USING DEM TO RECOGNIZE POSSIBLE MINOR STAYS OF VISTULIAN (WEICHSELIAN) ICE-SHEET MARGIN IN THE WIELKOPOLSKA LOWLAND

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ABSTRACT. By using Digital Elevation Models (DEM) for identification of lineaments patterns and other morphometrical features it is possible to recognize at least some of the less apparent location of former ice-sheet margins. This study provide a new data for regional model of Vistulian (Weichselian) ice-sheet recession in the Wielkopolska Lowland, by showing possible minor stays of ice-margin in this area. For main analysis we used five test areas for which we made more detailed models from topographical maps. Our analysis suggests that there is possible to select areas of probable short stays of ice-sheet during recession. We found that in many cases lineations derived only from Digital Terrain Elevation Dataset level 2 (DTED2) are not clearly visible in more detailed models. The visual interpretation works well for DTED2 model but in models derived from topographic maps this method is far too subjective. Much better option is to use trend deviations maps. Maps of spatial distribution of directional elements should be computed not only for the whole area of study but also for its smaller parts. Using of DTED2 model we point out three types of lineations: small-scale and large-scale lineations connected by us with different scale stays of ice-sheet and straight lineaments. We proposed geomorphological interpretation of hill ridges in the Wagrowiec and Morasko test area as former ice-cored moraines. Our research led us to point out locations for further detailed geological research as well as several possible ice-sheet stays.

KEYWORDS: terrain lineaments; vistulian glaciation; geomorphometry, DTED2

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Introduction

One of the most characteristic features of young glacial landscape is strong relationship between relief, geology and genesis of terrain forms. With some probability, at the phase of terrain analysis, we can deduce about processes and environments, which has created selected landforms. More precise recognition of sedimental environment requires more detailed geological research combined with morphological analysis. The aim of this paper is to show some possibilities of using digital elevations models (DEMs) for recognizing probable minor
stays of Vistulian (Weichselian) ice-sheet and, in this way, designating areas for future detailed geological research. Landforms created during transgression and recession of ice-sheet are directly connected with ice-margin dynamics and ice-sheet thermal condition. Menzies (1996) split glacial sediment environment into three systems: subglacial, supraglacial and ice-marginal deposit. Most of terrain forms connected with subglacial system are parallel to ice-motion direction for example: flutes, drumlins and glacial channels. On the other hand, landforms created in an ice-marginal environment are usually perpendicular to ice-flow direction, and they imitate the shape of ice-lobes. Both types of landforms can be used for reconstruction of former ice-movement directions.

Using very simply analogy can be treated glacial transport system as a transmitter belt on which the debris from alimentation zone are transported to deposition zone (ice-sheet margin) (Boulton et al. 1985). A few model situations can be distinguished in relation to rate of frontal recession of active ice-sheet (Kaszprzak 2003):

1. Dynamic equilibrium - ice-sheet stationary for a long period of time (Fig. 1A). In this situation the amount of debris, which is getting to the ice-margin, is roughly the same as amount of debris, which is melted-out in marginal zone. The morphological effect of this process is accumulation of large volume of debris in that relatively small area. It results in creation of large terrain form, usually noticeable at regional scale.

2. After period of dynamic equilibrium, when the climate is warming up, ablation of ice-sheet is starting to tip over ice delivery and the ice-margin is starting to retreat. Three main types of recession can be distinguished:
   - Slow recession interrupted with middle-term stay of ice-sheet (Fig. 1B). In this situation amount of debris melting out in the surface of ice-margin is enough to preserve lot of dead-ice blocks. Hills build from dead-ice covered with debris are named ice-cored moraine. As is known from observation of modern glaciers, they usually follow the shape of ice-margin. At the first stage of landscape creation the ice-cored moraines build the highest elements of the relief. However, after dead-ice is melted, the relief becomes inverted and the hills replaced by kettle-holes.
   - Recession with short-term, local stays (Fig. 1C). When the rate of recession is increasing the depositional efficiency of ice-sheet is reduced. Quantity of debris is sufficient to preserve only isolated ice-blocks. This is not sufficient to create heterogeneous ice-cored moraine ridges and only single, isolated ice-cored hills and resulting kettle holes are visible. But they still reflect general shape of former ice-lobe.
   - Continuous recession (Fig. 1D). Stays do not interrupt the decay of ice-sheet. The amount of melted material is very low and evenly distributed with only a few dead-ice blocks. The resultant relief is flat, poorly differentiated with rare, chaotically distributed, kettle-holes.

Relief developed by processes mentioned above is usually deformed by erosion and accumulative effect of melt-water activity and therefore hard to interpret.

In this study we tried to find places of mid- and short term stays based on the features mentioned above. This type of study is valid only for areas of till plains, because they are relatively little transformed by other non-glacial processes.

In the Wielkopolska Lowland pattern of large terrain forms determines three stages of Vistulian ice-sheet decay: Leszno and Poznań phase with the latter Chodziez sub phase (Kozarz 1981, 1996). Shapes and ranges of these phases have been investigated relatively accurate. Smaller scale ice-front stops are however still not fully recognized because their traces are difficult for identification using geological methods. Here a different approach based on morphological analysis is proposed. By using the Digital Terrain Models for identification of lineaments patterns and other morphometrical features it is possible to recognize at least some of the less apparent location of former ice-sheet margins. This also should be helpful in finding former ice-streams (Clark & Stokes 2001). This study will provide a new, more detailed data for regional model of Vistulian ice-sheet recession in the Wielkopolska Lowland proposed by Kasprzak (2003) and give new data which could be useful for modelling of last glaciation in Europe.
Study Area

Our study area is located in the Wielkopolska Lowland (central-western Poland) in the area that was shaped during the Vistulian glaciation that occurred here in two phases: Leszno and Poznań, and Chodzież sub-phase which took place between 20k BP - 17.2 k BP (Kozarski 1981, 1995) (Fig. 2).

Research Methods

The whole area mentioned was used only for large-scale analysis of DTED2 (Digital Terrain Elevation Dataset level 2) and for overall glaciation context. For main analysis more detailed model from 1:10 000 topographical maps was used for five smaller test areas. Test field were chosen from different geomorphologic types of terrain: moraine complexes, hummocky moraines and till plains (Fig. 2).

For each test area two DTMs were created. The first one was generated from topographic maps 1:10 000 in PUWG 1992 projection (uniform for entire area of Poland) - called TOPO model. The assumed horizontal accuracy of this maps is about 5 meters and vertical is about 1.6 meter (Kistowski, Iwańska 1997). The second one was generated from DTED2 model, which horizontal resolution assumed to be about 30 meters. All analysis listed below were performed either in TNT Mips, LandSurf or Microdem software.

In the following the research steps are presented in detail:

- DTED2 data was distributed in Latitude/Longitude projection and it was necessary to transform it into 1992 PUWG plain coordinates projection.
- For the chosen test areas contours were interpolated from DTED2 with 1.25 meter intervals. The value was chosen for convenience - this is the basic interval on polish topographical maps in 1:10 000 scale.
- In the next step a search for lineations was performed on the whole study area by using visualizations based on DTED2 model (i.e. shaded relief and slopes).
- TOPO model was generated from data obtained from topographical maps. If it was possible the vector maps in DGN format were used - contours were separated and corresponding Z values were transmitted on resulting vector lines.
- If vector maps were not available scanned analogue maps were used. They were georeferenced and re-sampled in order to minimize possible distortions and combined into one mosaic. On that background semi-automated vectorization of contour lines and was performed corresponding Z values were transmitted on resulting vector lines.
- Vector elevation data was interpolated to raster using minimal curvature algorithm with spatial resolution of 3 meters. The same parameters for all test areas was used.
- To extract the lineaments from DEM's visual method based on Jordan & Schott (2005) and Jordan et al. (2005) was used. Shaded relief models were calculated at an azimuth interval of 45°, constant isopilation inclination of 50° and at least six-time vertical exaggeration (dependent on the flatness of the surface). 
- Then lineaments were identified by visual inspection of resulting rasters. For proper localization of ridges and valleys we used overlaid contour map from topographical maps as well as from DTED2.
- Using contours map and shaded relief we designated manually long axis of isolated hills and pits (kettle-holes) and then resulting vector maps were used for further analysis of spatial distribution of these forms - density of forms per area unit and rose diagrams.
- Digital models were used to calculate basic morphometric features: slope, aspect, absolute heights.
- Contours length per area unit calculation was approximated by using cell count value and standard deviation for grid cells based on rasterized contour maps.
- For each area trend function and trend deviation analysis was performed and used for confirming previously found and for finding new lineations.

Results

DTED2 model analysis

Three groups of lineations were recognized using different visualizations based on DTED2 models (Fig. 3). Comparison with existing cartographic materials and literature revealed that some of the elements that were found (mainly the local culminations - end moraines or ice
lobe contact sedimentary scarp) in southern and middle part of research area correspond to maximum range of two phases: Leszno and Poznań. However, it was impossible to outline range of these phases in the whole research area. The Chodzież sub-phase is much less apparent; it was possible only to recognize one such mark there.

At least 160 smaller lineations were also found. In the south-western part of the area they are arranged in the lobe-like shape. It confirms the view known from literature (Kasprzak 2003) - mostly based on geological research - that this area was shaped by Ślawa Śląska ice lobe (Fig. 4A). In the north-eastern part of the area numerous lineations were found. The first group of them is known from previous research i.e. Kozarski (1962). The main part is usually described as the end moraines of oscillations. The second group consists mainly of small hillock ridges and ice-lobes sedimentary scarp, which are not mentioned in the literature. According to the shape and toposheet situation of these forms we think that it is possible to classify them as the marks of the short- and medium-term stages of ice-margin (Fig. 4C). Some of this lineations form the lobe-like structures, which we called i.e. Mieścisko Lobe (north-western part of Fig. 4C), Janowiec Lobe (eastern part of Fig. 4C) and Morasko Lobe (Fig. 3 and 9).

In the area between range of Leszno and Poznań phase we found some strange straight liniments (Fig. 3 and 4B). It is uncertain what is the genesis of those forms. Pattern of these lineaments is similar to patterns associated in literature i.e. Clark (1997), Smith et al. (2000), Clark & Meehan (2001), Evans et al. (2006), Smith et al. (2006) with drumlin fields. This would suggest that these forms are of subglacial genesis and thus they can mark the direction of ice-sheet transgression from north-west. In literature, however, the different direction N-NE is pointed out (i.e. Górska, Kaczmarek 1995, Górska 2000).

TOPO model analysis

Based on analysis mentioned above four test areas with different type of lineations were selected. In this way, it is possible to see if previously marked lineations are emphasized in more detailed scale or, in contrary to that - they are becoming blurred and indistinguishable. It has been found that with bigger amount of information the visual interpretation becomes increasingly more difficult and it is necessary to employ more sophisticated methods. Below results of using a few of such methods are presented. For the Wagrowiec test area detailed description of applied methods as well as possible geomorphological interpretation are shown. For other test areas only short description of main differences was given.

Wagrowiec test area

This is the largest test area - about 360 km² is divided into three main geomorphological units. At the southern part there is an ice-margin valley of Węda River, in the western part an outwash plain, and the rest is taken up by hummocky moraine slit by large subglacial channels. Using visualization method proposed by Jordan (2001) it is possible to find only four unquestionable lineaments - ridges of hillocks in northern (3) and eastern part of the area (Fig. 7).

The map of long axis direction of elongated kettle-holes and locally hillocks as well as the map of kettle-holes density (Fig. 7) failed to show any more significant lineations.

On the other hand, the map of contour lines that separate those polynets (that consisted of polygons of certain area filled with uniform color for better interpretation) were helpful for connection some of the hillocks into one ridge that runs from north-west to south-east in the middle part of the area. But certainly the best method for distinguishing lineaments in the Wagrowiec area was the map of trend deviations, which allowed us to find three more of them. Generally, in the Wagrowiec test area 6 large lineations and 12 smaller were outlined (Fig. 6).

The research area was split into 8 parts, each one different from others in: absolute and relative height, direction of long axis of kettle-holes and hillocks, relief character. For each part of terrain morphological analysis were made and orientation of directional elements and its density per square kilometer were calculated (Fig. 7):

- Area 1. It is the outwash plain split with the river valley. The most characteristic forms of this area are four Pleistocene dunes. They are the main reason why analysis of long axis of directional elements shows mainly the WNW to EES direction and they are also responsible for number of hillocks being more than two times greater than number of kettle-holes.
- Area 2. Encompasses an ice-margin valley of Węda river and the subglacial channels. The number of directional elements is very low and their direction E-W is rather the result of much younger water erosion than glacial processes.
- Area 3. In this area of hummocky moraine the predominant direction of long axis elements is SW-NE. It confirms the lineation that was found using the DTED2 model and visual inspection of TOPO model, but it contradicts the lineaments derived from the map of trend deviations.
- Area 4. This part has quite complicated morphological situation. Lineaments de-
Fig. 5. Terrain lineations in Wagrowiec derived from shading and slopes. TOPO model

Fig. 6. Main and secondary terrain lineation derived using map of trend deviation and map of contours density. TOPO model. Wagrowiec test area
rived with different methods are contradictory in general and only the analysis of long axis direction and map of trend deviations are consistent.
- Area 5 consists of one higher and rather flat piece of terrain and three distinctive ridges running from NW to SE. They are characterized by high value of absolute heights but their general direction is different than direction of kettle-holes and hillocks long-axis. The spacing between ridges is roughly uniform – about 1000 -1200 m. It is the only area where the direction of long-axis of kettle-holes is different than hillocks.
- Area 6. The situation here is unclear and it is hard to find regularities, even the direction long axis of kettle-holes is devoid of trend. There is only one stretch of small hillock running from N to S and high isolated mountain near it.
- Area 7. It is a terrain depression in which long-axis of kettle-holes and hillock are mainly W-E. The overall number of directional elements is lower than in other hummocky-moraine areas of our study.
- Area 8 includes the highest parts of testing area. There is also the highest density of kettle-holes and hillocks, but their long-axis directions are very chaotic. Main characteristic is the arced ridge in the western part of the area, which has very few kettle-holes.

Interpretation

Based on following interpretation we are assuming that generally direction of ice recession was from SW to NE.

The relief of areas 1 and 2 (Fig. 7) is not the result of direct influence of ice-masse but rather of proglacial meltwaters. The ice-marginal valley of Welna river has probably destroyed almost all traces of ice-marginal sediments. From the south to north the first track of possible ice-sheet margin stays is a ridge I. It consists of series of small hills not clearly visible in terrain. Large numbers of kettle-holes suggest that this relief is the result of decay of numerous blocks of dead-ice.

The ridges II, III and IV (Fig. 6) may be viewed as a record of three regular ice-sheet stops. The depressions between ridges were probably shaped by proglacial meltwaters running to the subglacial channels. Meltwater erosion combined with dead-ice melting might be a reason why there is a difference between orientation of kettle-holes and hillock.

The ridge V (Fig. 6) marks the youngest stay of ice-sheet recession at the test area. The large (about 2000 m width in N-S direction) parallel depression on his northern side is probably the effect of accelerated recession - large amounts of marginal melt-waters carved it and caused the overall orientation of hillock and kettle-holes to become W-E.

The ridge VI (Fig. 6) has no clear interpretation. His characteristic arc shape is not coherent with the direction of ice recession accepted by us. The high value of relative height (c. 12 -18 m), very steep slopes, and lack of kettle-hollows exclude dead-ice genesis. It might be the remain of older structure that survived from time of transgression, although this is less probably. On the other hand, its vicinity to subglacial channels may suggest that this is an effect of erosion activity of subglacial water. The relief of Area VIII (Fig. 7), especially large number of hillocks and kettle-holes suggests that it was the place of decay of rather large block of dead-ice.

The small ridge A (Fig. 6) with direction contrary to 5 main ridges could be a mark of beginning of the differentiation of main ice lobe into two smaller lobes. This hypothesis may be confirmed by direction of long-axis of kettle holes and hillocks as well as presence of terrain depression. The characteristic shape of small ridges B and C, consisted from chains of small hills and oriented in one similar direction, let us classify them as the eskers.

Interpretation mentioned above is based only on morphological analysis. Full recognition of sedimentary environment requires detailed geological research, especially in the area of ridge VI and A (Fig. 6). For the rest of small ridges also is lack of reliable interpretation in many cases.
Galtony, Morasko, Mościsko and Oborniki test areas

All of areas were subjected to the same pattern of analysis. Although they represented different kinds of terrain, similar methods proved to be useful for recognition of glacial lineations. Detailed study of orientation of long-axis of kettle-holes and hillocks together with visual interpretation of shaded relief allowed us to divide each area in smaller parts of different kind of relief. In this way we were able to use appropriate method of analysis for each part of test area. In all but one case (Oborniki test area) the distribution of trend deviations (especially either 6 and 8 level trend) proved to be the most reliable and helpful for deriving lineations. In this way elements not visible in any other way could be found.

In case of test area Mościsko (Fig. 8) were found that lineations derived from visual inspection failed to recognize that areas 2 and 3 are remains of two separate events at least according to orientation of directional elements, absolute heights and especially the trend deviations. The last one also showed two distinct chains of hills in the southern part of the study area (Fig. 9). This is an example that lineations, which are clearly visible on DEM’s either derived from topographical maps or DTED2 data, should be further tested for at least basic morphometrical values. This is especially true for DTED2 data.

Test area Morasko showed central part of Morasko hobe – one of the highest culmination of Poznań phase (Fig. 10). Genesis of this large form is usually associated with older glaciations (Krygowski 1960, 1961, 1964; Stankowski

Fig. 8. Density and long-axis distribution of kettle-holes and hillock for selected areas. TOPO model. Mościsko test area

Fig. 9. Map of trend deviations. TOPO model. Mościsko test area

Fig. 10. Forms after decay or ice-cored moraines ridges. TOPO model. Morasko test area
201). However, chains of small hillocks overlying main form, can be connected with recesses phase of Vistulian glaciation. They build small terrain linations, with almost equal spacing between them - roughly 250-300 meters. We interpret these small landforms as forms that remained after decay of ice-cored moraine. This and overall relief pattern suggest that in this area, during the decay of vistulian ice-sheet the rate of ice-sheet recession was slowed down. For some time ice-sheet was in state of dynamic equilibrium and next the recession was revived.

In cases of both the Oborniki and Gultowy test areas we could not form reliable interpretations of ice-sheet movements. It was caused by different reasons, either because the lination was too complicated or the relief was too transformed by younger processes in order to make any reliable assumptions.

Summary

Our analysis suggests that there is possible to select areas of probable short stays of ice-sheet during recession. It was found that in many cases linations derived only from DTED2 are not clearly visible in more detailed models because they are obscured by smaller elements and it is necessary to use different methods and morphometric parameters. Below main points of our analysis are presented:

- Even the most detailed DTED2 model is appropriate only for studying the larger, regional linations. The main elements needed for analysis of short stays of ice-sheet i.e. kettle-holes and hillocks are too small even for 30 meter spatial resolution of DTED2 model. However, they are more useful than is suggested by Guth (2006), at least in case of our study areas.
- The visual interpretation works well for DTED2 model but on TOPO model this method is far too subjective. Much better option could be, for example, using the trend deviations maps (Fig. 6 and 9).
- Maps of spatial distribution of directional elements (kettle-holes) and directional elements should be computed not only for the whole area of study but also for its smaller parts. In this way it is possible to make more valid assumptions about genesis of the relief being studied.
- In general any DEM of reasonable size (at least several km?) should be divided into smaller parts using some basic analysis method (i.e. visual interpretation of shaded relief and absolute and relative height differences) and after that subjected to more sophisticated analysis. This will lead to attributing them one of possible geneties.
- Using of DTED2 model three types of linations were pointed out. Apart form small- and large-scale linations, connected with different scale stays of ice-sheet, also were found straight linations that have no reliable interpretation.
- Using TOPO model we proposed geomorphological interpretation of hill ridges in the Wągrowiec and Morasko test area as former ice-cored moraines. Our research led us to point out several locations to detailed geological research which may confirm our interpretation estimating the dynamics of the last ice sheet]. Wydawnictwo PTWN, 28, Poznań.


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