.3 m/km to WNW. The bedrock surface is intersected by several palaeo-incisions reaching up to 144 m below present sea level (Juškevics et al., 1998) (Fig. 3). Devonian sandstone, dolomitic marl, clay, dolomite and gypsum are overlaid by more than 70 m of Quaternary glacigenic, glaciofluvial, glaciolacustrine, lacustrine and marine deposits (Meirons and Straume, 1979; Juškevics et al., 1998). It is likely that an extensive and complex pre-LGM aged Pleistocene sedimentary record is preserved in the depression of the Baltic Sea, but until deep-sea drilling projects have been completed (e.g. Kotilainen et al., 2004) our interpretations must be based on adjacent terrestrial exposures.

2. Regional setting

2.1. Sedimentology and stratigraphy

The intertill deposits, that are the subject of this paper, were discussed and interpreted as marine by Konshin et al. (1970) and Veinbergs and Savvaitov (1970). Danilans (1973) attributed them to the Holsteinian age, whereas Serebryanniy et al. (1977) suggested that they were deposited during the Middle Weichselian.

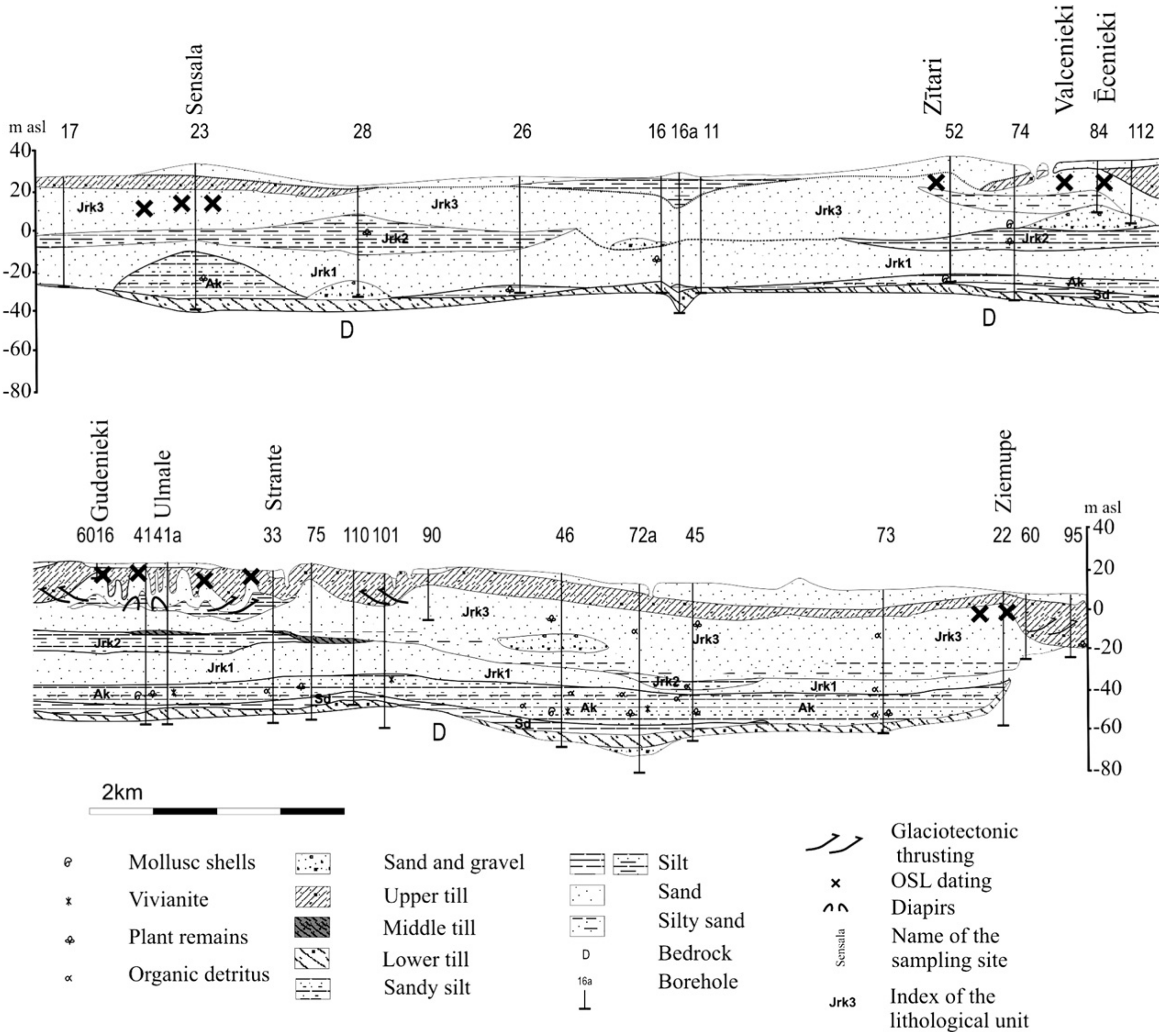


Fig. 4. Geological cross-section of the Pleistocene sequence in Western Latvia (modified after Kalnina et al., 2000). See Fig. 2 for the location of boreholes used for construction of this geological section. Symbols of lithological units discussed in the paper: Sd – Sudrabi beds; Ak – Akmenrags Formation; Jrk1, Jrk2, Jrk3 – units of Jurkalne Formation.

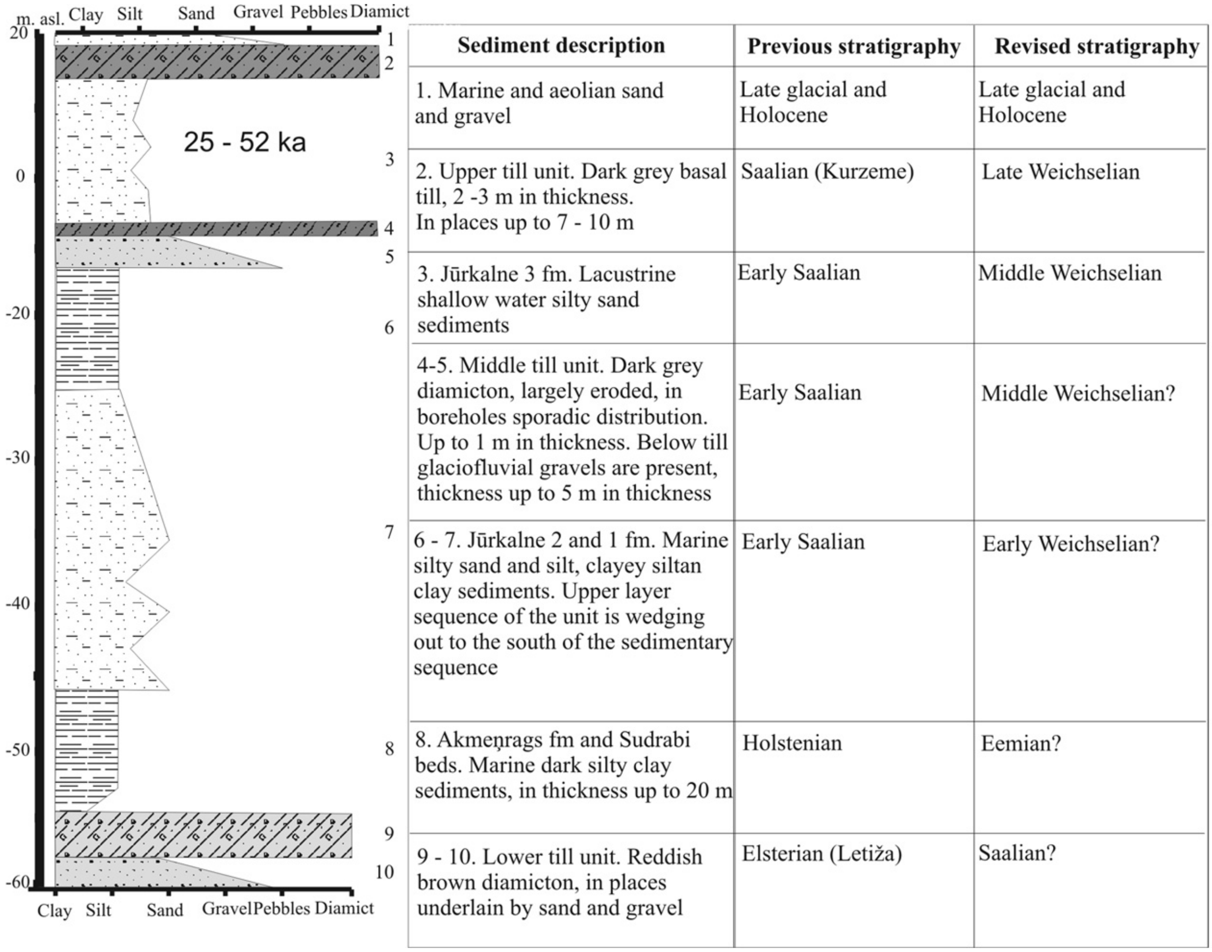
Three glacial-period diamict levels, interlayered by warmer-period marine silt and sand sediments have been distinguished on the basis of lithology and palynology (Kalnina et al., 2000) (Fig. 5). The basal reddish brown till, attributed to the Elsterian glaciation by Danilans (1973), Segliņš (1987) and Kalnina et al. (2000), overlies Devonian bedrock. This till unit is observed in most of the boreholes and is usually 2–3 m thick (Fig. 4).

The lowermost till is overlain by 25–30 m of clay, clayey silt and silt which form a coarsening upwards sequence. The lower part of the sequence, with a thickness of 1.5–6.0 m is fine grained and rich in organic material. Segliņš (1987) and Kalnina (2001) named this unit the Sudrabi beds (Sd on Fig. 3) within Akmenrags Formation (Ak on Fig. 3). Macrofossil and palynological analyses of these clays have identified plant remains, fragments of mollusc shells, particularly *Portlandia arctica*, ostracods and foraminifera (Konshin et al., 1970; Charamisinava, 1971; Kalnina, 2001). Segliņš (1987) suggested a Late Elsterian age for the Sudrabi member.

The Akmenrags Formation is composed of two facies – lower silt to sandy silt, and an upper sandy facies which are restricted to the southern part of the study area (Segliņš, 1987). The lower silty facies cover the lower clay sediments conformably, and its thickness increases up to 13 m near the Akmenrags (Figs. 2 and 4). Charamisinava (1971) reports several marine, brackish and freshwater diatom species from these deposits, but the marine species are dominant. The abundance of diatoms increases upwards. The silty lower part of the deposit is rich in disseminated organic matter, particularly plant remains, but also ostracods, foraminifera, diatoms and fragments of marine mollusc shells. Based upon the results of macrofossil and palynological investigations Konshin et al. (1970), Danilans (1973), Segliņš (1987), Kalnina et al. (2000) and Kalnina (2001) have assigned this sequence to the Pulvernieki (Holsteinian) Interglacial.

However, no reliable absolute dates are available to test the established stratigraphic interpretations and the confusion associated with these interpretations is highlighted by the fact that diatom studies have resulted in Charamisinava (1971) correlating the silty sediment to the Eemian Interglacial, and pollen studies by Meirons and Straume (1979) suggest that the assemblages show a close similarity with that of the Felicianova (Eemian) pollen record.

The Akmenrags Formation is overlain by 10–20 m of predominantly fine (0.1–0.25 mm) sand and silty sand, named by Kalnina (2001) as the lower Member of the Jurkalne Formation (Jrk1, see Fig. 3). Kalnina et al. (2000) noted signs of glaciotectonic



Sediment description	Previous stratigraphy	Revised stratigraphy
1. Marine and aeolian sand and gravel	Late glacial and Holocene	Late glacial and Holocene
2. Upper till unit. Dark grey basal till, 2 -3 m in thickness. In places up to 7 - 10 m	Saalian (Kurzeme)	Late Weichselian
3. Jūrkalne 3 fm. Lacustrine shallow water silty sand sediments	Early Saalian	Middle Weichselian
4-5. Middle till unit. Dark grey diamicton, largely eroded, in boreholes sporadic distribution. Up to 1 m in thickness. Below till glaciofluvial gravels are present, thickness up to 5 m in thickness	Early Saalian	Middle Weichselian?
6 - 7. Jūrkalne 2 and 1 fm. Marine silty sand and silt, clayey siltan clay sediments. Upper layer sequence of the unit is wedging out to the south of the sedimentary sequence	Early Saalian	Early Weichselian?
8. Akmeņrags fm and Sudrabi beds. Marine dark silty clay sediments, in thickness up to 20 m	Holstenian	Eemian?
9 - 10. Lower till unit. Reddish brown diamicton, in places underlain by sand and gravel	Elsterian (Letiža)	Saalian?

Fig. 5. Generalised representation of the Quaternary sequence in western Latvia with the previously established and reinterpreted chronostratigraphy.

deformation at the contact with the overlying diamicton south of Strante (Fig. 2) and conclude that "most pollen of Jrk1 sands appears to be redeposited" (Kalnina et al., 2000, p. 104). It should be noted that current understanding places the glaciotectonised silt at the Strante coastal bluffs into the upper Member of the Jurkalne Formation (Jrk2) and not to the Akmenrags Formation.

The Jurkalne 2 (Jrk2) silts overlie the Jrk1 unit (Kalnina et al., 2000) and the upper part of Jrk2 is often heavily dislocated due to diapirism. This means that it is difficult to determine correctly its initial position, distribution and thickness (Fig. 4). The organic content of these units is low although some brackish diatoms have been reported from the Jrk1 unit (Segliņš, 1987) and some marine diatoms from Jrk2 (Charamisinava, 1971). Kalnina et al. (2000) suggested open tundra vegetation during deposition of these silty sediments. Both Members have been correlated to the Early Saalian Stage (Segliņš, 1987; Kalnina et al., 2000; Kalnina, 2001).

The Jrk1 and Jrk2 Members are overlaid discordantly by a thin, fragmented till bed and glaciofluvial sediments. The till has been reworked and is encountered in only a few boreholes and exposures. Traces of this unit exist over some 10 km^2 NE of Cape Akmenrags (Fig. 2) in the southern part of the study area, although it cannot always be recognised as a separate unit (Juškevics et al., 1998).

The Jrk2 silty sediment and fragmentary middle till unit are covered discordantly by the Jrk3 sand Member (Fig. 4) which is up to 40 m thick. At the southern end of the study area the Jrk3 Member lies directly on the lowest reddish brown till. The upper part of the Jrk3 Member outcrops in the coastal sections and has been sampled for OSL dating. Unfortunately no in-depth study of sedimentology of this unit has been carried out and sedimentological description is based on limited lithological descriptions from the outcrop and boreholes (Veinbergs and Savvaitov, 1970; Saks et al., 2007; Kalvans and Saks, 2008).

The Jrk3 Member is composed of very fine and fine- to medium-grained sand, interlayered with silt beds which are, in places, rich in organic matter, layers. At Sensala, Ulmale, Baltmuiža, Strante and Ziemupe sites (Figs. 2 and 4) the sandy sequence comprises up to 1 m thickness of fine to medium-grained sand beds with silty interlayers. The sequence at Ulmale and Baltmuiža sites is the most coarse-grained, with individual beds reaching up to 2 m in thickness. In places the sand is cross bedded and cross laminated, the latter being interpreted as low energy ripple structures. Occasionally, trough cross-stratification is observed and this is interpreted as deposition by higher energy traction currents during the migration of dunes/megaripples.

To the south of Sensala, at Zitari, Valcenieki and Gudenieki (Figs. 2 and 4) the sequence is characterized by up to 1 m thick parallel-stratified, fine to very fine-grained sand beds interlayered by sandy silt and silt beds, rich in organic matter. These deposits are interpreted to be formed as lower flow regime plane beds. The facies assemblage of the sedimentary units described above suggests an environment by low energy currents and the deposition of plane beds, occasionally interrupted by higher energy dune sedimentation. Typically however, deposition recorded by the sediments across the study area is generated by wave processes and suggests shallow water locations above the wave base. Thus we interpret this sedimentary sequence as being formed in shallow coastal and lagoonal conditions, an interpretation that coincides with conclusions of Veinbergs and Savvaitov (1970, pp. 75–76) who stated that the dominantly sandy sediment, with some silty and clayey laminae, was deposited in a littoral area "… in the upper part of the silt zone, in the lower and upper part of the coastal underwater slope, and in the beach and in lagoons."

Organic content of this unit is sparse, but freshwater diatoms have been reported from (Seglinš, 1987), indicating that Jrk3 sequence was deposited in a freshwater lake. The lagoonal facies at Gudenieki are richer in organic matter, and palynological macrofossil analyses have been used to allocate this unit to either the late Holsteinian (Pulvernieki) (Danilans, 1973) or Early Saalian time (Seglinš, 1987; Kalnina et al., 2000; Kalnina, 2001).

The till at the top of the sequence was originally attributed to the Saalian Stage (Danilans, 1973; Kalnina et al., 2000), or to a composite of Saalian and Weichselian till (Juškevics et al., 1998, geological sections to the Map of Quaternary Deposits). The uppermost till is typically 2 m thick, reaching a maximum of 7–8 m. The top of the till has been eroded during the development of the BalticIce Lake, so in many places boulder concentrations, boulder pavements or sandy sediments replace the diamicton. A two-layer interpretation was introduced by Dreimanis (1936), who assumed a penultimate (Saalian) age for this deposit. With only limited critical evaluation this suggestion has been preferred by later workers such as Konshin et al. (1970), Danilans (1973), Juškevics et al. (1998) and Kalnina et al. (2000) so that the main constituent of the Western Kursa Upland is considered to be Saalian till, with Weichselian till playing only a minor part in the Pleistocene sequence (Meirons and Straume, 1979).

It is clear, therefore that the chronostratigraphy of western Latvia is far from being resolved, and new independent dates are needed to clarify this situation.

2.2. Structural geology

Only the upper part of the Pleistocene sequence, which outcrops in the coastal bluffs, has been examined for structural geology. The structural architecture is dominated by a glaciotectonically deformed three-layer system – the silt and clay sediments at the bottom, sandy sediments in the middle and till at the top. This sequence is complicated by density-inversion and glaciotectonically induced structures.

All glaciotectonic deformation structures have been attributed to a deglaciation phase of the last Scandinavian ice sheet, when ice in the area formed active glacial tongues (Zelcs and Markots, 2004). Two different glaciotectonic assemblages have been described: (i) glaciotectonic structures associated with the marginal parts of the glacial tongues; (ii) glaciotectonic structures associated with the central parts of the glacial tongues.

The marginal glaciotectonic structures include unidirectional thrusting and/or folding with compressional stress direction at right angles to the overall direction of glacial movement. The Sensala, Gudenieki, Strante and Ziemupe sampling sites (Fig. 2) are at marginal (lateral) zones of the glacial tongues. Deformation in the central parts of the glacial tongues comprises uplifted diapiric structures with till preserved in the inter-diapiric spaces. There is little or no internal deformation. Ulmale and Baltmuiža sampling sites are taken from this structural province. The Zitari sampling site shows no signs of glaciotectonic activity and is interpreted as representing an area of the ice stagnation during the last deglaciation.

Examination of sampling sites from the zones of glacially- or density-driven deformation indicates that the sampled sediments could have been uplifted from deeper levels with the sequence. This means that the age distribution needs to be interpreted with caution.

3. Methods

Sensala (01, 02 and 03), Zitari and Valcenieki OSL samples (Table 1) were collected in copper tubes 2.5 cm in diameter and 50 cm in length. Samples were obtained by hammering the tubes into a previously cleaned outcrop. At each sampling site 4 tubes of the sediment were collected. In addition, an extra sample was collected for moisture and gamma dose measurements at points 20–30 cm above and below the respective sampling site.

The Ecenieki, Gudenieki, Ulmale (01 and 02), Baltmuiža, Strante and Ziemupe (01 and 02) OSL samples were collected by coring into the outcrop, using an Eijkelkamp liner sampler set for sampling undisturbed soft soils. A sample was collected in the 4.5 × 40 cm PVC tube, which was placed in a container in a dark environment. Additionally an extra sample for moisture and gamma dose measurements was collected 20–30 cm above and below each sampling site.

In all cases OSL samples were collected from at least 0.5 m thick, well sorted fine to medium-grained sand layers. All of the samples were treated and processed at the University of Helsinki Dating Laboratory using quartz and feldspar from the 210–297 μm size fraction.

In this study, beta dose rates were measured from the untreated sample material with a Risø GM-25-5 beta multicounter

Table 1
Luminescence dates for all samples from the Baltic Sea coastal region.

Sample	Size range (μm)	Mineral used	Method OSL/IRSL	Dose rate (mGy/a)	Absorbed dose (Gy)	Age (ka)
Sensala 01	210–297	Quartz/Feldspar	OSL/IRSL	2.06	87.8 ± 10.35	43 ± 5.0
Sensala 02	210	Quartz/Feldspar	OSL/IRSL	1.75	78 ± 13.36	45 ± 7.7
Sensala 03	210	Quartz/Feldspar	OSL/IRSL	1.55	67.9 ± 15.57	44 ± 10
Zītari	210	Quartz/Feldspar	OSL/IRSL	1.51	55.64 ± 10.65	37 ± 7.1
Ēcenieki	210	Quartz/Feldspar	OSL/IRSL	1.77	58.4 ± 5.22	33 ± 3.4
Gudenieki	210	Quartz/Feldspar	OSL/IRSL	2.34	105.8 ± 9.89	45 ± 4.2
Valcenieki	210	Quartz/Feldspar	OSL/IRSL	1.30	53.1 ± 12.88	41 ± 9.9
Ulmale 01	210	Quartz/Feldspar	OSL/IRSL	1.45	37.9 ± 5.62	26 ± 4.1
Ulmale 02	210	Quartz/Feldspar	OSL/IRSL	1.41	39.6 ± 6.13	28 ± 4.6
Baltmuiža	210	Quartz/Feldspar	OSL/IRSL	1.59	41.5 ± 3.64	26 ± 2.6
Strante	210	Quartz/Feldspar	OSL/IRSL	2.00	68.6 ± 8.54	34 ± 4.6
Ziemupe 01	210	Quartz/Feldspar	OSL/IRSL	1.54	72.8 ± 7.43	47 ± 5.4
Ziemupe 02	210	Quartz/Feldspar	OSL/IRSL	2.01	105 ± 19.8	52 ± 10

(Bøtter-Jensen and Mejdahl, 1988). The conversion of the measured beta dose rate to absorbed dose is based on fitting the measurements to values from a set of reference samples of Finnish soil with known U, Th and K content as determined by neutron activation (University of Helsinki Dating Laboratory, unpublished data). The conversion includes correction for grain size with the assumption that the measured material is dry.

The water content of the samples was measured in the laboratory by weighing material, from the side of the tube, after it was saturated with water and again after drying. For samples Sensala 01, 02 and 03, Zitari and Valcenieki water content was assumed to be 20% (Eskola K.O., pers. com., 2009), which somewhat overestimates the real conditions.

The dose rate measurements of the purified quartz and feldspar samples were determined according to a single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000). The quartz and feldspar were density separated from separated sand fractions and OSL-measurements were calculated using blue-LED and infrared stimulation on feldspar.

4. Results

All the OSL samples were taken from the upper sandy sediment sequence Jurkalne 3 (Jrk3) (Fig. 4). In all cases a clear relationship was observed between the fine sand and the overlying till (uppermost till unit). Further details of individual sites can be found in Saks et al. (2007) (for Sensala) and Kalvans and Saks (2008) (for Ziemupe); and other site descriptions can be found in numerous field symposium guides and conference proceedings (Zelcs, 2004, pp. 35–56). The natural luminescence values intersected the linear part of the growth curves for all of the samples, and no saturation problems were encountered (Fig. 6A and B).

OSL samples at the Sensala site were collected from the sand beds outcropping in the coastal bluffs. Samples were collected some 50–100 m apart. In all cases at least 0.5 m thick, well sorted fine sand layer was selected. Sensala 01 sample was collected 2 m below the upper till unit, while at the Sensala 02–03 sampling sites upper till was absent. In all cases samples were collected at least 3 m below the surface, to insure that no contamination from soil forming processes. All of the OSL ages obtained from these samples are in a close range (43–45 ka, see Table 1 for more detail). The OSL signal obtained from the Sensala samples show a wide range of results (Table 1). This is attributed to rapid sedimentation and differential bleaching of the sand material, which increase the separation of the results. The OSL results from Sensala, based on feldspar, overestimate the age of the sample, or the results are otherwise insecure. In contrast, those based on infrared stimulation (IRSL) are in good agreement with the results obtained from quartz with OSL. This suggests that the sand has been affected by sunlight for only short periods during transport and deposition, and the relatively slow OSL-traps were bleached only partially.

Gudenieki sampling site is situated on the northern slope of the Gudenieki gully, at the coastal bluffs (Fig. 2). The sample was collected from the fine-grained sand layer overlaid by finely laminated silty clay and clay and interlayers of sand, rich in organic content. Sample was collected from the 1.2 m horizontal depth and approximately 1.5 m from the top of the bluff, which could be a source of error due to possible contamination from soil processes. The OSL age obtained for this sample is 45 ± 4.2 ka, which is somewhat older than closest samples at Ēcenieki and Ulmale. It is not clear whether contamination of the sampled layer has occurred, or the older ages are due to glaciotectonic thrusting at this site.

Valcenieki sample was collected 180 m S from the Valcenieki gully (Fig. 2), in a depth of 1.5 m of the cleaned exposure. The sample was collected in the thinly laminated sediments of fine sand and silty sand and silt. The OSL age of the sample yields 41 ± 9.9 ka.

Zitari sample was collected 200 m N from the Zitari gully, 5.1 m below surface of the cleaned-up fresh exposure (Fig. 2). The sample was collected from the well sorted fine-grained sand overlaid by sandy upper till. Upper till is laminated and partially sorted, suggesting deposition under water column. The OSL age of this sample yields 37 ± 7.1 ka, which is in good agreement with the closest Valcenieki sample, which has also similar glaciotectonic setting.

The analyses based on the samples from Gudenieki, Valcenieki and Zitari sample in general, gave good results from the quartz measurements and incomplete results from the feldspar. The feldspar measurements give considerably older ages than OSL from quartz, again signifying that sedimentation was rapid and the sand had not been bleached by sunlight. The grain size of the Gudenieki samples has proved to be too small and the amount of feldspar extracted was not ideal with respect to sample size and quality. The potassium content of the feldspar used in the Valcenieki sample was quite high (about 10.2%) with the result that inner dose rate for the feldspar had to be calculated, leading to a change of total dose rate of feldspar to about 2.10786 mGy/a. In effect this inner dose rate may introduce some error into the results. The results on the feldspars from the Zitari sample show large variation with ages ranging from close to the results obtained with quartz up ages to ages about three times the quartz age. Once more this suggests that deposition of the sands was so rapid that feldspar was not completely bleached.

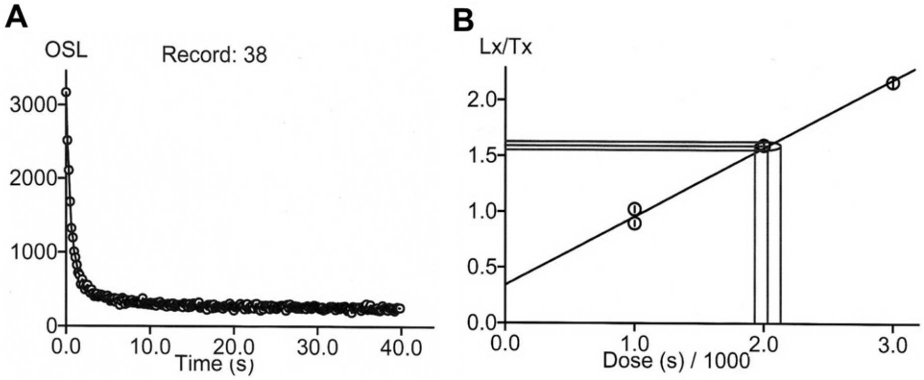


Fig. 6. Shine down curve (A) and growth curve (B) from an aliquot from Strante sample (quartz). This is typical of the results obtained from Ulmale, Baltmuiža, Ziemupe and Strante. The signal strength is quite good and the natural OSL (Ln/Tn) intercepts the growth curve well below the saturation levels. The black lines in B illustrate the errors of the Ln/Tn measurements and the dose estimate.

Baltmuiža sample were collected from the cleaned section at the coastal bluffs, in approximately 3 m depth. Sampled layers are situated between diapir structures, but no glaciotectonic disturbance is present. The sample was collected from the plane-parallel laminated fine-grained sand bed with some admixture of silty particles. Thickness of the individual laminas does not exceed 2 cm. Above the sampled layers occasional current ripple marks are present. According to sedimentalogical description coastal and/or shallow water depositional environment is suggested for this section of the coastal bluffs.

Ulmale sample 01 was collected in a 3 m depth below the surface. Lacustrine sediments at this site are composed of fine- to medium-grained, up to 1 m thick sand beds overlain by the upper till, with characteristic current ripple marks. The sedimentary properties suggest that this was deposited in a shallow water environment similar to that at the Baltmuiža site. Ulmale sample 02 was collected under similar conditions, some 100 m to the south from the Ulmale 01 sample. The sedimentary structures of these deposits are similar, with characteristic current ripple lamination. Both these samples were taken between the two diapir structures. Structural analysis of these outcrops suggests that interdiapir spaces were formed by the downward movement responding to the rising of diapirs, inhibiting these areas from glacial erosion (Saks et al., in review). This could explain the overall younger OSL ages in Ulmale and Baltmuiža samples when compared to other sampling sites.

The OSL age of Baltmuiža sampling site (26 ± 2.6 ka) and nearby Ulmale sampling sites (26 ± 4.1 and 28 ± 4.6 ka) are the youngest obtained from these sediments, and probably mark the final stage in the process of infilling the lacustrine basin of the study area.

Strante sample was collected some 200 m to south from the Strante gully. The sample was obtained from an approximately 30 cm thick, well sorted fine-grained sand layer, overlain and underlain by thinly laminated beds, containing some organic matter. The sand material is glaciotectonically stressed, but the bedding of the sand is preserved. Some 10 m to south, a thrust fault surface can be traced, suggesting that the sample has been thrust upwards as a more or less undisturbed block. The OSL age of the Strante sample is 34 ± 4.6 ka, which falls in the middle of the age distribution.

Ecenieki sample was collected at the Ecenieki gully, in a cleaned Section 3 m below the top. The sample was taken from the 30 cm thick medium- to fine-grained sand layer within the plane-parallel laminated sand and silty sand beds. The OSL age of this sample is 33 ± 3.4 ka.

Ziemupe samples 01 and 02 are taken from a site which is a considerable distance from other sample localities to the south (Fig. 2). Sample Ziemupe 02 was obtained from the cleaned section on the flank of the diapir fold. The sampled lacustrine sediments here have plane-parallel laminated structure, but the grain size is varying from silty sand to fine-grained sand. The sampled layer is overlain by upper till.

Ziemupe 01 sample was collected in a cleaned section some 200 m from the site of Ziemupe 02 sample point. The sediments here that have been used for dating are better sorted, and current ripple laminated fine-grained sands are common. As at the Ziemupe 02 sampling site, this sample was also collected on the wing of the diapir fold. In both cases no inter layer glaciotectonic disturbances are observed. The OSL age obtained for these samples (Ziemupe 01 − 47 ± 5.4 ka and Ziemupe 02 − 52 ± 10 ka) represents the oldest part of the lacustrine sediments, and possibly marks the beginning of the deposition of the freshwater lake sediments in the study area.

Dating results on samples from Baltmuiža, Strante, Ecenieki, Ziemupe and Ulmale show clear age distribution, although amount of material suitable for analysis from the Ziemupe 02 sample was very limited due to the fine grained nature of the sand unit.

In addition to the problems caused by differential bleaching and inherent problems with the luminescence method, variations in ages may be controlled variations in the amounts of glaciotectonic deformation which may have moved older sediments into contact with, or the position of younger sediments.

5. Discussion

MIS 3 experienced a number of abrupt climatic oscillations consisting of warming phases known as Dansgaard-Oeschger events, interrupted by short periods of cold conditions (Van Meerback et al., 2009). These changes are reflected in a number of ways depending upon the sedimentology of the geological and environmental systems and climate-induced fluctuations in sea level are likely to be one of the effects of these changes that should be reflected in depositional records. Rabineau et al. (2006) estimate that global sea level was 30–80 m lower than present at the beginning of MIS 3, and 65–95 m lower at the end of MIS 3. Given the limited extent of the Middle Weichselian Scandinavian glaciation, the magnitude of isostatic depression is likely to be significantly smaller than the fall of global sea level. Middle Weichselian deposits from western Latvia do not indicate these changes suggesting that the study area was well above the global Middle Weichselian sea level and sediment sequence was deposited in a freshwater lake, isolated from the ocean by barriers to the west (Danish straits) and northeast (outlet to the White Sea).

The youngest luminescence ages are from the central part of the sandy sediment sequence (Jurkalne 3 (Jrk3)). This can be explained as a consequence of a gradual fall in water level in the basin. The youngest obtained ages ~26 ± 4.1 ka (Table 1) provide evidence that can be used to determine when the last Scandinavian glaciation reached the south east part of the Baltic Sea region. This age supports a late onset and rapid advance of Late Weichselian glaciation in the southeast Baltic region and supports the findings of Satkunas et al. (2009) who reported lacustrine sediments and peat ~33,000 cal a BP from a site relatively close to the study area in the northwest Lithuania. Radiocarbon dates on peat with wood remains below reworked till at Jonionys (stratotype for the Merkine (Eemian) interglacial) has yielded a radiocarbon age of 31,500 + 2300/−1800 BP (Gaigalas et al., 2001). Similar maximum ages of the last glacial advance (36,000 to 32,000 years BP) obtained with radiocarbon and TL dating methods are suggested by data compiled of Zelcs and Markots (2004). Kalm (2006) has demonstrated that Estonia was ice free between 43.2 and 26.8 ka BP. Thus a consistent picture is emerging for the timing of Late Weichselian advance in the region.

The oldest ages from Ziemupe site were derived fro the basal part of the upper sandy sequence (Jurkalne 3 (Jrk3)). In this part of the section Jrk1 Member and Jrk2 Member, along with the Akmenrags Formation are missing, while the upper sandy member (Jrk3) lies directly on the lowest till (Fig. 4). The overall thickness of the Pleistocene sediments here is only 20–30 m. Thus, with the evidence that is available it is possible to conclude that deposition of the upper sandy sequence (Jurkalne 3 (Jrk3)) started to form at around 50 ka BP, towards the beginning of the MIS 3. Salonen et al. (2008) have presented evidence of the Middle Weichselian deglaciation, which occurred in northern Finland between 62 and 57 ka BP, and corresponds with the oldest ages obtained here. These ages give a date for the possible onset of the Middle Weichselian Baltic Interstadial Lake.

The MIS 3 age for the freshwater Jurkalne 3 (Jrk3) unit means that the upper till unit was deposited during the Late Weichselian glaciation (LGM) (Saks et al., 2007), and is not the combined sediments of Late Weichselian and Saalian glaciations as suggested by Juškevics et al. (1998), Kalnina et al. (2000), and Kalnina (2001). These results also challenge the established stratigraphical subdivision of the Pleistocene sediments below the dated unit.

The sediments that have been subjected to our OSL dating programme have previously been assigned to either late Holsteinian (Pulvernieki) (Danilans, 1973) and Early Saalian time (Seglinš, 1987; Kalnina et al., 2000), or in the comparatively small depressions at Plašumi and Grini (Kalnina, 2001, p. 157) to Late Eemian time. In the light of the new OSL dates none of these interpretations seem to be valid. However, the possibility that the dated sandy sequence was deposited significantly later than the underlying silt-clay-rich sediments cannot be excluded.

The age of glacial sediments below lacustrine dated sediments is still open to question, the minimum age is limited to beginning of MIS3 or the end of MIS4, but the maximum age is not constrained by any reliable absolute dating ages. However, based on the evidence below we suggest a new interpretation. Svendsen et al. (2004) confirm that after the last Eemian interglacial three large continental glaciation phases can be distinguished in Northern Eurasia – the Early, Middle and Late Weichselian cold stages. They conclude that the Middle Weichselian glaciation extended into the territory of Estonia and within the depression of the Baltic Sea to the southwest. We suggest that traces of this glaciation are observed in the western Latvia lowlands as well, indicating that the ice covered most of the depression of the Baltic Sea at that time. Additionally it is difficult to imagine that the Saalian glaciation, which extended far beyond the limits of the Weichselian ice sheets, would have left only a few patches of glacial and glaciofluvial deposits squeezed between two thick sequences of unconsolidated basin sediments deposited during warm phases. Regional data suggests that deposits of the Early Pleistocene and even the Middle Pleistocene sequences were destroyed or incomplete due to vigorous erosion of subsequent glaciations (Raukas et al., 2004). Therefore we suggest that these patch of sediment are the glacial deposits of Middle Weichselian (MIS 4) age, formed by a glacial advance that was spatially more limited than the Saalian glaciation.

The new findings have implications regarding the interpretation of the Pleistocene sediments underlying the dated sediment sequence. We also propose that the soft sediments resting on the bedrock slope were susceptible to large-scale glaciotectonic deformation, similar to those described by Andersen (2004) in the southeast Danish North Sea region. This process and associated redeposition may be a reason for the observed mixing of faunal and floral remains from different habitats. For instance the lower marine clay (Akmenrags Formation) contains fragments of the *P. arctica* shells (Meirons and Straume, 1979; Seglinš, 1987; Kalnina et al., 2000; Kalnina, 2001). Dreimanis (pers. com., 2010) reported on occasional findings of the *P. arctica* shells in coastal outcrops south of Jurkalne and elsewhere, presumably in the silt and silty clayey sediments from the Jrk2 unit (See Fig. 5 for stratigraphical position).

Also, marine diatoms were encountered in the Jrk2 (Seglinš, 1987). ESR dating of the *P. arctica* shells from Pleistocene marine sediments at Licupe in central Latvia gives ages of 88.5 ± 7.3 and 97.8 ± 8.2 ka BP (Molodkov et al., 1998). These Early Weichselian interstadial marine sediments have been rafted and transported subglacially by the Riga ice stream during the last glaciation to central Latvia, a distance of at least 120 km from their original location in the Gulf of Riga (Dreimanis and Zelcs, 1995). Therefore further development of improved stratigraphy for the lowermost part of the Pleistocene sequence needs high-resolution seismic and borehole data, and reliable absolute age measurements.

6. Conclusions

OSL dating results of the freshwater lacustrine sediments from western Latvia suggest deposition during the Middle Weichselian (MIS3) time. The ages obtained bracket the age of the basin from the early Middle Weichselian time (52 and 47 ka) to the end of the Middle Weichselian time (25–26 ka). New OSL dates indicate the need for substantial re-evaluation of the upper part of Quaternary sedimentary sequence within the region. The results also indicate the need for a critical re-examination and re-interpretation the lowermost part of Pleistocene sequence in western Latvia. This work is needed in order to place the Quaternary history of the southeast Baltic region in a wider perspective, particularly with respect to the evolution of the Baltic depression through Pleistocene interglacials and interstadials. More caution should be exercised in evaluating the macrofossil and palynological data because most of the coastal and lagoonal facies in the study area were deposited in relatively shallow depths above the wave base, and much of the Pleistocene sequence has been glaciotectonically stressed and deformed at least twice, thus complicating any palaeoenvironmental interpretation.

1) The upper till unit was deposited during the Late Weichselian glaciation, rather than during the Saalian or combined Saalian and Late Weichselian glaciations as previously suggested
2) A large, freshwater lake existed in the Baltic depression during Middle Weichselian/MIS 3 at least from 52 to 25 ka. These ages allow a more definite maximum age limit to be determined for the latest Scandinavian ice sheet reaching western Latvia.
3) The Pleistocene sediments below the dated sandy sequences are interpreted as follows: (a). The middle till unit probably belongs to the Middle Weichselian glaciation (MIS 4). (b). Jrk1 and Jrk2 units are assumed to be Early Weichselian or Late Eemian. (c) The Akmenrags Formation is correlated with the Eemian Interglacial (MIS 5), and not the Holsteinian. (d) The lower diamicton is likely to have been deposited during the Saalian glaciation. It is suggested that erosion by Saalian age ice destroyed the evidence for the Elsterian glaciation in the study area. These are provisional presumptions that require independent absolute age dates for confirmation.

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