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Thickness distribution of quaternary deposits in the formerly glaciated part of the East European plain

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A thickness map of Quaternary deposits in the south-eastern sector of the last Scandinavian Ice Sheet (SIS) and in areas of Middle Pleistocene Moscow (Warthe) and the Dniepr (Drente) stages of the Late Saalian glaciation on the East European Plain is presented (Main Map). The map of the thickness and related statistics of the Quaternary deposits were calculated from the difference between the current digital terrain model and the bedrock surface topography model. The distribution of Quaternary deposits shows that 29% of the mapped territory has sediments less than 25 m thick, 16% more than 100 m and 1.2% more than 200 m. Within the SIS area, the thickness of sediments in the southern sector exceeds threefold the sediment thickness in the eastern flank. This difference is attributed to the bedrock depression in the south-east of the Baltic Syneclise rather than to glacial dynamics. The calculated average thickness of the sediments within the SIS area is ca 50 m, in the formerly glaciated area outside the LGM it is ca 61 m and outside the glaciated area ca 14 m. Our study confirms that, in formerly glaciated areas, the spatial distribution of sediments did amplify the differences in glacial bed topography with the exception of the southern and eastern flanks of the Moscow glaciation area where exceptionally thick Quaternary deposits have inverted bedrock depressions into elevated areas in recent terrain. We suggest that the map presented improves existing knowledge of this area by adding detail and thus contributing to the on-going development of numerical ice-sheet models.

Keywords: bedrock surface topography; digital elevation model; Pleistocene; Scandinavian Ice Sheets

1. Introduction

The modelling of palaeo ice sheets increasingly demands detailed numerical data on glacial geomorphology and sediment distribution. Numerous studies have shown that glacial bed topography controls the direction and velocity of ice flow (Winsborrow, Clark, & Stokes, 2010), resulting in glacial erosion, transport and deposition of the existing uneven distribution of sediments. It has long been recognised that the formerly glaciated Fennoscandia and adjoining area show large spatial differences in the thicknesses of the Quaternary deposits and exhibit distinct patterns of glacial scouring and accumulation. Kleman, Stroeven, and Lundqvist (2008) summarise and explain the spatial pattern of sediment distribution in the area with a complex model of a
climate related chain of events, where each subsequent event has potentially preserved, remobilised, or removed deposits that were available at the close of the previous event. Their overall conclusion results in a model of the pattern of glacial drift and scouring zones. However, the modelling of the locations and flow directions of ice-streams in the south-eastern sector of the last Scandinavian Ice Sheets (SIS) have demonstrated complex patterns and also that the spatial distribution of Quaternary deposits is extremely uneven and has much more complex patterns than presented by Kleman et al. (2008) and Amantov, Fjeldskaar, and Cathles (2011). In this study, we present a thickness map of Quaternary deposits in the formerly glaciated area on the East European Plain. The initial data available on glacial paleogeography and landform distribution from this region, utilised in ice-sheet or deglaciation models (Arnold & Sharp, 2002; Boulton, Dongelmans, Punkari, & Broadgate, 2001; Boulton, Hagdorn, Maillot, & Zatsepin, 2009; Ehlers & Gibbard, 2004; Kalm, 2012; Kleman & Glasser, 2007; Kleman et al., 2008; Naslund, Rodhe, Fastook, & Holmlund, 2003), has been rather limited and many details, particularly sediment distribution relative to bedrock topography and ice-stream locations, are not well known. The purpose of this mapping is to define the extent and thickness of the major deposits of the Quaternary age to support further numerical modelling of glacial events in the area.

2. Methods

The mapped area (1,013,571 km$^2$) on the East European Plain covers the territory from the Baltic Sea coast in the west (20° E to 40° E) and is bounded by 52° N and 60° N in the meridional direction (Figure 1). Using MapInfo 10.0 software, the thickness map of the Quaternary deposits was

![Figure 1. Location of the mapped area on the East European Plain with an indication of the maximum extent of the last SIS.](image)
simulated as the difference between the current digital elevation model (DEM) and the bedrock surface topography model. The DEM data with a relative spatial resolution of \( \sim 30 \text{ m} \) were derived from the Shuttle Radar Topography Mission (International Centre for Tropical Agriculture, 2004. Hole-filled seamless SRTM data V1. http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm; last accessed 12.09.2011). According to the original SRTM requirement specification, the absolute vertical height accuracy of the CGIAR-CSI SRTM data should be \( \leq 16 \text{ m} \).

The areas of the large lakes, Lake Ladoga and Lake Peipsi, were updated with bathymetry data. As there is no existing bedrock topography map for the whole study area, we used different accessible published and unpublished sources to compile the digital bedrock topography model. Local and/or national bedrock maps of the Baltic countries (Meirons, Straume, & Juškevics, 1974; Miidel, Noormets, Hang, Floden, & Bjerkeus, 2001; Siaupa, 2003; Tavast & Raukas, 1982), Poland (Ber, 2000), Belarus (Komarovsky, 2009; Mander, 1973; Valchik, Zus, Fedenya, & Karabanov, 1990) and Russia (Breslav, 1971; Isachenkov, 1982; Orlenok, 2002; Sammet, Suschenko, & Ekman, 1967; Tatarnikov, 2007), although compiled at very different times, provided the best available information. Often the original bedrock topography maps/sketches had a little or no geographic information and their geometric correction (registration) was required before it was possible to use the data within a geographic information system (GIS). All these sources, at different scales and accuracies, were digitised and then using interpolation (triangulation with smoothing), a raster map together with a 3D model of the bedrock surface topography for the whole study area was created. In presenting the map and simulating the thickness distribution of Quaternary deposits, we temporarily excluded data from deep and narrow erosional valleys on the bedrock surface, the known distribution of which over the study area is very uneven and knowledge about their morphology is spatially limited.

For the spatial analysis, we tentatively divided the mapped area into four zones with three sub-zones (Figure 2). The first zone is a continental area of distribution of Late Weichselian glaciation (Vistulian in Polish, Valday in Russian) with three sub-zones: from the Baltic Sea coast to the Sakala (in Estonia) and Luga ice-marginal zones (1A); the area between the latter and the Middle Lithuanian (Krestets in Russia) ice-marginal zone (1B) and from the Middle Lithuanian to the last glacial maximum (LGM) zone (1C). The second zone holds the area between the LGM and the maximum extent of the Moscow (Warthe) glaciation and the third zone is bounded by the maximum extent lines of the Moscow (Warthe) and the Dniepr (Drente) stages of Late Saalian glaciation. A rather small area outside the glaciated territory is currently defined as a fourth zone. Additionally, the SIS area was divided into four sub-meridionally oriented sectors (Figure 3) which follow the nomenclature of the main ice-stream complexes from Kalm (2012).

3. Recent terrain of the study area

The study area is located within the East European Plain, which, in this area, coincides with the East European craton. This explains the flat terrain with an average altitude of \( \sim 145 \text{ m} \) and with maximum heights in the Valday region of about 353 m above sea level (a.s.l.) (Figure 4). Most areas lie between 100 and 200 m a.s.l. (59.6%). However, altitudes up to 100 m dominate inside the LGM zone (51.5%), while in other zones they comprise less than 3%. In contrast, altitudes above 200 m are most common in the fourth zone (72.6%), have a significant spread in the second and third zones (25.4% and 20.9% respectively), and cover only 5.8% in the first zone. The area has been repeatedly subject to the expansion of large continental ice sheets. The glacial-accumulative topography is best seen in the area of the Late Weichselian glaciation in the NW and W with an average altitude of \( \sim 73 \text{ m} \). There, meridionally oriented glacial depressions mark the footprints of major ice lobes (Kalm, 2012), while interlobate zones in between are marked by a radial series of insular like uplands (Figure 4). In the northern part
Figure 2. Zoning of mapped territory with selected statistics on the spatial distribution of the Quaternary sediment thicknesses.
plinth-type uplands (Ižora, Pandivere and Sakala), with outstanding bedrock cores and thin (<10 m) Quaternary cover, remain lower (125–175 m) compared to the average of 225–350 m characteristic of the glacial-accumulative heights with thick Quaternary cover (up to 200 m) located in the central and southern parts of the SIS extension area. A series of outstanding uplands (Vepsa, Tihvin, Valday, Vitebsk, Minsk and Ošmyan) mark the LGM zone of the SIS and are also characteristic of the areas of the Moscow (Warthe) and the Dniepr (Drente) stages of the Late Saalian glaciation (Figure 4). There, the original glacial-accumulative topography has been modified by erosion. The uplands and ranges of hills alternate with broad valleys, outwash and alluvial low-lying (130 m) plains, the latter, alternating with till plains, being more characteristic of the southern and eastern parts of the study area. The southern part of the Central Russian Upland, with an average altitude of 220 m and gently sloping terrain towards the south, represents a non-glaciated terrain in the SE part of the study area and is characterised by a dense network of deep (60–80 m) erosional valleys cut into loessial loams.

4. Bedrock topography
A bedrock topography map is the first compilation of available data for the whole study area covering the formerly glaciated and part non-glaciated area of the East European Plain (Figure 5). Distribution of the bedrock surface altitude shows that 57% of it lies between 25 and 125 m a.s.l. Altitude varies within the range of ~415 m (between ~128 and 287 m a.s.l.), while 92%
of the territory lies above the current sea level and the average level of the bedrock surface is \( \approx 89 \) m. In this calculation, we have not counted extreme depths recorded in deeply incised bedrock valleys reaching, for example, \(-273\) m a.s.l. in Latvia (Isachenkov, 1988; Meirons et al., 1974), \(-208\) m a.s.l. in Estonia (Raukas & Tavast, 1982) and \(-122\) m a.s.l. in northern Belarus (Komarovsky, 2009). The highest bedrock elevations in the study area are recorded in the western part of Valday Heights (\(\approx 230\) m a.s.l.) with a maximum 287 m a.s.l (Isachenkov, 1988) at Selizharovo. The lowest areas are located on the Baltic Sea coast in north-eastern Poland (Mazuria), the Sambia Peninsula of Russia (Kaliningrad District) and south-western Lithuania, where, in the Baltic Syncline area, the bedrock goes down to 128.3 m below sea level (b.s.l.) (Kondratene & Vonsavičius, 1994). At a large scale, the topography of the bedrock surface is very well reflected in the recent terrain of the study area (Figures 4 and 5). Larger depressions (Gulf of Riga, Lake Peipsi and Ladoga–Ilmen) as well as elevations (Pandivere, Ižora, Haanja, Vidzeme, Latgale, Kursa, Luga, Bežanitsy, Valday, and Tihvin) are clearly seen in both the current topography and on the surface of the bedrock (Figures 4 and 5). Here the exception is the southern region of the Baltic Syncline and the eastern flank of the Moscow glaciation area where deep bedrock depressions are not reflected in the current topography.

5. **Spatial distribution of the thicknesses of Quaternary deposits**
The thickness map of Quaternary deposits (Figure 6) reflects the differences between the current terrain and the bedrock surface topography models. The thickness of the Quaternary sediments in
the study area is highly variable, ranging from 0 m to 359 m (with the maximum in the Baltic Synclise) and \(\approx 55.4\) m on average (Figure 6). However, 29% of the mapped territory has a sediment thickness of less than 25 m, 12% less than 10 m. Sixteen per cent of the territory has Quaternary cover thicker than 100 m and only 1.2% more than 200 m (Figure 6). Although variable, one can observe an overall trend between sediment thickness and the physiographic regions. Thus, the thickness of Quaternary strata is greatest in the LGM zone (average thickness 75–84 m) and it decreases in both directions from the LGM (Figure 2). This is consistent with the overall conclusion of Kleman et al. (2008), that glacial drift is thickest at the SIS margin.

Outside the LGM, in the areas of the Middle Pleistocene Moscow (Warthe) and the Dniepr (Drente) stages of the Late Saalian glaciation, the average Quaternary thickness is 75 m and 32 m respectively which exceeds the average (14.8 m) of the sediment thickness outside the formerly glaciated area (Figure 2). The thickness distributions within the Late Weichselian SIS area and in the area of the Moscow glaciation are similar (Figure 2), although in the Moscow glaciation area the exceeding thicknesses are more evenly distributed. In comparison, the thickness distribution of Quaternary overburden in the Late Saalian glaciation area is rather different. Thus, the maximum sediment thickness is only \(\approx 157\) m and 90% of the territory is covered by less than 75 m of sediment, which remains almost twofold below the corresponding figures in the LW SIS area (359 m and 120 m) and in the area of Moscow glaciation (324 m and 135 m). Such a decreased sediment thickness is explained by repeated intensive erosion in the course of different glaciations following the Dniepr stage and their feeding with Volga River melt-water drainage system. The erosion of weathering products has been prevalent in the non-glaciated zone of the study area, where the thickness distribution of the Quaternary sediments is very similar to the sub-zone 1A (Figure 2) on the Baltic Sea coast with prevailing glacial erosion during the last Scandinavian glaciation.
Inside the LGM in the study area, the thickness of the Quaternary deposits decreases fourfold towards the Baltic Sea coast in the NW (Figure 2) and the thinnest sediment cover (0–5 m) occurs in the areas of bedrock elevations where the bedrock surface is near or forms the ground surface. These calculations broadly support the Kleman et al. (2008) measure between the intermediate (<25 m) and thick drift zones (>25 m) border which runs from the Gulf of Riga to the southern shores of Lake Onega (Kleman et al., 2008) and follows the Karukapp (1997) boundary between the erosion dominated dome and the accumulation dominated peripheral zone of the LW ice sheet. In the intermediate drift zone (Kleman et al., 2008), embracing north Estonia and the St. Petersburg region of north-west Russia, the bedrock elevations (Pandivere and Izora, see Figure 4) with a very thin cover (<10 m) of glacial sediments, comprising only Late Weichselian tills and related deposits (Malachovsky & Markov, 1969; Raukas & Kajak, 1997), are characteristic. At the proximal and distal slopes of these heights, locally the thickness of the Quaternary reaches 75 m. This characteristic of the sediment distribution refers to the strong glacial erosion on the tops of the bedrock-cored elevations, while at their proximal and distal slopes, sediments were preserved from the erosion of successive glaciations or were more easily trapped and released from the glacier. South-east of that zone, on the ‘thick drift area’ of Kleman et al. (2008), the areas of bedrock elevation have very thick (>100 m) Quaternary cover, consisting of 5–7 till layers and related glacial deposits (Guobyte & Satkūnas, 2011; Isachenkov, 1988; Kalm, Raukas, Rattas, & Lasberg, 2011; Raukas, 1978; Zelčs, Markots, Nartišs, & Saks, 2011). However, between these bedrock-cored elevations, which are called insular accumulative heights (Aboltins et al., 1989), are lowland areas with much thinner (normally <20 m) Quaternary sequences. This pattern of sediment distribution, which was earlier described
in Baltic countries (Aboltinš et al., 1989; Guobyte & Satkūnas, 2011; Raukas & Kajak, 1997; Zelčs et al., 2011), is a general feature for the area of last glaciation where the spatial distribution of Quaternary sediments amplified the glacier bed topography. The presence of five to seven different-aged till layers in the thick Quaternary sequences on the uplands of contemporary topography suggests that amplification of the glacier bed topography has repeatedly occurred through the succession of Quaternary glaciations.

Within our study area, exceptions occur in the southern Baltic Syneclise area within the LGM and in the southern and eastern flanks of the Moscow glaciation (zone 2). In these areas, an exceptionally thick (max 359 m) sequence of Quaternary deposits have inverted deep bedrock depressions into elevated areas in recent terrain (Figures 4–6). Most likely, these wide depocentres are determined by the bedrock topography which, in NE Poland and S Lithuania, displays a glacially sculptured SE trending depression (Figure 5). Outside the LGM, this depression cuts into a valley-like NE to SW-oriented depression with an elevated southern edge (Figure 5). Similarly irregular in shape but N to S oriented, an elongated depression (depth ≏ 100 m) is located in the eastern flank of the Moscow glaciation area (Figure 5). These perpendicular to the ice movement, over-deepened bedrock depressions served as obstacles to the ice movement with a corresponding increased sediment release. Also, both areas mark the maximum extent and corresponding high sediment drift zone of the Middle Pleistocene Moscow glaciation which certainly influenced the final structure of the above exceptional depocentres.

Many investigations have demonstrated the differences in timing, glacial dynamics and sediment drift between the southern and eastern flanks of the last Scandinavian glaciation.

We compare here the thickness distribution of the Quaternary overburden in four radial sectors within the last SIS area in the East European Plain (Figure 3), which were tentatively defined by Kalm (2012) following complex ice-stream areas. Our calculations demonstrate that there are no considerable differences between the three easternmost sectors where the average thickness of the Quaternary sediments ranges between 37.8 and 44.4 m and, rather similarly, less than 100 m of overburden covers roughly 90% of the sectors territories (Figure 3). In contrast, for the southern area of the SIS in W Lithuania and NE Poland, the calculated average thickness of the Quaternary cover is almost threefold compared to the above central and eastern SIS areas and 50% of the sector’s territory is covered by an over 100 m thick overburden. However, caution must be exercised in drawing further conclusions regarding the spatial differences in the glacial drift, as the southern sector currently analysed (B4) fully covers the over-deepened bedrock depression of the southern Baltic Syneclise area filled with glacial drift material of several glaciations (Ber, 2006).

6. Conclusions

The presented map of the thickness and related statistics of Quaternary deposits were calculated from the differences between the current DEM and the bedrock surface topography model of the continental part of the western EEC. The map covers an area of 1,013,571 km² of which 984,623 km² (97%) has undergone a dynamic and complex history of expanding and retreating ice sheets during different Pleistocene glaciations, including the Late Weichselian glaciation (419,660 km², 41.4% of the mapped area). Sediment thickness in the study area is highly variable, ranging from 0 m to 359 m (55.4 m on average); 29% of the mapped territory has a sediment thickness of less than 25 m, 16% of more than 100 m and only 1.2% of more than 200 m. These estimates include errors due to inaccuracies in DEM and bedrock topography models. The overall distribution of Quaternary sediments is consistent with earlier views on glacial drift, as the thickest (75–84 m) cover appears at or close to the LGM zone and decreases two to fourfold towards both sides of the zone, being ≏ 15 m on average outside the glaciated territory.
General features of the glaciated area prove that the spatial distribution of the Quaternary sediments did amplify the differences in the glacial bed topography, with the exceptions of the southern Baltic Syncline area and in the southern and eastern flank of the Middle Pleistocene Moscow glaciation where glacial drift has inverted deep bedrock depressions to the elevated areas of the modern terrain. This study adds new detail and spatial coverage using laterally homogeneous DEMs. The picture emerging is expected to have implications for further modelling of glacial events in the area.

Software

Scanning of printed materials and image processing was performed using Corel Photo Paint 12. Data were processed using MapInfo 10.0, with further 3D modelling using MapInfo Vertical Mapper 3.5. The statistics were produced using the MapInfo add-on Engage 3D and final map production was performed using CorelDraw Graphics Suite 12.

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