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THE INFLUENCE OF SUB-QUATERNARY BASEMENT ON THE RELIEF IN THE EASTERN PART OF THE POMERANIAN LAKELAND, POLAND

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Abstract: Geological mapping works, conducted on 1:50,000 litho-petrographic map sheets of the South Baltic coast and the eastern part of the Pomerania Lakeland, show a clear relationship between large landforms of this area, like: subglacial channels, Wieżyca Hill, the ice lobe that accumulated Gardno moraine deposits, and sub-Quaternary relief. These landforms came into existence as a result of reactivation of pre-existing fault zones in the sub-Cainozoic basement, due to the ice mass loading during successive Pleistocene ice-sheet advances. Subglacial channels developed and thick tills and ice-dammed lake deposits were accumulated in the region. The subglacial channels and morainic belts are now dominating landforms in the Pomeranian Lakeland.

Key words: relief of the top of sub-Quaternary deposits, subglacial channels, Kaszuby Lakeland, Bytów Lakeland, Gardno Lowland, Poland.

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INTRODUCTION

Geological mapping works, conducted by the author for over thirty years in the South Baltic coast and the eastern part of the Pomeranian Lakeland, from the Żuławy Wiślane border to Bytów, Słupia River valley, Słupsk and Lake Gardno (Fig. 1), made it possible to draw some conclusions about the lithology of Quaternary sediments. They show a clear relationship between the present-day topography and sub-Quaternary relief of this area. My hypothesis is that the sub-Quaternary relief is not the one inherited from Neogene and preglacial times, but it formed during the successive Pleistocene ice-sheet advances.

RESEARCH METHODS

I conducted geological mapping works on 12 sheets of the 1:50,000 Detailed Geological Map of Poland (DGMP) to examine the geological architecture of Quaternary sediments (Petelski, 1998, 1999, 2000a, b, 2001, 2002, 2003a,b, 2005, 2006, 2008, 2009). Geological structure of Quaternary deposits was studied by special research boreholes. The origin of glacial deposits and stratigraphy of tills was interpreted based on lithological and petrographic investigations (Lisicki, 2003). Analysis of the boreholes drilled for the DGMP and all archival boreholes ever drilled in this area enabled for the construction of relief maps of the top of sub-Quaternary strata. Geophysical resistivity surveys were performed along geological cross-sections. They confirmed the presence of sub-Quaternary landforms described in the paper. Zones of glaciotectonic disturbances in the study area were identified and analysed as well.

GEOLOGICAL SETTING OF THE SUB-QUATERNARY BASEMENT VS. THE RELIEF OF THE EASTERN PART OF THE POMERANIAN LAKELAND

The eastern part of the Pomeranian Lakeland, spanning the Kaszuby and Bytów lakelands, is a highly elevated area (over 200 m a.s.l.) of morainic plateaus with some culminations attaining 230–250 m a.s.l. There occurs the highest point of the European Lowlands – Wieżyca (329 m a.s.l.). The surfaces of the morainic plateaus are composed of tills. The area is transected by four systems of large subglacial channels; from the east these are: the Dąbrowskie and Patulskie lakes valley, Raduńskie lakes valley, Gowidlińskie Lake valley and Jasień Lake valley. A few tens of metres high prominent escarpments bound the valleys. The valleys' bottoms or water levels of the valleys' lakes lie 60–70 m lower than the surfaces of the surrounding morainic plateaus. Taking into account the depths of the lakes, the differences in elevation between the plateau surface and the valley bottom range from 80 to 100 m.

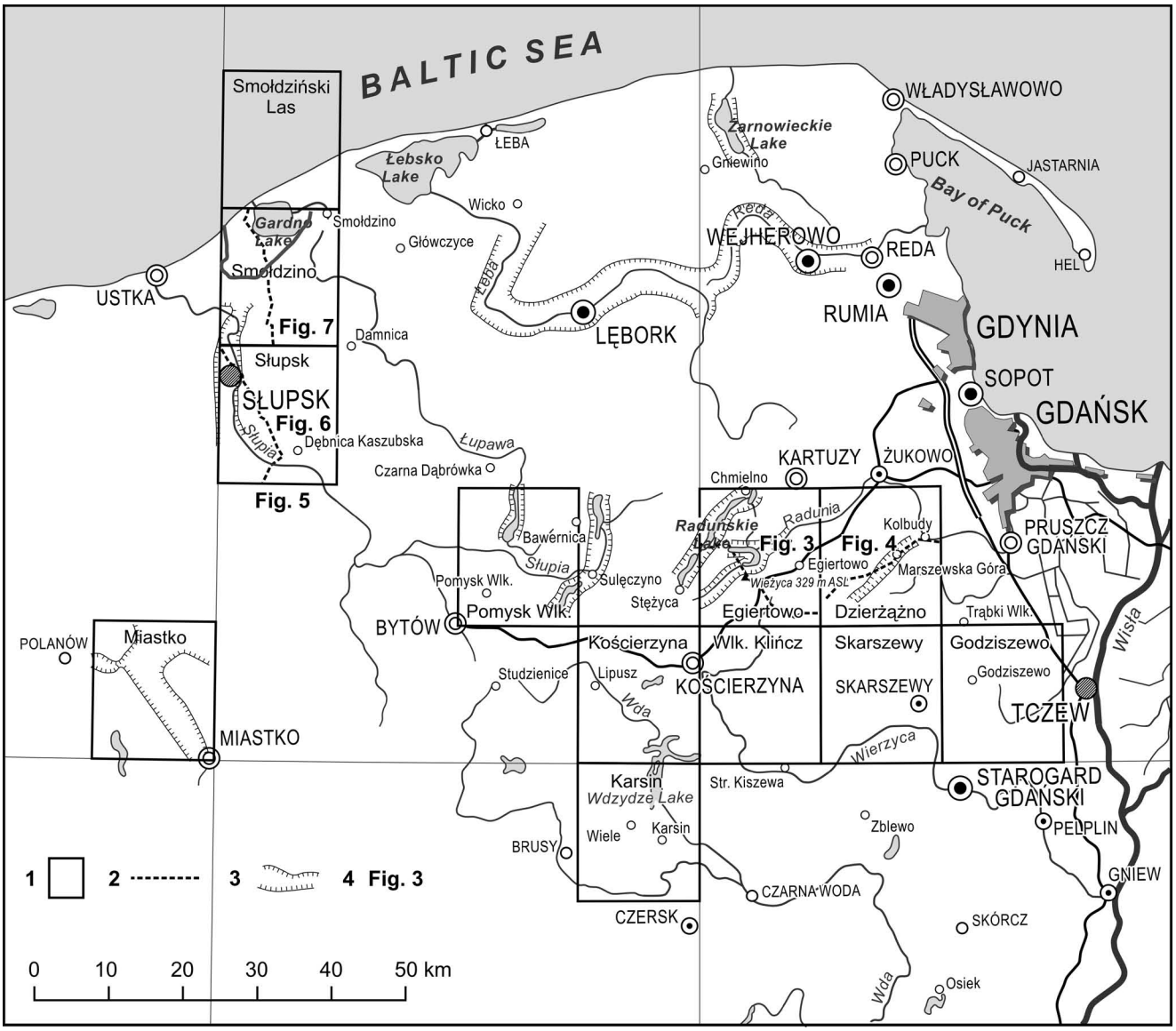

Fig. 1. Location of areas discussed in the paper: *1* – location of the sheets of the Detailed Geological Map of Poland, scale 1:50,000, prepared by the author, *2* – location of geological cross-sections, *3* – location of lake valleys presented in the paper, *4* – location of individual figures

The morainic plateaus of the Kaszuby and Bytów lakelands descend southwards to the elevation of 160–150 m a.s.l. They adjoin here a zone of outwash plains deposited during the Pomeranian Phase of the Vistulian (Weichselian) Glaciation. Towards the north, the plateau areas descend and pass into coastal morainic plateaus of Damnica and Żarnowiec. The coastal plateaus are situated at much lower elevations (100 m a.s.l.) than the morainic areas of the lakelands.

The morainic plateaus are commonly referred to as lakeland ridges. This term is justified not only by the high elevations of these areas but also by their subsurface geological structure. The sub-Quaternary bedrock of this region lies at higher elevations than it does in the areas situated to the south and north of the lakeland ridge. The top of Miocene strata that underlie the Quaternary succession in the lakeland ridge is located at elevations ranging from 100 m a.s.l. in the Bytów Lakeland to 60–80 m a.s.l. in the Kaszuby Lakeland (Fig. 2). The top of Miocene strata descends northwards. In the South Baltic coast, it lies at elevations ranging from 20 m b.s.l. to 60 m b.s.l. To the south of the lakeland ridge, in the outwash plains area, the top of Miocene strata descends to 20–40 m a.s.l.

In previous papers (Zaborski, 1933; Okołowicz, 1956; Piasecki, 1958, 1962; Pachucki, 1961; Sylwestrzak, 1961, 1972, 1973, 1978; Galon, 1967, 1968; Roszko, 1968; Beniuszys, 1968; Szukalski, 1968; Augustowski, 1969) concerning the relief and geological structure of the eastern part of the Pomeranian Lakeland, lithology of Quaternary sediments and their relationship to the subsurface geological structure of the area was neglected. The exceptions are the works devoted to the Gdańsk region, presented by Mojski (1979, 2002), who indicated a clear relationship between the present-day topography of the area and the relief and geological structure of Neogene strata.

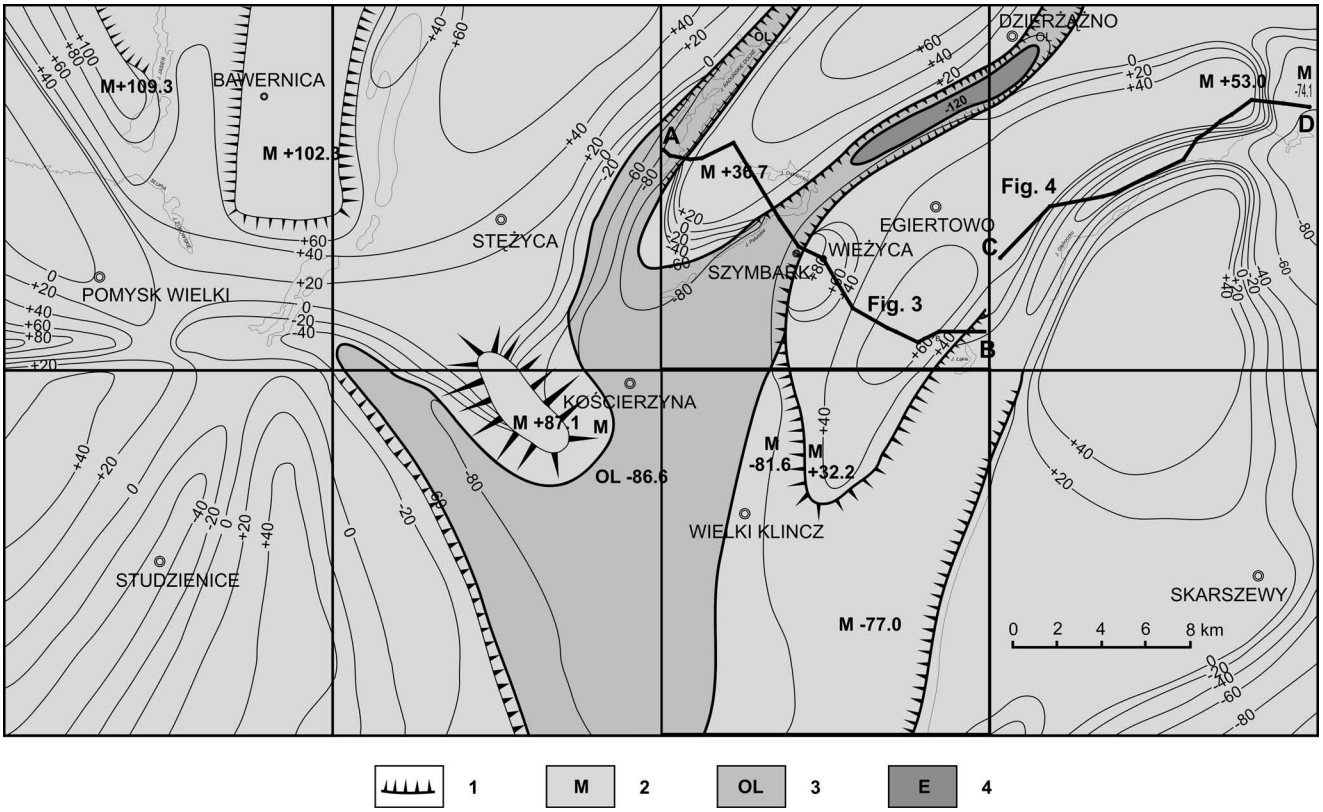

Fig. 2. Relief of the top of sub-Quaternary strata in the Kaszuby and Bytów lakelands; location of geological cross-sections from Figures 3 and 4: *1* – edges in relief of the top of sub-Quaternary strata, M – Miocene sands, Ol – Oligocene sands and silts, E – Eocene sands

Geological works conducted by myself on 12 sheets of the DGMP revealed a relationship between large subglacial channels and the sub-Quaternary basement relief.

The Raduńskie Lake tunnel valley and the Dąbrowskie and Patulskie lake tunnel valley (Fig. 3) occur in the area where the deep Raduńska and Patulska subglacial channels (fault-bounded valleys) are incised in the top of the Miocene. The valleys' bottoms are situated at 80–120 m b.s.l. elevation and lie 140–180 m lower than the surrounding areas where the top of the Miocene is located at 60 m a.s.l. The trend of these subglacial channels and their geological structure is documented by 30 archival boreholes and research boreholes drilled for the purposes of the DGMP. The Quaternary section drilled in the Patulska valley is over 308 m thick (a borehole at Szymbark, sheet Egiertowo of the DGMP). The bottoms of both valleys are lined with deposits of the oldest (Narewian; Menapian) glaciation. The Raduńska valley is filled with glacial deposits, including ice-dammed lake silts and clays, Narewian–Menapian, Sanian–Elsterian 2, Odranian–Saalian 1 and Wartanian–Saalian 2 till horizons, and glaciofluvial sands. Fluvial sediments of the Lubawa (Saalian 1/Saalian 2) Interglacial comprise only a 4 m-thick series of the entire 266-m-thick depositional succession filling the valley.

The Patulska valley, in contrast to the Raduńska valley, is filled mainly by very thick tills of the Odranian (Saalian 1) Glaciation (56.0 m) and Wartanian (Saalian 2) Glaciation (including Lower Stadial (76.0 m) and Middle Stadial (20.0 m)), as well as by glaciofluvial sands. Fluvial sediments in this 308-m-thick section are merely 8.0 m in thickness, and are represented by the Mazovian (Holsteinian) Interglacial sands.

The filling of both the valleys proves that they were sites of subglacial deposition throughout the entire Quaternary period. No signs of erosion is observed in the valleys' bottoms, thus they were not river valleys during interglacial periods.

Deep valleys cut into the sub-Quaternary basement formed and developed in the Quaternary. During Neogene and preglacial (Early Pleistocene) times, variations in the relief of the top of Miocene strata were the same as today. Such high variations in the elevation of the top of the Miocene would have had to be reduced by glacial erosion and accumulation. At the site of the present-day deep Raduńska and Patulska valleys, there were probably shallow topographic depressions, most likely river valleys. During the Narewian (Menapian) ice-sheet advance, the valleys became filled with tills and glaciofluvial sands.

The covering of the area by the advancing ice sheet resulted in reactivation of pre-existing fault zones within the sub-Cenozoic basement. After the ice retreat, isostatic rebound of the Earth's crust occurred in the area that was previously deformed due to ice loading. The uplift continued with different speed along the pre-existing fault zones, resulting in the formation of a horst. The amplitude of vertical movements along the fault lines attained a few tens of metres.

The same situation occurred during the successive ice-sheet advances. Always at the same sites, along the fault

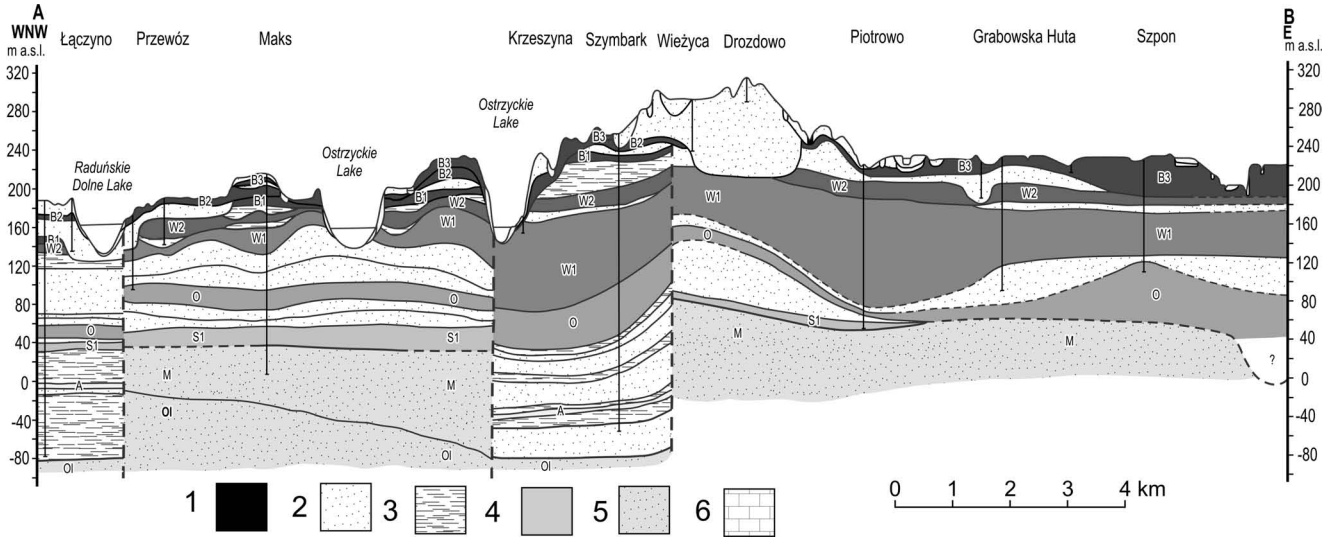

Fig. 3. Geological cross-section through the Raduńskie lakes valley and the Dąbrowskie and Patulskie lakes valley. Cr – Cretaceous, Ol – Oligocene, M – Miocene; Glaciations: A – Narevian (Menapian), N – Nidanian (Elsterian 1), S – Sanian 1 (Elsterian 2), G – Sanian 2 (Elsterian 2), O – Odranian (Saalian 1), W – Wartanian (Saalian 2), B – Vistulian (Weichselian); *1* – peat, *2* – sands, *3* – clays, *4* – tills, *5* – Neogene and Palaeogene sands, *6* – Cretaceous chalk and marl

zones, subglacial channels developed during the following glaciations. Thick till series were deposited in these valleys, which were subsequently deformed by glaciotectonic processes. The trend of the valleys coincides with that of photolineaments identified by Bażyński *et al.* (1984) and Graniczny *et al.* (1987, 1995) indicating that these landforms are associated with the tectonic structure of the basement.The Wieżyca Hill is located upon a fault zone at the boundary between the Patulska valley and the area of the uplifted top of Miocene strata (up to 60 m a.s.l. in elevation; Fig. 3). The hill is a large crevasse-fill landform attaining the elevation of over 250 m a.s.l., whose individual peaks exceed 300 m a.s.l. and the summit is at 329 m a.s.l. (the highest hill of the European Lowlands). The thickness of sand-gravel-boulder sediments composing the Wieżyca Hill exceeds 53 m.

The formation of such a large crevasse-fill landform was possible owing to its location upon a fault zone where a set of crevasses developed in the ice sheet when its front was to the south of the study area and the ice mass was relatively thick.

To the east of Wieżyca, the NE–SW-trending Marszewo valley is situated. It is deeply incised (60–70 m) into the surrounding Przywidz Plateau that rises to the elevation of over 200 m a.s.l. To the east, between Kolbudy and Czerniewo, the plateau is bordered by a high (70–80 m) edge sloping towards the Żuławy Wiślane Lowland. The trend of the Marszewo valley and the plateau-bounding edge is closely related to the ancient landforms observed in the sub-Quaternary basement.

The N–S-trending ancient edge is 100 m high. It separates the area of elevated top of Miocene strata (40 m a.s.l.) in the Kaszuby Lakeland from the area where the top of the Miocene is situated at the elevation below 60 m b.s.l. in the Żuławy Wiślane region. At the foot of the edge, there is a thick complex (60 m) of Narewian (Menapian), Nidanian (Elsterian 1), Sanian 1 and Sanian 2 (Elsterian 2) tills. The ancient Marszewo valley is incised to a depth of 80 m below the top of Miocene strata that lies at 40 m a.s.l. (Fig. 4). Its bottom is lined with the Augustovian (Bavelian *s.l.*) Interglacial fluvial sands and gravels overlain by Nidanian Glaciation deposits (tills interlayered by ice-dammed lake sediments, 53 m in thickness).

The valleys of the Raduńskie lakes and Dąbrowskie and Patulskie lakes, as well as the Marszewo valley and the edge of the Kaszuby Lakeland between Kolbudy and Czerniewo clearly follow the direction of pre-existing landforms observed in the sub-Quaternary basement. Sediments of the oldest glaciation (Menapian) and South-Polish (Elsterian) glaciations of all these landforms fill the valleys (relief depressions) in the top of Neogene strata.

In the areas where the top of sub-Quaternary basement is situated at high elevations, sediments of the oldest and South-Polish glaciations are absent. Glacial deposition started here with the Middle-Polish (Saalian) Glatiation (Odranian and Wartanian) sediments that smoothed the rough relief of older glaciation periods. Geological cross-sections through the Raduńskie, Dąbrowskie and Patulskie lake valleys (Fig. 3), the Marszewo valley, and the Kaszuby Lakeland between Kolbudy and Czerniewo (Fig. 4) differ in the number of identified till horizons, which was proved based on litho-petrographic investigations conducted for the DGMP.

A similar type of geological structure is observed in the eastern part of the Bytów Lakeland where the course of the Jasień Lake valley is related to the trend of an ancient valley observed in the sub-Quaternary basement. A more interesting issue is the problem of the boundary between the Odra and Vistula ice lobes of the Pomeranian Phase of the Main Stadial of the Vistulian (Weichselian) Glaciation. The boundary is drawn across the Bawernica morainic plateau rising above 200 m a.s.l. (Keilhack, 1898; Okołowicz,

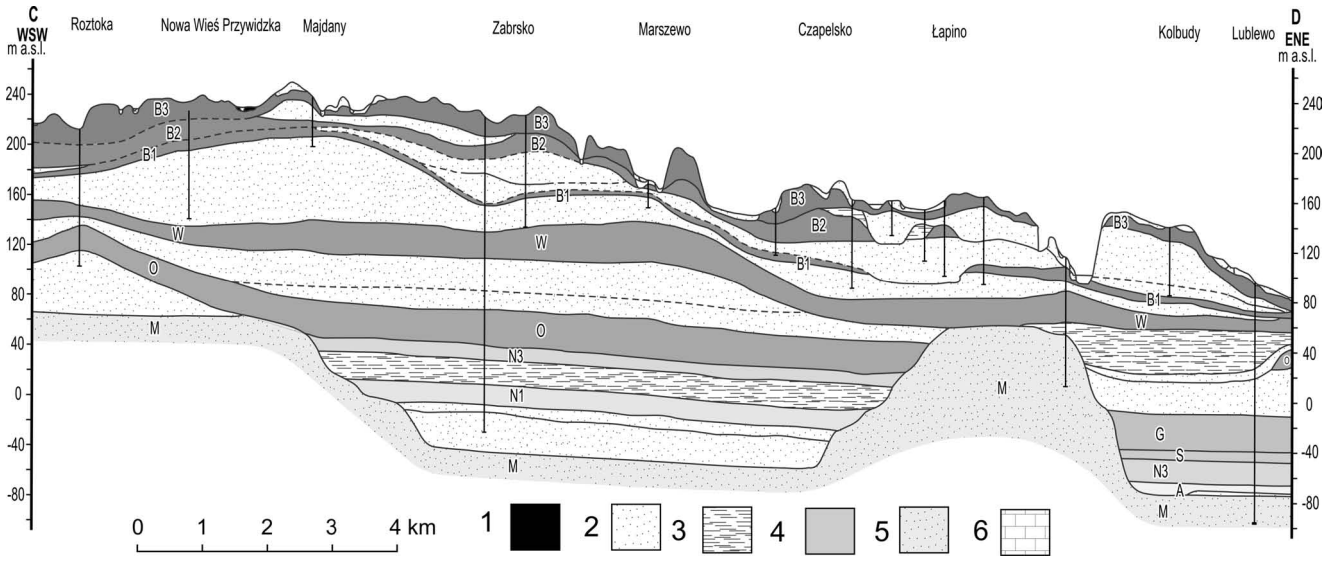

Fig. 4. Geological cross-section through the Marszewo valley. For explanations see Fig. 3

1956; Sylwestrzak, 1972; Petelski, 1998), where individual peaks exceed 225 m a.s.l. The Bawernica plateau coincides with the area where the top of Neogene strata lies at very high elevations (over 100 m a.s.l.). Ancient subglacial channels occur on both sides of the elevated sub-Quaternary bedrock. Their bottoms are at depths of 30–40 m a.s.l. These ancient channels are associated with large subglacial channels observed at the surface: the Jasień Lake subglacial channel running to the west of the Bawernica morainic plateau, and the Gowidlińskie Lake subglacial channels occurring to the east of the plateau.

In the central part of the Bytów Lakeland, north of Miastko, the morainic plateau is dissected by deep valleys and its elevation exceeds 200 m a.s.l. The valley bottoms lie 80–100 m below the plateau surface. The courses of the valleys coincide with the trends of ancient valleys in the sub-Quaternary basement (Petelski *et al.*, 2009).

The ancient valleys of the Bytów Lakeland, like those in the Kaszuby Lakeland, are filled with sediments of the oldest glaciation and the South Polish glaciations. No deposits of these ages have been found in areas of the elevated top of Neogene strata. Sediments of the Odranian, Wartanian and Vistulian glaciations cover both the study area and the ancient depressions in the sub-Quaternary surface, smoothing the rough relief of the sub-Quaternary bedrock.

SOUTH BALTIC COASTLAND

I conducted geological investigations in the Gardno Lowland, Reda–Łeba ice-marginal valley and Żarnowiec Lake region of the Baltic coastland (Petelski, 1975, 1976, 1978, 1985, 1990; Petelski & Jurys, 1989).

Since the beginning of the 20th century, many discussions have been made on the formation of the Reda–Łeba ice-marginal valley. However, Petelski and Sadurski (1987a, b, 1988) indicated a relationship between these landforms and ancient valleys that existed in the present-day ice-marginal valley throughout the entire Quaternary period. They also pointed out to the relationship between these landforms and the Żarnowiec Lake tunnel valley, which was a subglacial channel during the Quaternary. The formation and significance of the Żarnowiec Lake tunnel valley at the site where a fault cuts the Palaeozoic basement have been confirmed by many authors (*cf.* Dadlez, 1990; Znosko, 1998).

A different situation existed in the Gardno Lowland where one of the best-documented lobal patterns in Poland exists. Although the area was described already in the 20th century literature (Borne, 1857; Jentzsch, 1914; Bülow, 1924, 1930, 1932; Hartnack, 1926; Halicki, 1947; Giedrojć-Juraha, 1949; Rosa, 1963, 1964, 1968; Bartkowski, 1965; Roszko, 1968; Sylwestrzak, 1972, 1973, 1979; Petelski, 1975, 1976, 1978, 1985; Petelski & Jurys, 1989; Mojski & Orłowski, 1978; Tobolski, 1984, 1989; Rotnicki, 1987, 1994, 1999; Rotnicki & Borówka, 1990, 1994; Wojciechowski, 1988, 1990; Florek & Orłowski, 1991; Dobrzyński *et al.*, 1991; Jasiewicz, 1998, 1999; Czerniawska, 1999, 2004), reconstruction of a relatively detailed image of both the lithology of the Quaternary series and the relief of the top of Neogene strata was possible in 2003–2006 only (Petelski, 2005, 2006; Fig. 5). Geological studies carried out in this area over the last years have shown a clear relationship between the relief of the area and the relief of the sub-Quaternary basement.

The dominant landform of the sub-Quaternary basement is an extensive valley. It begins south of Słupsk and then runs across Słupsk to Włynkówko, where it turns northeastwards to Smołdzino and then towards the north beneath the Baltic Sea floor. The bottom of the valley is uneven; it slopes at different angles. In Słupsk, it is located at a depth of more than 140 m b.s.l. (Fig. 6), between Włynkówko and Smołdzino – below 120 m b.s.l. (Fig. 7), whereas north of Smołdzino it reaches a depth of 257 m b.s.l. The width of the landform varies between 2 and 3 km.

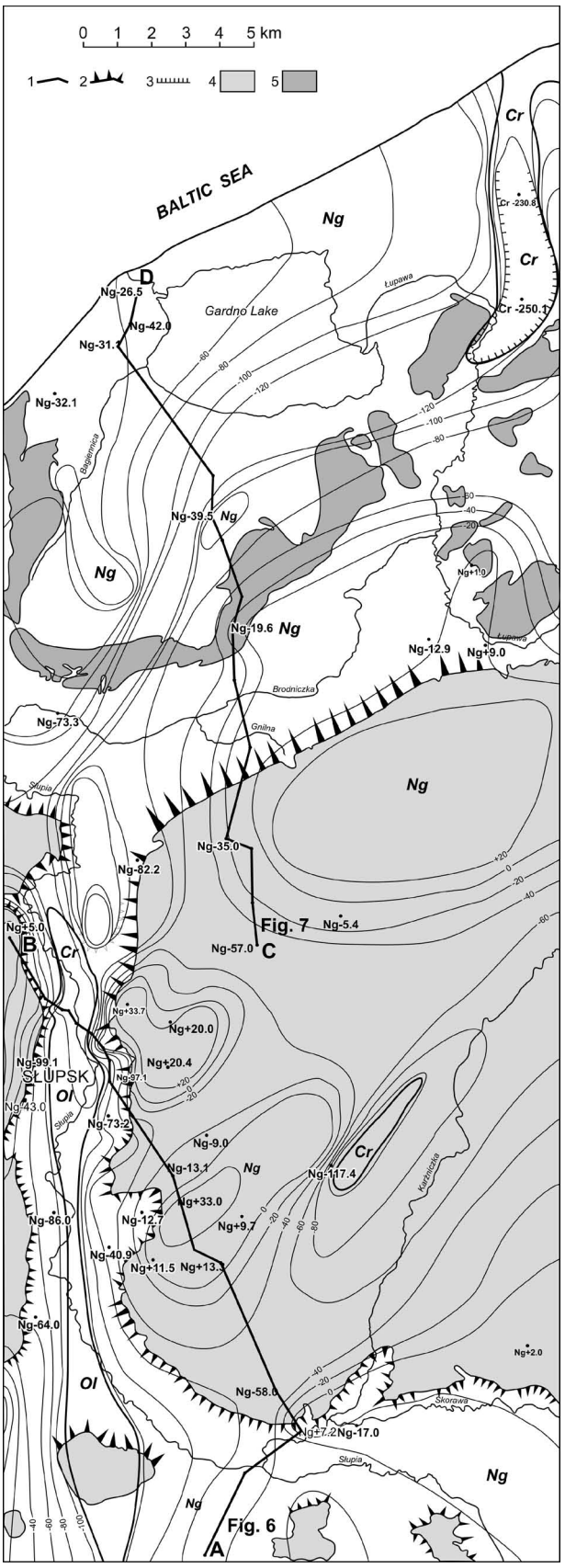

Fig. 5. Relief of sub-Quaternary strata in the Gardno Lowland and Słupsk region; location of geological cross-sections from Figures 6 and 7. *1* – geological cross-section lines, *2* – edges of morainic plateau, *3* – morainic plateau, *4* – Gardno frontal moraines, *5* – edges in relief of the top of sub-Quaternary strata

The valley is surrounded by areas where the top of Neogene strata is situated at elevations of 0 to 20 m a.s.l. The only region where the top of Neogene strata occurs at lower elevations (40–60 m b.s.l.) is the northern part of the study area.

The basic elements of the present-day relief of the study area coincide with the trend of both the ancient depressions observed in the top of the Neogene and the accompanying glaciotectonic deformation zones. The position of the ice lobe that accumulated Gardno moraine deposits was controlled by a depression in the top of Neogene strata, which accompanies the above-mentioned valley. The course of the northern edge of the Damnica morainic plateau coincides with the trend of the southern edge of an ancient valley running between Włynkówko and Smołdzino. The subglacial channel, containing the Słupia River between Kawkowo and Włynkówko, runs along an ancient valley observed in the top of Neogene strata.

As in the case of the Kaszuby and Bytów lakelands where the ancient valleys are filled with sediments of the oldest glaciation and the South-Polish glaciations, the valley running from Słupsk through Włynkówko and Smołdzino, and farther northwards under the Baltic Sea floor, is filled with Narewian, Nidanian, Sanian 1 and Sanian 2 deposits. No fluvial sediments have been found here. In the valley section that crosses the Słupsk region, the sediments are represented by Narewian, Sanian 1 and Sanian 2 tills inter- bedded by glaciofluvial sands and gravels. They are strongly glaciotectonically deformed and represent an example of the valley-side glaciotectonics (Dadlez & Jaroszewski, 1994). Between Włynkówko and Smołdzino, the valley is filled with a thick (88 m) complex of till horizons (also strongly glaciotectonically deformed) deposited during the Narewian, Nidanian, Sanian and Odranian glaciations, with no intervening sediments observed. To the north of Smołdzino, the bottom of the valley is at 263 m b.s.l elevation. It is filled with thick till series of the following glaciations: Narewian (72 m), Nidanian (24 m) and Sanian (59 m). The tills are separated by glaciofluvial sands, whose thickness is small as compared to the till thickness. In the area outside the ancient valley, where the top of the Neogene is at higher elevations, the glacial succession commences with the Odranian or Wartanian sediments which levelled the variable relief of the top of the Neogene. Geological cross-sections presented in Figures 6 and 7 differ in the number of identified tills, as documented by litho-petrographic investigations of the DGMP. Geological structure and tectonic setting of the sub-Quaternary basement were thoroughly explored in the South Baltic area by geophysical methods including high-resolution seismic surveys (Kramarska *et al.*, 1999; Krzywiec *et al.*, 2003). There is a clear relationship between the Cretaceous–Cainozoic lithologies and the orientation of fault zones in the Palaeozoic basement. Therefore, the occurrence of glaciotectonic deformation zones in the Słupsk region (Figs 6, 7) is supposed to be constrained by the block-type tectonics of the Cretaceous succession.

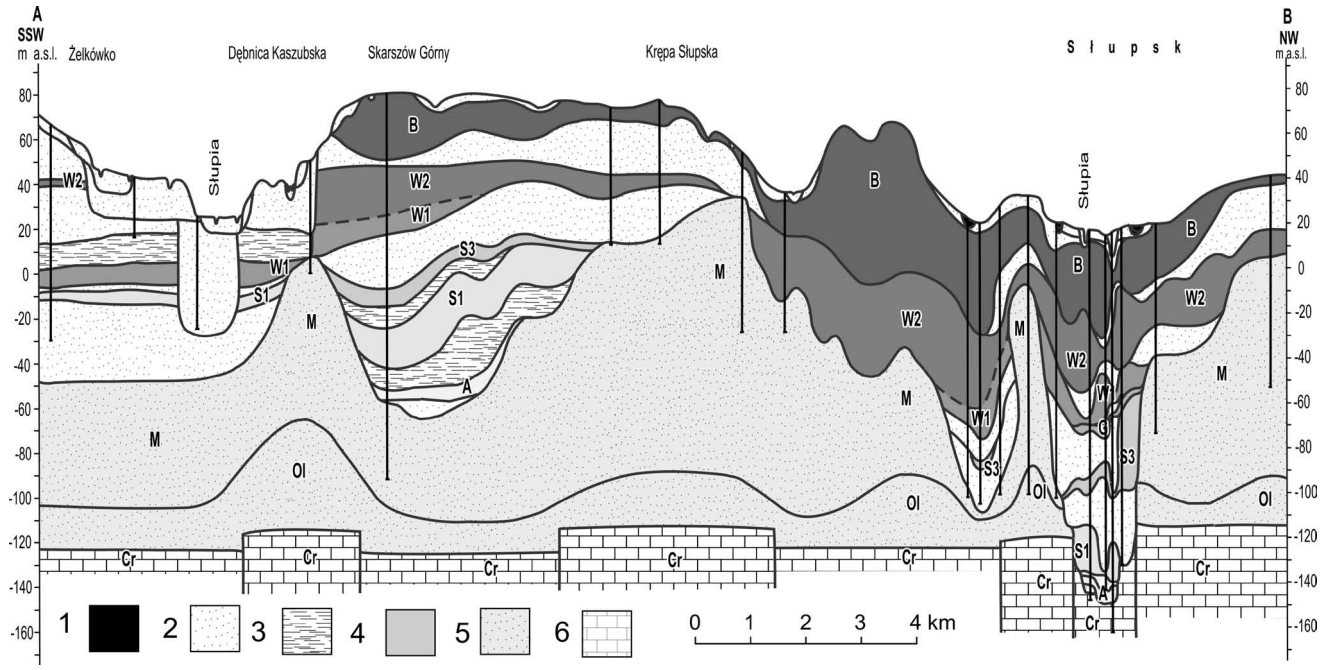

Fig. 6. Geological cross-section through the Damnica Plateau and Słupia River valley. For explanations see Fig. 3

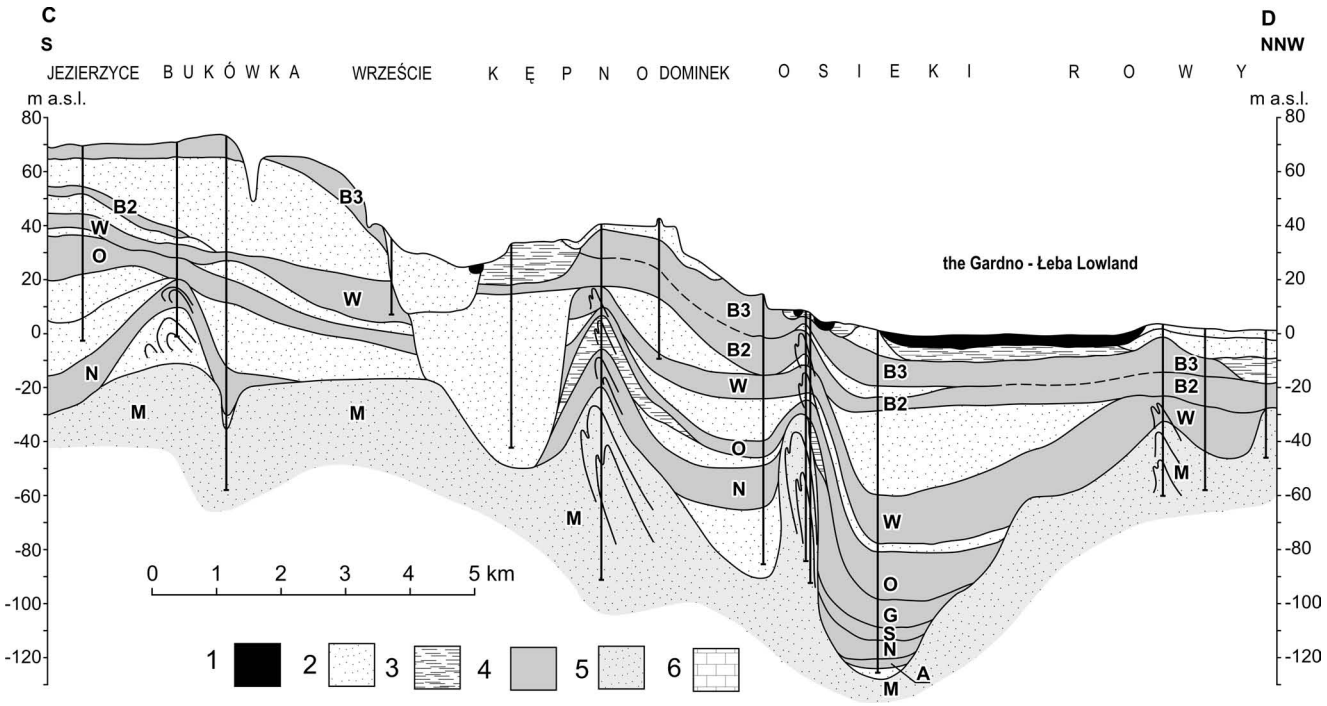

Fig. 7. Geological cross-section through the Gardno Lowland and Damnica Plateau. For explanations see Fig. 3

CONCLUSIONS

The origin of the ancient valleys from the South Baltic coastland and Kaszuby and Bytów lakelands is the same and consists in reactivation of fault zones pre-existing in the sub-Cainozoic basement due to the ice mass loading during successive ice-sheet advances. These areas were subsequently the sites of development of subglacial channels where thick till horizons and ice-dammed lake sediments accumulated.

The trend of the valleys coincides with photolineaments identified by Bażyński *et al.* (1984), indicating that these landforms are related to the tectonic structure of the basement. According to Dadlez (1976, 1989, 1990) and Znosko (1998), the Żarnowiec Lake tunnel valley is located on a fault zone within the Palaeozoic basement.

The Gardno valley, in particular its northern section whose bottom is at 263 m b.s.l. elevation, can be compared with ancient valleys described from the floor of the South Baltic Sea (Kramarska *et al.*, 1999) where high-resolution reflection seismic data revealed their relation to the fault zones of the Palaeozoic basement.

Isostatic movements of the Earth's crust along the rejuvenated fault zones caused reactivation of the pre-existing subglacial channels during successive Pleistocene glaciations. It is worth noting, however, that the process was more intense in Mid-Pleistocene times, probably due to neotectonic movements of the Kuyavian and Mazovian phases (Baraniecka, 1975) that were superimposed on the isostatic crustal movements. The variations in the geological structure style (discontinuous deformation in the Raduńskie lake tunnel valley, Dąbrowskie and Patulskie lake tunnel valley, and in the zone of strong glaciotectonic deformation in the Słupsk tunnel valley; quiet deposition in the Marszewo tunnel valley) were caused by variable intensity of isostatic crustal movements in the study area. Large and deep tunnel valleys, filled with strongly deformed sediments, developed in areas of intense vertical crustal motions.

All the subglacial channels are filled with sediments of the oldest glaciation and the South-Polish glaciations. These sediments are absent from the surrounding areas where the top of Neogene strata was being uplifted and the sediments have been removed. The Upper Pleistocene deposits cover the whole of the study area, levelling differentiated relief of the top of Neogene strata.

The boundary between the Odra and Vistula ice lobes of the Pomeranian Phase of the Main Stadial of the Vistulian Glaciation runs across the Bawernica morainic plateau. This is an area of highly elevated top of Neogene strata (above 100 m a.s.l.). The uplifting movements of this area favoured separation of the ice into two ice lobes: the Odra and Vistula lobes.

The influence of the relief of the sub-Quaternary basement on the present-day topography of this area is much stronger than previously thought. The locations of large subglacial channels and high topographic edges, the position of the highest culmination of the Pomeranian Lakeland (Wieżyca) and the boundary between the Odra and Vistula ice lobes are all related to the relief of the top of Neogene strata. The relief formed as a result of vertical movements of the Earth's crust during the Pleistocene.

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