Studia Quaternaria, vol. 36, no. 2 (2019): 147–159 DOI: 10.24425/sq.2019.126386

LARGE-SCALE DEFORMATIONS IN NEOGENE DEPOSITS NEAR DOBRZYŃ ON THE VISTULA (CENTRAL POLAND) – THRUSTING FROM N/NE OR VALLEY-SIDE GLACIOTECTONICS IN THE PŁOCK BASIN?

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Abstract:

The article is focused on the most recent investigations of glaciotectonic structures in high escarpment exposures of the Vistula valley from Dobrzyń to Kuzki in the western part of the Płock Basin. Deformations involve Neogene and occasionally the Lower Pleistocene deposits and they are not expressed as landforms. Structural investigations and analysis of archival geological data provided new information on the origin of large-scale shear structures. Results obtained are clearly contrary to the concept of Brykczyński (1982) regarding valley-side glaciotectonics in the Płock Basin. An emergence of the extensive zone of serial thrust structures of significant amplitude (up to 100–150 m) was found to have not been controlled by a palaeovalley. A driving mechanism is interpreted as a gravity spreading in front of ice sheets advancing from north-northeast during the South Polish Complex (Dorst-Elsterian).

Key words: soft-sediment deformations, glaciotectonics, structural analysis, Pleistocene, Płock Basin

Manuscript received 31 October 2018, accepted 30 May 2019

INTRODUCTION

The authors have drawn attention to difficulties encountered so far in explaining the origin of large- (dozens of metres) and medium-scale (several metres) deformation structures in the Neogene and locally, the Quaternary deposits. They are partly exposed in the high northern escarp of the Vistula valley between Płock, Dobrzyń and Włocławek (Fig. 1). The first description of deformations in the Neogene deposits, visible in the western part of the Płock Basin, was provided by Pusch in 1836. From the beginning of the 20th century, they aroused interest of many researchers. Lewiński and Samsonowicz (1918) presented an interesting idea on development of deformations, indicating that they resulted from "squeezing-out of plastic, water-saturated sediments from under the ice sheet". Ber (1960, 1968), Jaroszewski (1963, 1991), Skompski (1969, 1995), Brykczyński (1982) and Ruszczyńska-Szenajch (1985) also advocated a glaciotectonic origin of these deformations. The other explanations comprised a flow of plastic Neogene deposits on the eastern slope of the elevated flank of the Kuyavian Anticlinorium in the bedrock (Lewiński, 1924; Różycki, 1967; Banach, 1973) or a dominant effect of a tectonic factor *sensu stricto* (Łyczewska, 1964; Baraniecka, 1975).

The most comprehensive study on deformations in the Neogene deposits in the Płock Basin was done by Brykczyński (1982). Based on numerous measurements of deformation structures exposed on the right-bank scarp of the Vistula, he distinguished glaciotectonic mesostructures represented by various folds, including imbricated ones. According to Brykczyński (1982), such deformations are concentrated along a side of the pre-Vistula valley, but axes of folds and thrust planes form *en echelon* rows on both sides of the buried valley, amplitude of deformations decreases towards till plains and structures verge outwards from the paleo-valley. Brykczyński (1982) interpreted the studied structures as a manifestation of the so-called valley-side glaciotectonics associated with an advancing ice sheet (glacial lobe) along a relief-predisposed valley area.

This idea of Brykczyński referred at first to the Vistula valley near Warsaw (Brykczyńska and Brykczyński, 1974) and later also to the Płock Basin (Brykczyński, 1982). It is still in use in many studies concerning the Quaternary of Poland (e.g. Ber and Krzyszkowski, 2004; Mojski, 2005)

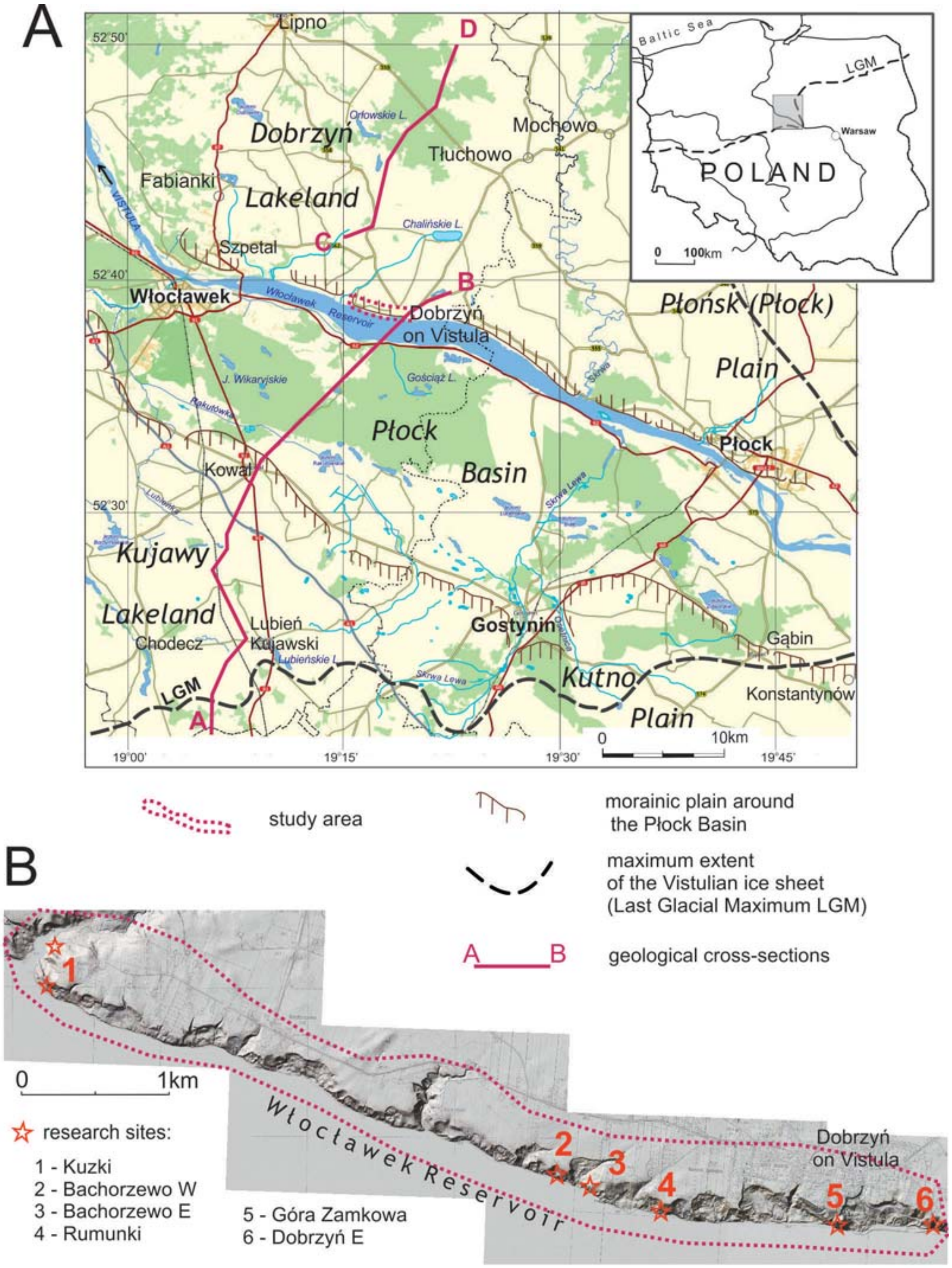


Fig. 1. Location of the study area (A) and research sites in the vicinity of Dobrzyń on the Vistula (B).

and the term valley-side glaciotectonics is used in an entirely general sense to define any large-scale glaciotectonic structures present along river valleys (e.g. Bujakowski *et al.*, 2014). However, the concept of the side-valley glaciotectonics in the Płock Basin area is incompatible with observations, done not only by the researchers of the so-called Płock lobe (Skompski, 1969, 1995; Roman, 2010b) but also of the authors who focused on the glaciotectonics (Ruszczyńska-Szejnach, 1985; Jaroszewski, 1963, 1991).

In recent years, the present authors thoroughly examined a geological structure of the area discussed as part of the work for the Detailed Geological Map of Poland in scale 1:50,000 (Roman, 2011, 2012; Żuk, 2013) and did not confirm presence of valley-side glaciotectonics in the Płock Basin and its surroundings. Therefore, in 2015 structural studies of deformations exposed in the Vistula escarpment between Dobrzyń and Kuzki were undertaken, combined with analysis of data from boreholes and archived geophysical reports from adjacent areas. The aim of this paper is to present results of research of deformation structures in the Neogene deposits, to conclude on their origin and to refer to the issue of valley-side glaciotectonics in the Płock Basin.

RESEARCH SCOPE AND METHODS

Results of studies of deformation structures exposed in the high side of the Płock Basin between Dobrzyń on the Vistula and Kuzki are presented. The research was carried out at 6 sites (Fig. 1), providing 11 exposures in the Vistula scarp. At present, the scarp forms a steep cliff of the Włocławek Reservoir and is subjected to intensive mass movements; hence research sites were selected to ensure that the sediments studied are not a colluvium. Field measurements and analysis of distribution of deformation mesostructures were carried out in 2015. In addition, a query of archived materials was done, including borehole logs, mapping contributions and geophysical reports. It was important to reach a comprehensive photographic documentation and sketches of the walls of the Vistula scarp from 1970s, collected by Brykczyński (1982), to compare recent and previous structural measurements in the same locations.

A classic method of geological structural analysis was used in the study of glaciotectonic deformations in agreement with the previously justified procedures (e.g. Berthelsen, 1978; Brodzikowski, 1980; Houmark-Nielsen and Berthelsen, 1981; Rotnicki, 1983; Jaroszewski, 1991; Aber and Ber, 2007). It allows for a systematic approach to complex, sometimes multi-phase deformed glacial sequences and enables identification of kinetostratigraphic units associated with deformation stages caused by successive ice-sheet advances (Berthelsen, 1978).

The structural analysis focused on determination of type and scale of structures, measuring their orientation and vergence, assessing mutual relations in data interpretation on spherical diagrams, as well as constructing elements of their geometry on the Wulff's grid (e.g. axes of folds, based on position of their limbs). Initial hierarchic setting of the structures according to their scale was done, distinguishing first-order structures, a few to several dozen of metres in size (e.g. folds, thrusts, faults) and second-order deformation structures (drag folds, shears, cleavage, normal complementary faults), a few to several dozens of centimetres in size. Structural analysis was an important link in determining the ice-sheet movement direction. The main glaciotectonic stress (transport) directions were reconstructed both by adopting the assumption of Rotnicki (1976) that the extent of glaciotectonic structures is consistent with a course of ice-sheet edges, while their vergence with direction of ice-sheet advance and in accordance with principles of mechanical interpretation of faults (Jaroszewski, 1980). In addition, range and distribution of glaciotectonic structures in relation to palaeorelief were examined. Structural measurements were compiled on spherical diagrams as projections on a lower hemisphere, using the Tectonics FP program (Ortner *et al.*, 2002). In the text, figures and photographs, a conventional three-part record of the position of the layers (strike/dip and dip direction, e.g. 110/25°N) was used.

GEOLOGICAL SETTING

The study area is located in the Płock Basin and its surroundings and is located within two structural units distinguished in the sub-Cenozoic basement: the Kuyavian Swell covering the western part of the valley and the Płock Trough located to the east of the Gostynin-Włocławek line. These structural units are composed of Mesozoic and Upper Permian (Zechstein) formations. The top Mesozoic surface occurs from 40–60 m a.s.l. in the zone of salt anticlines on the eastern slope of the Kuyavian Swell to 148.9 m b.s.l. in the Płock Basin at Bobrowiczki (southern part of the city of Płock) (Roman, 2010b). The Mesozoic succession is unconformably overlain by continuous Cenozoic cover of varied thickness and composed of Paleogene, Neogene and Quaternary deposits. The Paleogene is represented mainly by the Oligocene glauconite sand, while the Neogene is composed of sand, carbonaceous sand, mud, clay and brown coal of the Lower and Middle Miocene (brown coal formation) and the so-called variegated clay, mud and sand of the Upper Miocene (Poznań Formation). The Neogene deposits, represented by the Middle and Upper Miocene, are exposed in the high northern side of the Vistula valley from Włocławek through Dobrzyń to Płock. Their distribution pattern is irregular and associated with glaciotectonic elevations of the Neogene surface. The elevations were formed by the oldest (Elsterian) ice sheet advance in this area (Skompski, 1969; Baraniecka and Skompski, 1978; Baraniecka, 1979).

The average thickness of the Quaternary is 40–55 m, with a considerable variation from 2.0 to 214.6 m. Stepwise changes of the Quaternary thickness are observed in areas of tectonic depressions above the crests of salt domes, in zones of glaciotectonic deformations and in deep valleys/subglacial channels cut into the pre-Quaternary basement. The Pleistocene sequence is most complete in upland areas around the Płock Basin (Figs 2 and 3). It is composed mainly of glacial tills (usually 2–4, rarely 5–6 beds), with intervening glaciofluvial sand and gravel, mud, and ice-dammed lake clay, locally fluvial sand and gravel. Occasionally, there are mineral and organic lacustrine sediments and peat of the Eemian Interglacial. On the other hand, in the lowland area of the Płock Basin fluvial, glaciofluvial and stagnant lake sediments dominate in the Pleistocene sequence, whereas tills occur sporadically. The oldest Pleistocene deposits are composed of preglacial fluvial sand and gravel exposed in the southern slope of the Płock Basin between Kowal and Gostynin (Roman, 2010a), as well as in the right-bank scarp of the Vistula west of Płock (Skompski, 1969). Younger than these is the fluvial series in the Gostynin region, correlated with the Podlasian Interglacial (Cromerian), which fills a narrow buried valley cut into Quaternary deposits (Roman, 2003, 2011). A bottom of this valley is located at the mean sea level. However, the deepest incisions in the pre-Quater-

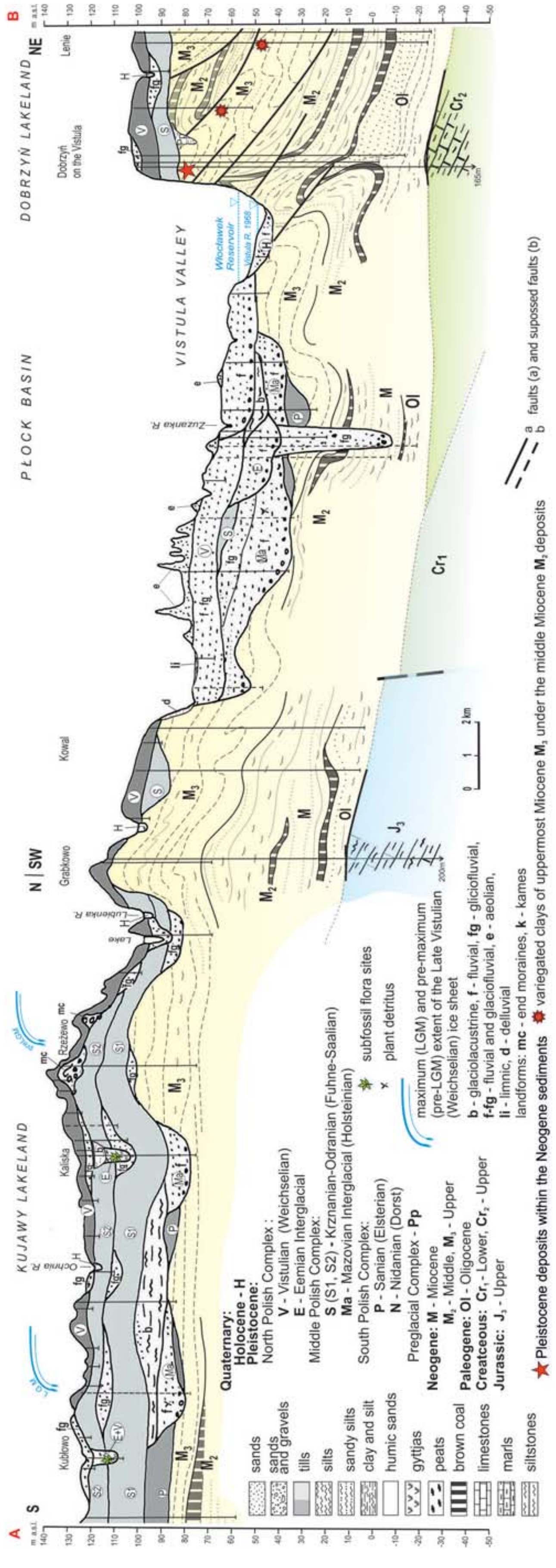


Fig. 2. Geological cross-section A-B: Kubłowo-Kaliska-Kowal-Dobrzyń on the Vistula (after Roman, 2010b, changed); Quaternary stratigraphy according to Marks *et al.* (2016).

nary basement (down to 40 m b.s.l.) occur in the vicinity of Włocławek (Mojski, 1958, 1960). They were formed by a subglacial meltwater during the first ice sheet advances in this area, representing the South Polish Complex (Dorst-Elsterian) (cf. Ber *et al.*, 2007; Marks *et al.*, 2016). These ice sheet advances are represented by two fragmentarily preserved glacial tills and by the currently studied glaciotectonites. The most intense deformations of the pre-Quaternary basement, especially of the Neogene deposits, took place in that time. They are expressed as thrust-fold structures with the amplitude reaching locally 100–150 m (Różański and Włodek, 2009; Roman, 2010b; Żuk, 2013). The upper part of these glaciotectonic structures is exposed in the high right-bank scarp of the Vistula valley between Płock and Włocławek. The Mazovian Interglacial (Holsteinian) was of critical importance for the formation of a vast depression in the Płock Basin. This was favoured by intensification of vertical tectonic movements that activated erosion and accumulation of a major river flowing SE-NW along the axis of the sub-Cenozoic basement structures (Baraniecka 1979; Roman 2003, 2010b). A widespread valley, which formed in the Mazovian Interglacial, predisposed development of subsequent, younger erosion-accumulation cycles related to outflow of glacial, glaciofluvial and fluvial waters, as well as favoured both development of extensive ice-dammed lakes and advances of glacial lobes during younger glaciations.

The Middle-Polish Complex (Fuhne-Saalian) sediments constitute the main part of the Quaternary cover in the morainic plains (Fig. 2). These are glacial tills (1–3 layers) as well as ice-dammed lake and glaciofluvial series. Glaciotectonic deformations are associated with the Saalian till; however, the Neogene deposits are not involved in deformations, amplitude of which is 30–40 m at most. In the Płock Basin, the Eemian Interglacial sediments are represented by fluvial sand and gravel of a single cycle, whereas in a till plain area – by residual lags, as well as lacustrine sediments and peat, pollen-analyzed at Kaliska, Łanięta and Kubłowo (Domosławska-Baraniecka, 1965; Balwierz and Roman, 2002; Roman and Balwierz, 2010). The incision of the major Eemian river in the Płock Basin (pre-Vistula) did not exceed a depth of valleys in the Mazovian Interglacial (Holsteinian), i.e. 40–50 m above a sea level.

The oldest deposits of the Vistulian Glaciation (Weichselian) are represented by lacustrine sediments and peat at Kubłowo, followed by glacial, glaciofluvial and fluvial sediments. The Płock Basin area and the surrounding morainic plains were within the range of the so-called Płock lobe, which marks a maximum limit of the last ice sheet in central Poland during the Poznań Phase (Skompski, 1969; Roman, 2010b) and deposited a till that overlies Eemian sediments at Kaliska (Fig. 2). Presence of glaciotectonic deformations is associated with the youngest till, but they reach a depth not exceeding 15 m and their occurrence is limited to marginal landforms from the advance (overriden push-moraines) and maximum range of the ice sheet (Roman, 2009, 2010b). In the Płock Basin, glaciofluvial sandy sediments are widespread. They built extensive ice-marginal streamway (pradolina) terraces on the left bank of the Vistula. The topmost Pleistocene sediments are represented primarily by fluvial deposits of the supra-inundation terraces of the Vistula and its tributaries, deluvial deposits, aeolian sand covers and single parabolic dunes or extensive dune fields. Lacustrine sediments and peat are also known from the termination of the Pleistocene. The Holocene is represented mainly by fluvial (flood terrace), aeolian, deluvial, colluvial and lacustrine-boggy sediments, as well as by embankments.

DEFORMATIONS IN NEOGENE DEPOSITS BETWEEN DOBRZYŃ AND KUZKI

The complex of glaciotectonically deformed Neogene deposits comprises the Middle Miocene (M_2) sediments of the brown coal association and variegated clay, sand and mud of the Upper Miocene Poznań Formation (M_3). Based on borehole data, the deformations involve occasionally also the Quaternary sediments, including preglacial sand and gravel, and the oldest till (cf. Skompski, 1969; Roman, 2010b). Only the upper part of the complex is exposed in high slopes of the Vistula valley between Dobrzyń and Włocławek, reaching 25 m above the present water level of the Włocławek Reservoir. The top of the complex is truncated and covered with 5–25 m thick Quaternary series, including 2–3 tills and intervening glaciofluvial and glaciolimnic sediments. The analysed glaciotectonic deformations are not reflected in the contemporary relief, which means that they are a fossil feature, and the hill in Szpetal on the right bank of the Vistula near Włocławek is the only exception. Between Płock, Dobrzyń and Włocławek the deformed Neogene deposits occur several tens of metres higher than the original Neogene top surface. In the sub-Quaternary basement, they form a more or less continuous hummock, over 40 km long, elevated to 90 m a.s.l. and trending WNW-ESE, generally as the Płock Basin axis (cf. Ruszczyńska-Szenajch, 1985; Różański and Włodek, 2009; Roman, 2010b). In the northern neighbourhood of Dobrzyń, the deformed Neogene deposits are located up to 100.4 m a.s.l., but there are deep depressions (96.6 m b.s.l.) in the sub-Quaternary basement, northwest of this elevation (Fig. 3).

Six research sites are described (11 newly studied exposure walls): Kuzki, Bachorzewo W, Bachorzewo E, Rumunki, Góra Zamkowa and Dobrzyń E (Fig. 1). The composite structural diagram presents macrostructure measurements (first-order structures) from all exposures examined.

Kuzki. The studies were carried out in three exposed walls in N-S, NNW-SSE and NW-SE intersections. Individual exposures were 20–45 m long with the wall heights from 6 to 12 m. Four packets (thrust sheets) of the Neogene deposits are distinguished, 2 to at least 7

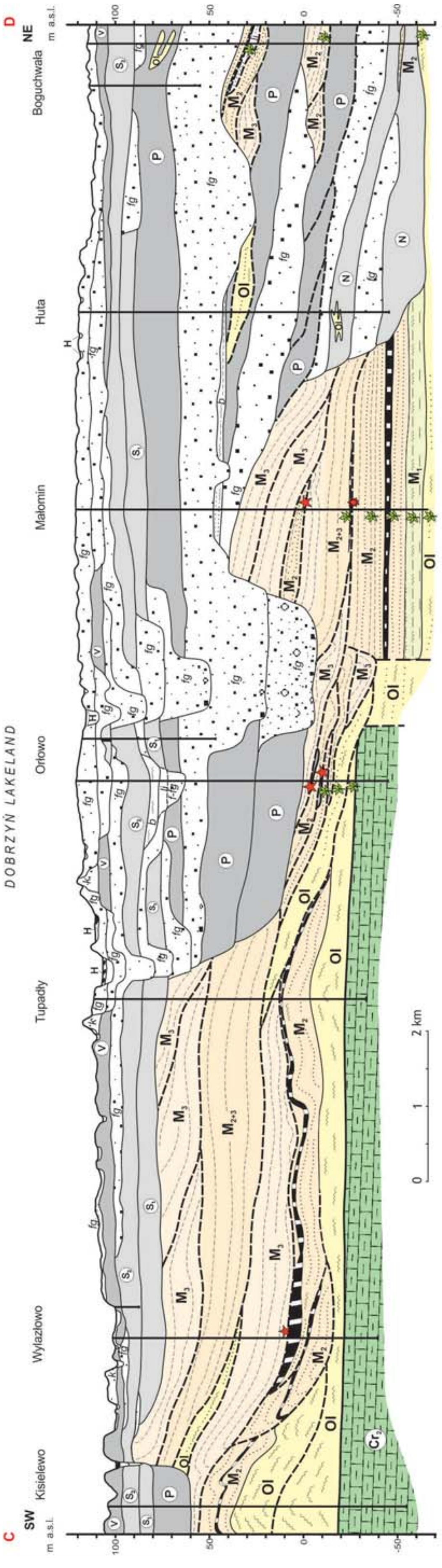


Fig. 3. Geological cross-section C-D: Kisielewo-Orłowo-Boguchwała (after Żuk, 2013, completed). For explanations see Fig. 2.

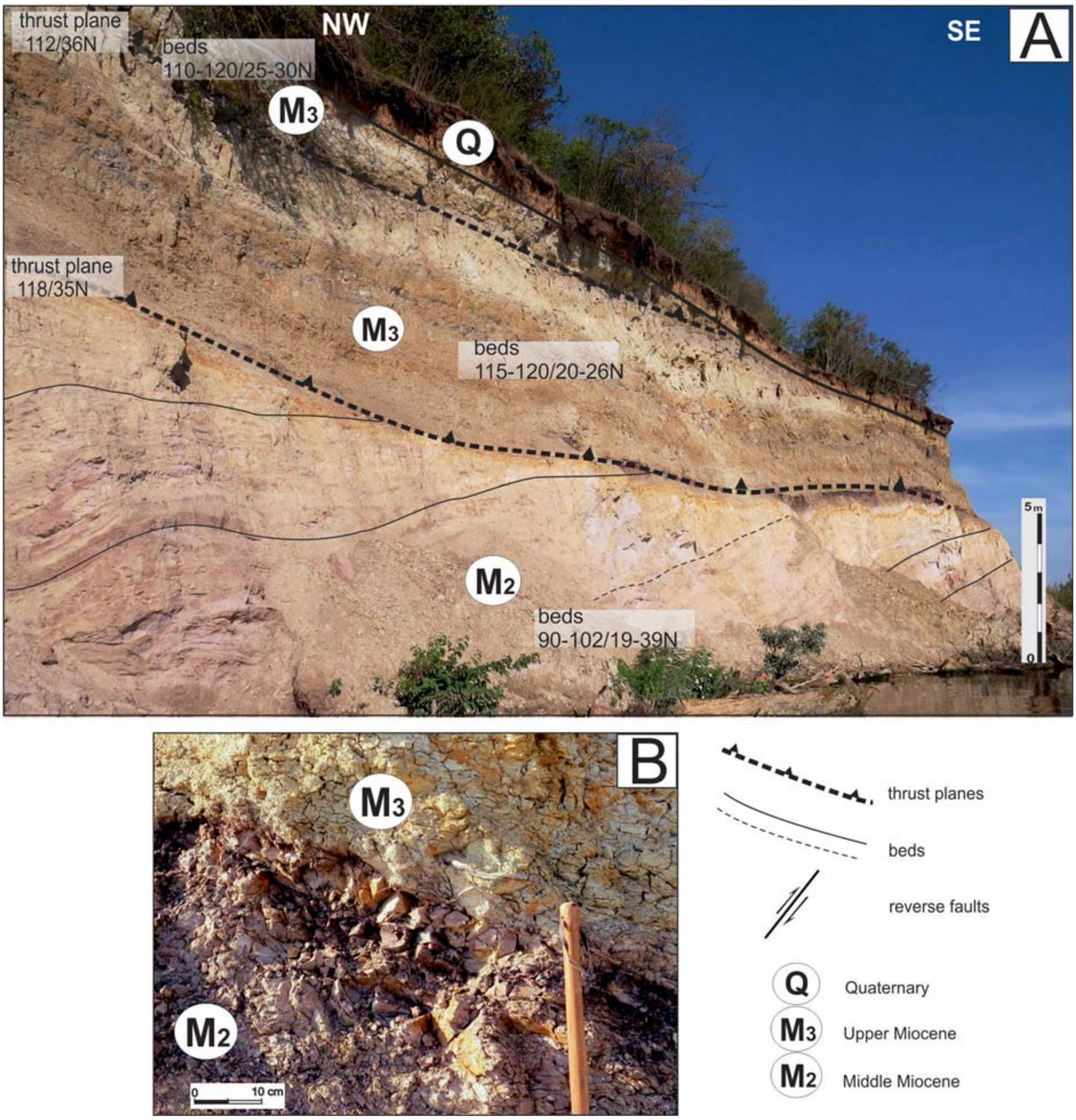


Fig. 4. The Kuzki site. A – Large-scale glaciotectonic disturbances in the Neogene deposits developed as result of thrusting from NNE. Note that both layers in particular patches and thrust planes dip to the north. B – Slip cleavage and breccia within a shear zone below the thrust sheet.

m thick, composed of alternating Middle (M_2) and Upper (M_3) Miocene sediments. Some packets are clearly visible in meridionally trending walls only. Individual packets are separated by extensive thrust planes. The section starts with the lowermost packet represented by the Middle Miocene (M_2) sand, sand with coal dust and coalified plant detritus, and silt. The azimuth of these layers is 90–102°, and they dip 19–39°N. They are separated from the next packet, composed of silt, silty sand and variegated clay (M_3) by an extensive thrust plane (118/35ºN). It is clearly underlined at the base by small deformation structures – slip cleavage and breccia (Fig. 4). In the small-scale deformation zone there are numerous gypsum crystals and rosettes. The azimuth of the Upper Miocene layers is 115–120° and the dip is 37–45°N. These deposits are truncated at the top by another thrust plane (100/38ºN) and covered with the Middle Miocene (M_2) deposits showing a sedimentary sequence resembling the layers of the lowermost packet. The second packet wedges out towards the south and therefore it is no longer visible in the NW-SE intersection walls (Fig. 4). The uppermost, fourth packet represents the Upper Miocene sediments (variegated clay, clayey mud and mud), which is also accentuated at the base by a thrust plane (112/36ºN). The packet layers dip northwards at 25–30º. All deformed Neogene deposits are truncated by erosion and covered by the Quaternary colluvia with gravel-sized Scandinavian erratics.

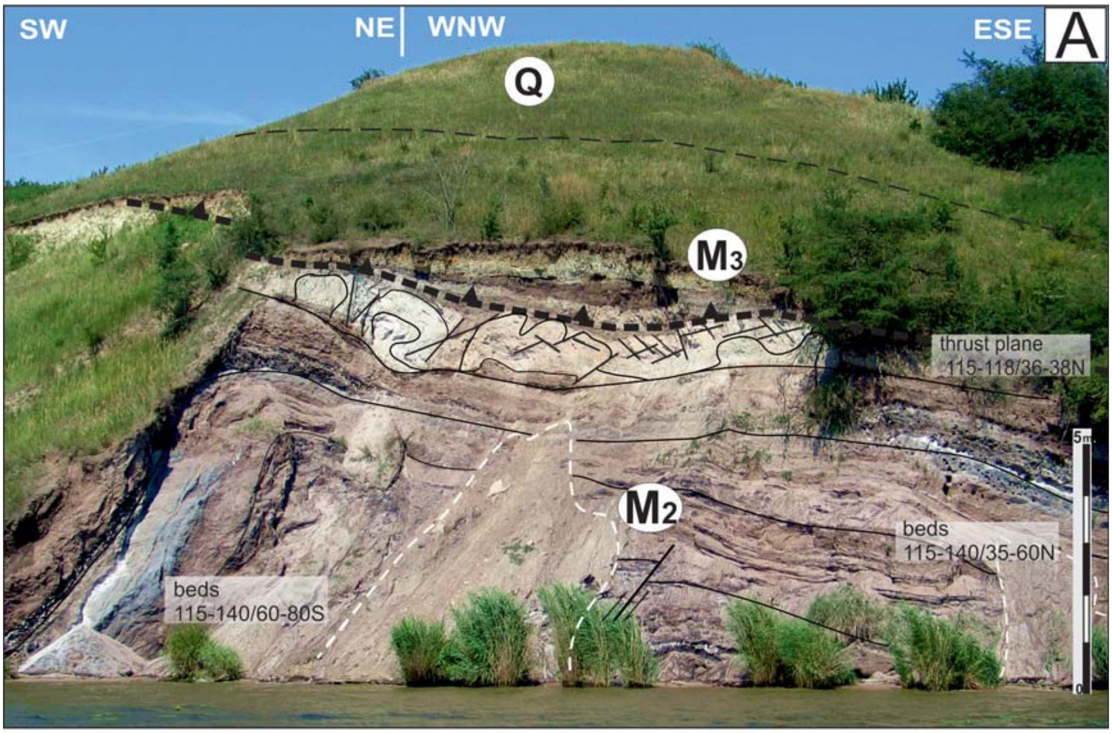
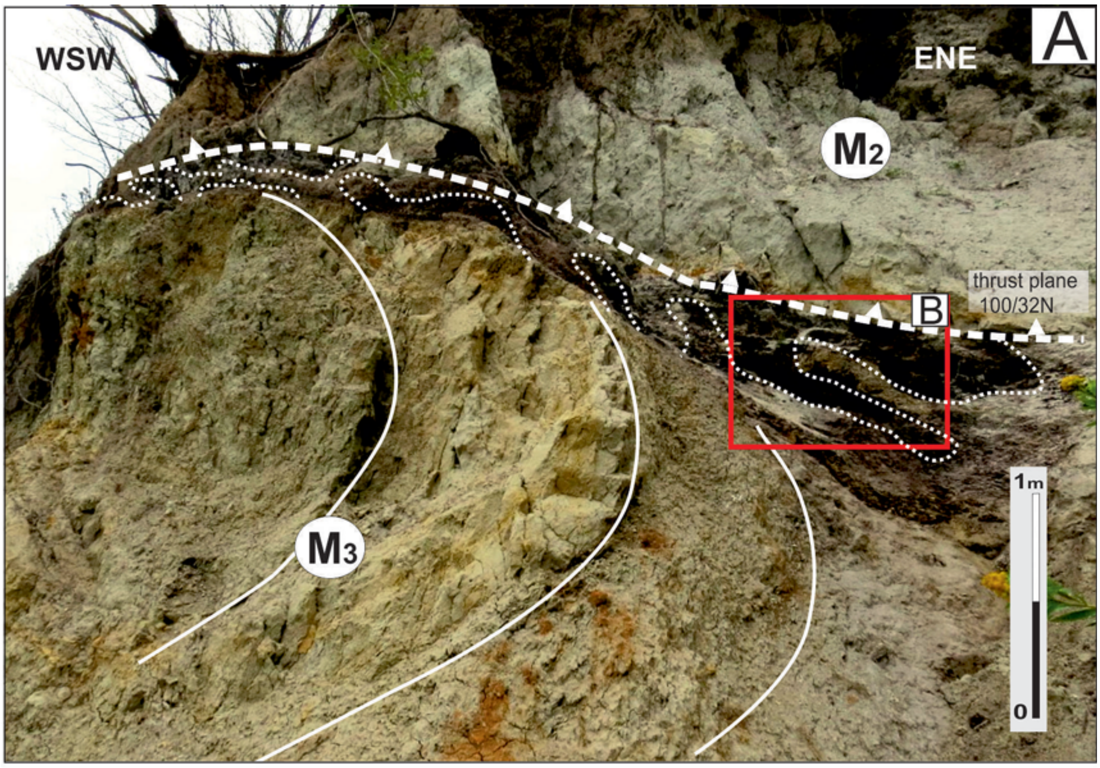


Fig. 5. The Bachorzewo E site. A – Large-scale anticline formed from the Middle Miocene (M_2) and cut by the overlapping Upper Miocene (M_3). In the shear zone, below the thrust, there are small second-order deformations expressed among others as Riedl shears and sheath folds. B – Asymmetric anticline with south vergence well visible in the exposure of SW-NE intersection. The anticline axis dips towards SE (122°) at 18°. For explanations see Fig. 4.

Bachorzewo W. A wall, 25-m high, exposes two packets inclined monoclinally towards the north, separated by a thrust plane that also dips northward. The lower packet, at least 20 m thick, is represented by deposits typical of the Middle Miocene brown coal formation (M_2). It is composed of silty sand laminated with mud or silt, carbonaceous mud with xylites and siderite concretions, as well as fine-grained sand with admixture of carbonized organic matter. Locally, a siltstone bed, several tens of centimetres thick, and thin lignite layers occur at the base of the exposed series. The strike azimuth in this packet is 100–115º and the layers dip at 30–35ºN.

The upper packet, composed of the Upper Miocene mud and clay, including variegated clay (M_3), was thrust upon older deposits over a surface running more or less longitudinally and inclined northwards at 52–55º. At the base of



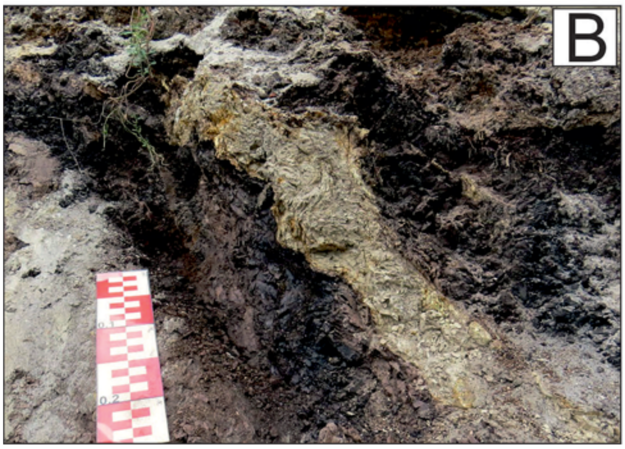


Fig. 6. The Rumunki site. A – Reverse drag fold in the Upper Miocene deposits, its geometry indicates displacement from N to S. B – Intense small shear deformations near the thrust zone (100–105/30°N) expressed as cleavage and disharmonic drag folds. For explanations see Fig. 4.

the thrust, there are small deformation structures with slip cleavage and tectonic breccia. The upper packet strata dip at 22–27ºN.

Bachorzewo E. In this site, two walls were available over the surface 30 m long and 9 m high in the SW-NE and WNW-ESE intersection, exposing an anticlinal fold truncated by an extensive thrust plane (Fig. 5A). The fold is composed of silty sand, mud and mudstone, brown coal and carbonaceous clay of the Middle Miocene (M_2). The thrust plane is overlain by the Upper Miocene variegated clay (M_3). The inclined southward-verging anticlinal fold is visible in the SW-NE wall only (Fig. 5B). The axis of the anticline dips south-eastwards (azimuth 118°) at 18°. Layers in the southern limb dip at 60–80ºS, whereas in the northern limb the strata dip at 35–60ºN. Small inverted faults are recorded here, several tens of centimetres in size, with the planes generally dipping northwards.

The other large-scale structure is a thrust plane truncating the upper part of the fold, overlain by the Upper Miocene (M_3) clay (Fig. 5A). Its strike azimuth is 115–118º and it dips towards the north at 34–36º (115–118/34–36ºN). The thrust zone is accentuated by a presence of small-scale shear structures in the form of sheath folds, Riedel shear sets and cleavage. In this zone, secondary accumulation of gypsum as single crystals or rosettes is a characteristic feature.

The southern fold vergence, as well as the thrust plane orientation, indicates that the main glaciotectonic transport direction was from NE to SW.

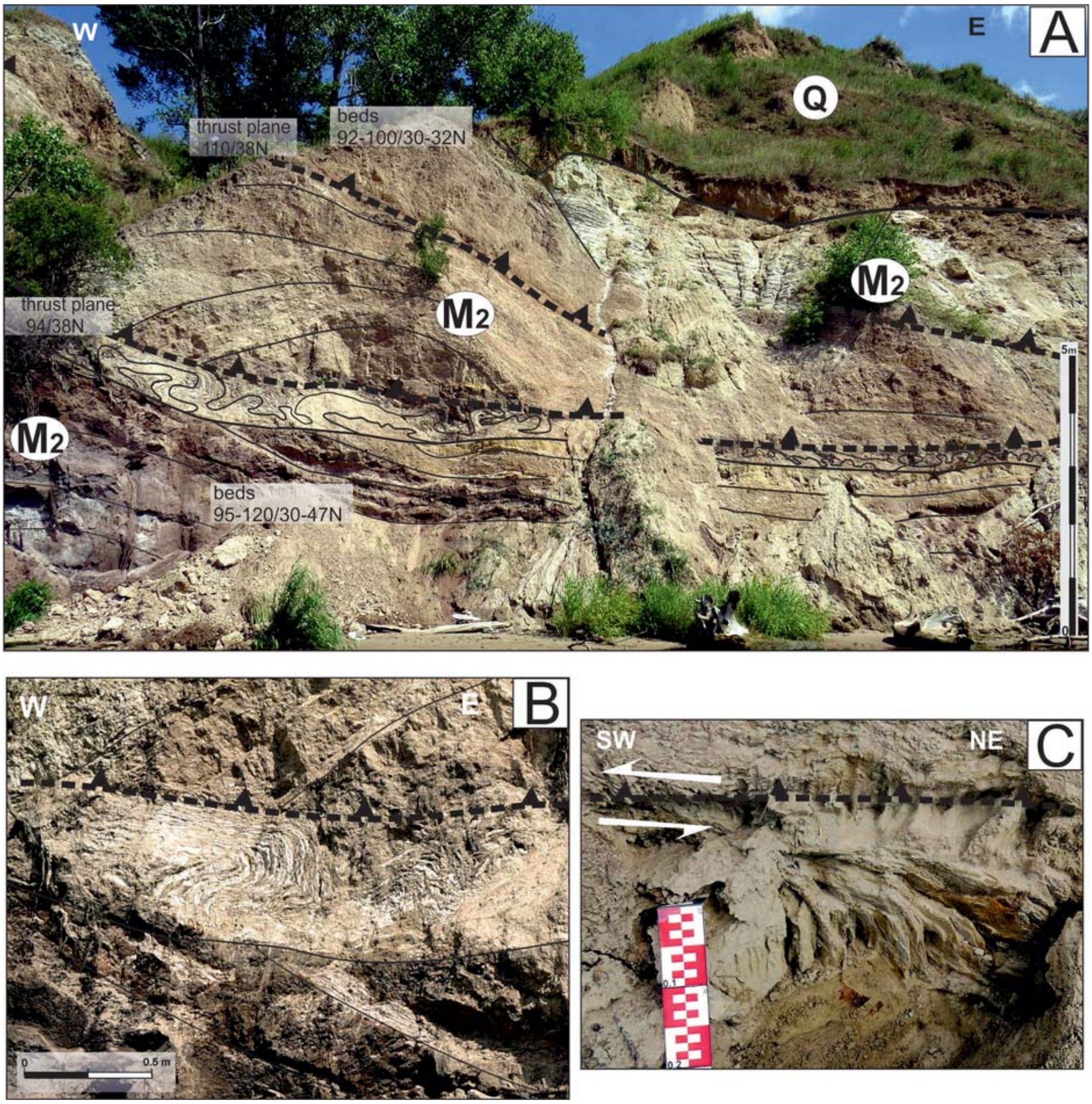


Fig. 7. The Góra Zamkowa site. A – Packets of brown coal formation (M_2) with first-order thrust plane in the floor. The thrust sheets dip towards N and NNE. The overlaps are underlined by second-order shear deformations. B – Small shear structures below the overlap expressed as a sheath fold. C – Drag folds accompanying the thrust planes, and showing well the direction of movement of packages from NNE towards SSW; white arrows indicate shear direction. For more explanations see Fig. 4.

Rumunki. At this site, three exposures were analysed in W-E and SW-NE intersections, 70 m long and 5–6 m high. They present a truncated anticline composed of the Middle Miocene sand-mud sediments with brown coal (M_2), thrust over the Upper Miocene-variegated clay (M_3). The thrust plane dips towards N/NNE, approximately at 30° (100–105/30–32°N). The anticline axis orientation (azimuth 119°) refers to the thrust plane strike, and is consistent with a course, both of the Vistula valley slope and the exposure walls. Therefore, in the central part of the site, the bed planes composed of carbonaceous silty mud, form a fold front. These planes are cut by two sets of regular fractures that form an orthogonal system. In the southern limb of the asymmetric anticline, the azimuth of layers is 110–130° and they dip steeply (70–82°) southwards, while in the northern limb the strike of the layers is similar (115–127°), but a dip is significantly smaller (30–45°N). Both the southern vergence of the fold and the orientation of the thrust plane suggest that the main glaciotectonic transport direction occurred from NNE to SSW.

In the western part of the site, the Upper Miocene variegated clay and mud occurring under the thrust plane form a reverse drag fold (Fig. 6A). Its geometry indicates that the movement direction of the overlying thrust sheet was generally from N to S. The thrust plane itself is accentuated by a layer of intensely deformed clay deposits, including carbonaceous clay. Small-scale shear structures in this layer are expressed as cleavage and disharmonic southward-verging drag folds (Fig. 6B). These structures confirm that displacements over the thrust planes were from N to S.

In the eastern part of the site, a complex of compressionally deformed sediments is cut by normal faults with fault plane strikes close to longitudinal and the dips of 47–55ºS (100/47ºS, 97/50ºS, 105/52ºS, 100/55ºS). A slip of the faults is at least 2 m. In the downthrown sides, the Upper Miocene (M_3) deposits are represented by variegated clay and creamy-pink claystone. Normal faults of such trend, which are located on the northern slope of the imbricated anticline, suggest that they might have been formed synchronously with a thrusting as compensatory displacements, caused by extension related to mass loss in hinterland of the thrust complex.

Góra Zamkowa. The wall, 10 m high and 35 m long, exposes three packets of the typical Middle Miocene sequence, which are separated by thrust planes (Fig. 7A). The packets (thrust sheets) are 1–5 m thick. Both layers of the lower and upper packets (lower packet: 95–120º/30–47ºN, upper packet: 92–100º/30–32ºN), as well as extensive thrust planes (94–105º/35–40ºN), generally dip towards the north. In turn, layers of the middle packet form an anticlinal fold with a near-horizontal axis running at azimuth of about 110º, bordered from the base and top by thrust planes. At the base of the lowest thrust plane (94/38ºN) there is a shear layer expressed by subordinate small-scale deformation structures in a form of drag and sheath folds, and sporadically by small shears (Fig. 7B). These structures occur in a zone of sand-mud sediments up to 0.6 m thick and they indicate a thrusting direction of the Neogene thrust sheets from NNE to SSW (Fig. 7C).

Dobrzyń E. The 7-m high wall reveals over a distance of 15 m a packet of monoclinally inclined strata of sedimentary sequence, characteristic of the Middle Miocene brown coal formation (M_2). These are silt laminated with fine-grained sand, as well as fine- and medium-grained sand with admixture of brown coal silt and coalified plant detritus. Occasionally, there is brown carbonaceous silt and thin brown coal layers. The azimuth of the layers is 80º and they are inclined towards the north at relatively large angle of 40–43º. In the western part of the exposure, the packet of inclined layers is cut by a normal fault (160/82ºN) with a displacement of ca. 1.0 m.

INTERPRETATION AND DISCUSSION OF RESULTS

The analyzed first-order glaciotectonic structures of the Middle and Upper Miocene deposits are expressed as imbricated thrusts (sites: Kuzki, Bachorzewo W, Góra Zamkowa) and asymmetrical folds (Bachorzewo E, Rumunki). The southern vergence of these structures, as well as W/NW-E/SE orientation of fold axes indicate the main disturbing stress from NNE to SSW (Fig. 8). Geometry of small-scale deformation structures below the thrust planes to 1.5 m depth and expressed as drag folds, sheath folds and Riedel shears confirms that the glaciotectonic transport generally from the north to south. A similar opinion regarding the glaciotectonic transport direction was previously proposed by Skompski (1969, 1995) and Jaroszewski (1991), based on research at individual sites revealing deformations in the Neogene deposits on the high side of the Płock Basin in the Dobrzyń region.

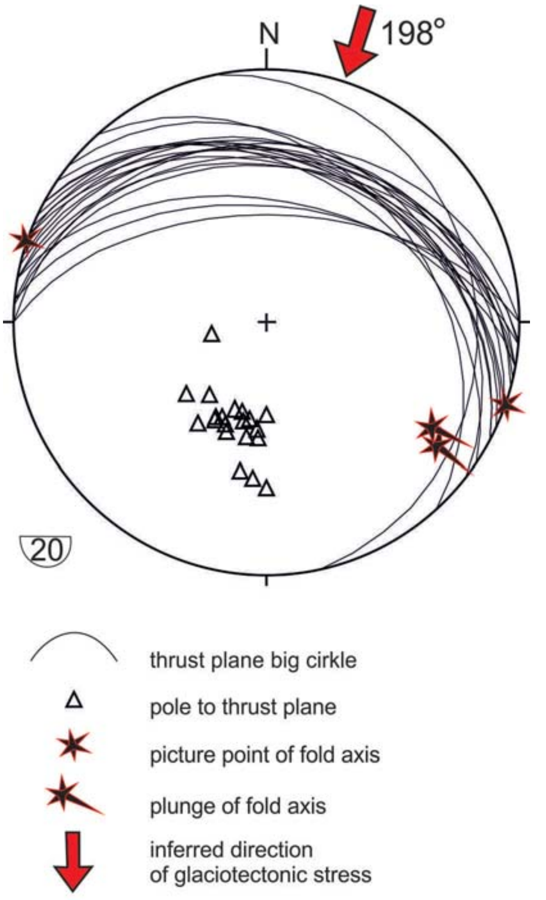


Fig. 8. Summary diagram of orientation of large-scale (first-order) glaciotectonic structures, thrust planes and fold axes, occurring in the Vistula valley scarp between Dobrzyń and Kuzki together with inferred direction of a glaciotectonic stress.

The ice sheet that provided large-scale glaciotectonic structures involving the Neogene and possibly also the Palaeogene deposits (Figs 2 and 3) was probably the first one that invaded the study area. At that time, the Neogene/Palaeogene soft deposits were least consolidated and most susceptible to deformations. An additional argument for such age is that the Quaternary sediments are only sporadically involved in deformations. Traces of Quaternary sediments among the Neogene deposits were found in a few boreholes only. On the other hand, researchers (including Ber, 1960; Jaroszewski, 1963; Skompski, 1969, 1995; Brykczyński, 1982; Roman, 2010b) agree that the lowermost till exposed in the scarp of the Vistula valley between Płock and Włocławek represents the Elsterian ice sheet i.e. the last ice sheet that disturbed the Neogene deposits.

Data from boreholes and geophysical surveys, as well as from studies documenting the glaciotectonic structures in the Płock Basin and its surroundings (Krzywiec *et al.*, 2005; Morawski, 2005a, b; Różański and Włodek, 2009; Żuk, 2013) prove that the Neogene deformations reach much deeper than observed in the exposures. Ruszczyńska-Szenajch (1985) also drew attention to this. Żuk (2013), when examining the area north of Dobrzyń, presented the Neogene and Paleogene deformations as imbricated thrusts, with the glaciotectonic transport towards the southwest (Fig. 3). The sediments were displaced from the deep Mochowo depression in the sub-Quaternary bedrock, about 20 km to NE of Dobrzyń (Lamparski, 1983). The Quaternary deposits overlie there directly the Cretaceous rocks (at Romatów at 96.6 m b.s.l.) and are removed towards the elevation near Dobrzyń, where the stacked Neogene deposits occur at 100.4 m a.s.l. in Mokowo (Żuk, 2013).

A quite different opinion was presented by Brykczyński (1982), who determined the ice-sheet stress from SW to NE. Such direction was to be consistent with his idea of valley-side glaciotectonics implying that an ice sheet advanced into a predisposed palaeovalley located in the present Płock Basin and the deposits were pushed outside from the depression.

When considering the scale and depth of the deformations (at least 100 m), their regional distribution, as well as co-occurrence of the deformed Neogene elevation and the depression in the sub-Quaternary basement, the idea of Brykczyński (1982) seems false. Deformations could not have developed in such a scale as result of ice sheet or a glacial lobe advance into the valley to exert impact on its both sides. Moreover, there is no evidence that the buried glaciotectonic structures involving the Neogene deposits disappear outwards from the palaeovalley as suggested by Brykczyński (1982). There is also no data on participation of fluvial deposits in the deformations; although such sediments should have been displaced along with the Neogene deposits. Another issue that raises doubts is a postulated presence of a large valley in the Płock Basin before the advance of the first ice sheet in the study area. A deep and extensive depression in the Płock Basin is documented in the Mazovian Interglacial only (cf. Mojski, 1958; Skompski, 1968, 1969; Wiśniewski, 1976; Baraniecka and Skompski, 1978; Brykczyński, 1986; Roman, 2003, 2011) and it could favour advance of a glacial lobe, and thus a valley-side glaciotectonics.

It is also worth mentioning of critical opinions of Morawski (1980, 2008) and Morawski and Sarnacka (1989) regarding the side-valley glaciotectonics in the Vistula valley near Warsaw, earlier suggested by Brykczyńska and Brykczyński (1974). Morawski and Sarnacka (1989) prove that large-scale glaciotectonic disturbances do not disappear if moving away from the palaeovalley and the authors connected the deformations with the Saalian. Therefore, glaciotectonic structures in the Płock Basin and those in the vicinity of Warsaw represent different generations and could not have been created during the same glacial event.

According to the authors, the formation of the extensive zone of serial thrust glaciotectonic structures with a considerable subsurface range was not conditioned by existence of a palaeovalley and therefore, the concept of Brykczyński (1982) on valley-side glaciotectonics in the Płock Basin should be rejected. Earlier, Ruszczyńska-Szenajch (1985) and Jaroszewski (1991) have also objected to the idea of Brykczyński; however, only Jaroszewski (1991) supported his doubts with structural research. Because only the upper part of large-scale deformations structures is available for research in the exposures, it is difficult to determine precisely a mechanism that formed the oldest and best pronounced (in terms of scale) glaciotectonic deformations in the Płock Basin. Most likely, cylindrical detachments in a frontal zone of an ice sheet were the main process leading to development of a large-scale glaciotectonic thrust complex (Rotnicki, 1976; Jaroszewski, 1991, 1994). It was due to differentiation load and lateral stress (compression) of an advancing glacier. In the study area, they resulted from thrusting from N/NE, while propagation of deformation structures was towards S/SW. A similar model was presented by Aber *et al.* (1989) and Kupetz (2001). This process is commonly referred to as the gravity spreading model (cf. Pedersen, 1987, 2005; Aber *et al.*, 1989; Andersen *et al.*, 2005). A deeply rooted complex of glaciotectonic thrust sheets, comprising Miocene and probably Oligocene deposits and similar to structures in the Płock Basin vicinity, was well recognized in Denmark and Poland thanks to high-resolution seismic data (Husse and Lykke-Andersen, 2000; Krzywiec *et al.*, 2005; Høyer *et al.*, 2013). It shows that deformations reach a certain depth defined as a décollement surface. In the case of the structures under consideration, the detachment surface corresponds probably to a regional Mesozoic–Cenozoic unconformity (Figs 2 and 3).

CONCLUSIONS

The results clearly contradict Brykczyński's (1982) opinion that macrostructures observed in the exposures near Dobrzyń on the Vistula were formed by the so-called valley-side glaciotectonics. The following facts support this view:

(1) S/SW vergence of folds and thrust planes, and thus directed not outwards (as implied by the assumptions of valley-side glaciotectonics), but towards the axis of a palaeovalley suggested by Brykczyński (1982);

(2) scale and spatial extent of structures, inadequate to a glacial lobe that invaded the valley;

(3) lack of evidence for existence of a deep and extensive valley, older than the South Polish Complex (Dorst-Elsterian), which could affect direction of both ice movement masses and glaciotectonic compression at the flanks;

(4) lack of disappearance of large-scale glaciotectonic thrust structures as moving away from the palaeovalley indicated by Brykczyński (1982). It is particularly true in the Dobrzyń region, located in a glacioelevation zone, where the deformed Neogene deposits reach up to 100.4 m a.s.l.

and there is a deep Mochowo glaciodepression (96.6 m b.s.l.) to the north, which is probably a source area for the material displaced glaciotectonically towards S/SW.

The driving mechanism leading to formation of a zone of rhythmic, southerly verging, large-scale thrust structures in the Dobrzyń region is interpreted to be gravity spreading in front of an ice sheet that advanced from N/NE during the South Polish Complex (Dorst-Elsterian).

Acknowledgements

Authors are grateful for the patient and constructive reviews of Wojciech Morawski and Dariusz Gałązka. This work was pretty supported by the Polish geological private firms GEOTECHNIKA-ŁÓDŹ Grzegorz Roman and SANDR Rafał Żuk, Warsaw. Thank you to the Polish Academy of Sciences, Department of Environmental Resources and Geohazards in Toruń, for the loan of floating equipment.

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