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MORPHOTECTONICS OF THE ICE-MARGINAL AND RIVER VALLEY OF THE LOWER DRWĘCA RIVER (NORTH-CENTRAL POLAND) IN THE LIGHT OF LINEAMENT AND DIGITAL TERRAIN MODEL ANALYSES

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Abstract

The role of neotectonic movements in shaping the ice-marginal and river valleys of the Polish Lowland during the Quaternary is poorly understood and is generally marginalised in favour of explanations invoking climatic factors or changes in the base level of erosion. However, the author points to their morphogenetic significance within the ice-marginal valley and the lower Drwęca valley, particularly in the Konstancjewo, Elgiszewo and Młyniec basins. The hypothesis was tested through analyses of the older basement, lineaments, and the morphology and morphometry of the ice-marginal valley and the southern part of the Chełmno Moraine Plateau, based on existing studies and a Digital Terrain Model. The results indicate the involvement of neotectonic movements during the period from the deglaciation of the study area to the end of the last glaciation.

Keywords

neotectonics • photolineaments • morpholineaments • Digital Elevation Model • deflection • Drwęca Valley • Chełmno Upland

Introduction

Climatic fluctuations and changes in the base level of erosion are traditionally viewed as the primary drivers of river- and ice-marginal-valley formation in the Polish Lowlands during the Quaternary. By contrast, the role of neotectonic movements is difficult to determine and is only sporadically analysed in morphogenetic studies of these relief forms so common to this area. However, ground movements in this area undoubtedly influenced the hydrographic network, the course of river erosion and accumulation, and the relief of valley floors (Mojski, 1980; Niewiarowski, 1983; Brykczyński, 1986; Borówka, 1991; Molewski, 2007, 2014). According to Mojski (2005), vertical movements of the

Earth's crust, including activity along fault lines, occurred in the Pleistocene, and their inclusion in palaeomorphogenesis accounts of the Polish Lowland may lead to new, non-obvious conclusions (see also Włodarski et al., 2026).

This study argues that the influence of ground movements on the formation of valleys in the Pleistocene is exemplified by the ice-marginal valley and river valley of the lower Drwęca River, which is the largest right-bank tributary of the lower Vistula, at 241 km long (Fig. 1).

This valley section is the subject of a monograph by Niewiarowski (1968), who states that its morphogenetic complexity makes it one of the most interesting valleys of the Polish Lowlands. The valley's formation began during the retreat of the last Pleistocene ice sheet during the Weichselian glaciation. In the initial stage, it was shaped by outwash waters flowing along what is now the lower Drwęca valley, probably following the line of older depressions. Then, during the Pomeranian phase of the last glaciation, the valley became an ice-marginal valley, as the meltwaters of the ice sheet and river waters drained through it. During this glacial phase, the lower section of the valley was joined by its more easterly and north-easterly section, reaching back to Lake Drwęckie and the Ostróda outwash plain (outside the study area). This was when the oldest and highest terraces (XI, X and IX) were formed. At that time, the ice-marginal valley was the eastern extension of the Toruń–Eberswalde ice-marginal valley. After glacial water outflow ceased, the valley was shaped only by river waters in the levels of the subsequent, lower terraces. The lowest Pleistocene terrace in the Drwęca valley is terrace IV, which most likely formed in the Younger Dryas. In the lower Drwęca section of the ice-marginal valley, at the level of terraces XI and X, and partly IX, bowl-like widenings were formed. Niewiarowski (1968) referred to these as the Rypin, Konstancjewo, Elgiszewo and Młyniec Basins.

Niewiarowski (1968) does not consider the genesis of these basins in detail, only stating that they are a typical feature of the ice-marginal valleys and great valleys of the Polish Lowland. He holds that the valley's considerable width, which is entirely disproportionate to the modern Drwęca, is the product of far more copious discharges (including meltwater from the ice sheet) and the presence of permafrost favouring intense lateral erosion.

Similarly, Galon (1972) states that the valley through which the lower section of the Drwęca River flows, although smaller than, for example, the Toruń–Eberswalde

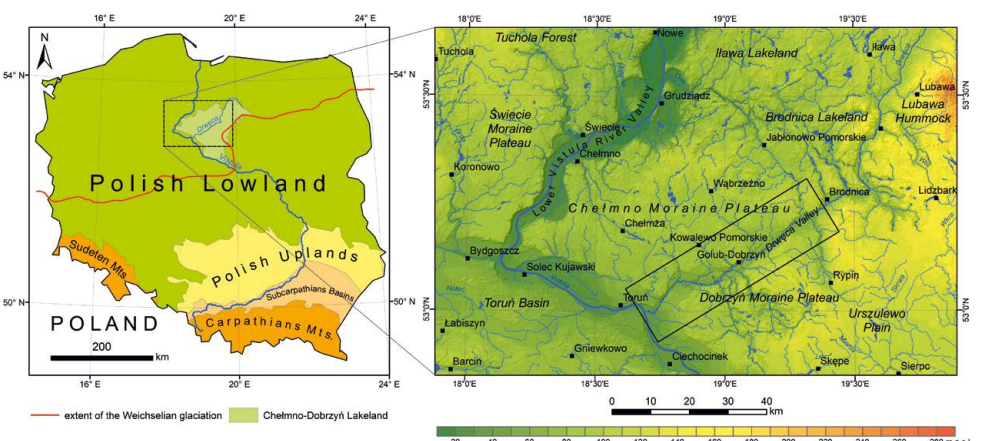


Figure 1. Location and physical map of the study area, indicating the studied section of the pradolina and lower Drwęca valley

ice-marginal valley, fully corresponds to the ice-marginal valley type; this identification is drawn primarily based on its variable outline, numerous basins and close correlation with the course of deglaciation during the Pomeranian phase of the Weichselian glaciation.

Accordingly, recognising that much of the wider valley is ice-marginal and thus not strictly "of" the lower Drwęca, I shall, for simplicity, employ the one-word Polish term for "ice-marginal valley" when referring herein to the entire complex as "the pradolina and lower Drwęca valley" or simply "the valley".

The research problem presented herein concerns the potential influence of neotectonics on the morphogenesis of the studied valley, and in particular the basins formed in its lower section. The research hypothesis is thus: The formation of the basins of the pradolina and lower Drwęca valley was induced by neotectonic activity.

This hypothesis and the related research were motivated by the observation of morphological similarities among the basins of this section of the ice-marginal valley and by terrain features of the southern part of the adjacent Chełmno Moraine Plateau:

- three of the four basins (Konstancjewo, Elgiszewo and Młyniec) are asymmetrical, i.e. developed at the right (north-western) edge of the ice-marginal valley, and are similar in shape and dimensions;
- the right-hand edges of the basins have a similar course, and their north-eastern sections have a similar, rectilinear direction;
- the orientations of these sections and of the morphological features of the southern Chełmno Moraine Plateau relate to the direction of potential faults in the deeper basement.

Study area

The Drwęca Valley lies within the Chełmno-Dobrzyń Lakeland macroregion in north-central Poland (Solon et al., 2018) (Fig. 1). The valley runs approximately north-east to south-west and extends for ~130 km, with widths varying from several hundred metres to ~8 km. To the west, it connects to the Toruń Basin, the largest basin in the lower Vistula.

The studied ~50-km-long section of the pradolina and lower Drwęca valley, oriented northeast–southwest, stretches from the mouth of the Rypienica River to the Drwęca (to the southwest of Brodnica) up to its connection with the Toruń Basin. As noted earlier, Niewiarowski (1968) distinguished four basins in this ice-marginal valley section – the Rypin, Konstancjewo, Elgiszewo and Młyniec Basins – separated by narrowings. The southern part of the Chełmno Moraine Plateau, adjacent to and northwest of the Drwęca valley, was also analysed in detail (Fig. 1).

In terms of the main tectonic units of Poland, on the sub-Cenozoic surface, the lower Drwęca valley and its surroundings lie mainly within the south-western part of the Kościerzyna-Puławy Synclinorium, whereas the Vistula mouth section in the Toruń Basin falls within the Mid-Polish Anticlinorium (Żelaźniewicz et al., 2011) (Fig. 2A). In terms of deeper tectonic units (below the Permian-Mesozoic and Cenozoic cover), the study area lies within the NW–SE-oriented Trans-European Suture Zone (TESZ) (Fig. 2B and cross-section A–B). This zone constitutes the boundary between the East European and the West European platforms. Here, a 3-5-km-thick complex of Zechstein-Mesozoic rocks overlies tectonically disturbed Palaeozoic rocks (Silurian-Carboniferous). Within this complex in the study area, several inferred and one confirmed NW–SE-trending faults have been identified (Dadlez et al., 1998) (Fig. 2C). It is assumed that these faults were reactivated in the Neogene and Quaternary (Zuchiewicz et al., 2007).

Owing to the regional scope of the analyses, these detailed study areas are shown within a broader surrounding region encompassing the pradolina and lower Drwęca valley and the Chełmno Moraine Plateau. This broader area (135×90 km) rises from 11 m a.s.l. in the lower Vistula Valley near Nowe to 281 m a.s.l. on the Lubawa Hummock (Fig. 1).

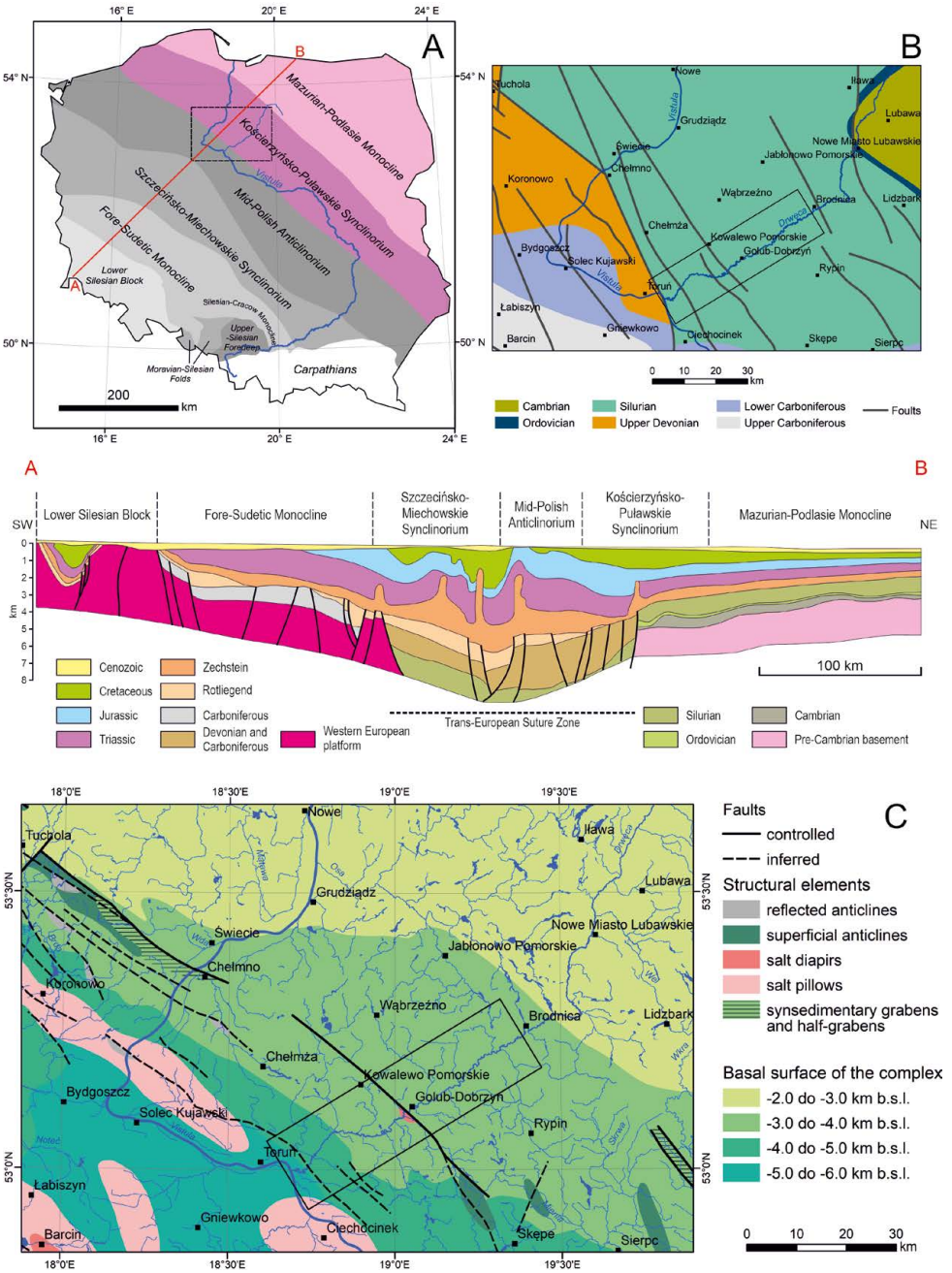


Figure 2. Tectonics of the area: A – map of the main tectonic units of Poland on the sub-Cenozoic surface and geological cross-section A–B showing the location of tectonic units that extend onto the sub-Cenozoic surface (Żelaźniewicz et al., 2011); B – fragment of the Geological Map of Poland without Cenozoic, Mesozoic and Permian formations 1:2,500,000 (Waksmundzka & Buła, 2017); C – fragment of the Zechstein-Mesozoic complex tectonic map 1:500,000 (Dadlez et al., 1998)

Data and methods

Figure 2 shows small-scale maps of the structure of the study area's older basement structure. They show its most important, generalised features, which are documented to varying degrees (Dadlez et al., 1998; Żelaźniewicz et al., 2011; Waksmundzka & Buła, 2017). In the first research stage, lineament (photo- and morpholineament) analysis was performed to refine the structural image of the older basement underlying the study area, including the pradolina and lower Drwęca valley and the southern Chełmno Moraine Plateau (Fig. 3).

The analysis of photolineaments as potential manifestations of neotectonic reactivation of deep dislocations (Ostaficzuk, 1981) was based on previously elaborated satellite photolineament maps covering the analysed area (Graniczny, 1991; Graniczny et al., 1995).

The morpholineament analysis was based on a Digital Terrain Model (DTM) using the "multi-coverage" method (Ozimkowski & Mardal, 1994; Karnkowski & Ozimkowski, 2001; Ozimkowski, 2010). "Multi-coverage" method enhances the objectivity of the visual lineament interpretation in satellite imagery and elevation models by comparing multiple independent interpretations (Ozimkowski & Mardal, 1994).

Multi-coverage morpholineament analysis was performed using a 25×25-m resolution, shaded DTM. Visual interpretation was conducted at 1:250,000 scale in ArcGIS Pro, using a constant 3× vertical exaggeration,

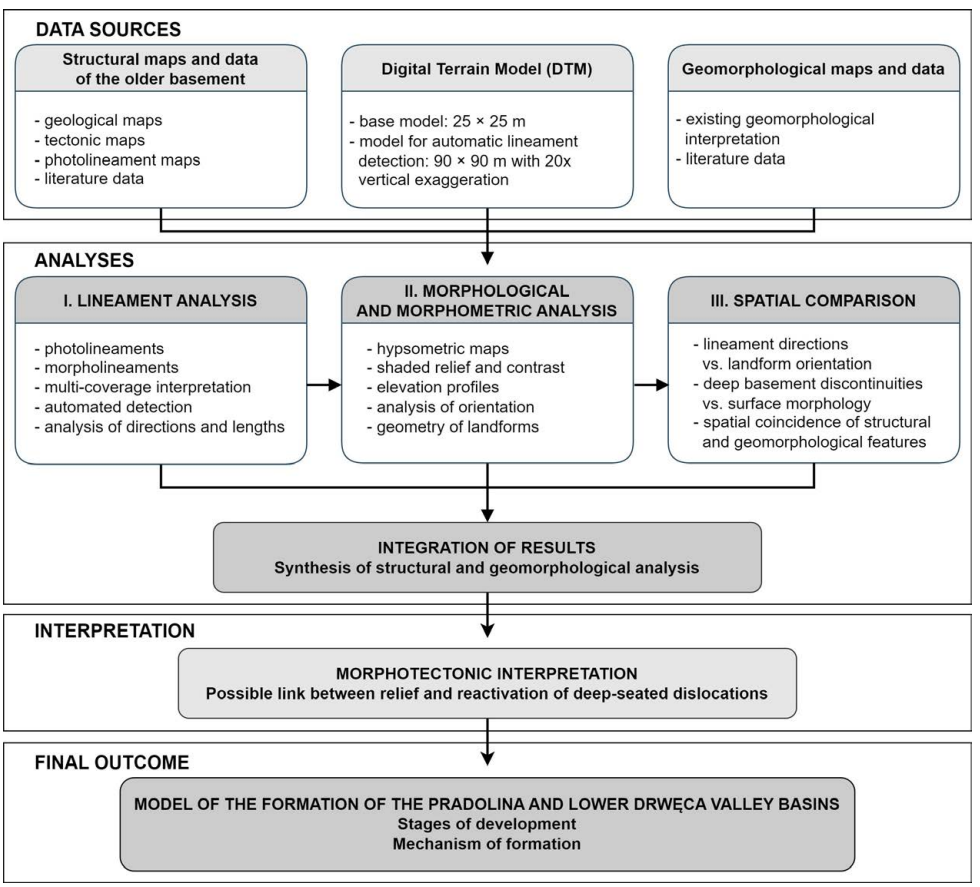


Figure 3. Research workflow

45° illumination angle, and two illumination directions of 45° and 315°. Interpretations were performed independently by 40 interpreters. For each interpreter, morpholineaments duplicated (by the two lighting directions) were removed. The morpholineaments of all interpreters were combined into a collective interpretation, and a density map of morpholineaments was then created. The zones of maximum morpholineament density mark the so-called "main lineaments" (Ozimkowski & Mardal, 1994).

Additionally, open-source automated lineament-detection tools were applied, including those from elevation models, i.e. LINDA (LINeament Detection and Analysis) (Masoud & Koike, 2017) and pyLEFA (pythonic Lineament Extraction Fracture Analysis) (Shevyrev & Boriskina, 2025). These applications for automatic lineament detection are based on various algorithms, input formats (ASCII, TIFF) and digital image-processing techniques. The features of the extracted lineaments partly depend on the subjective setting of detection parameters, and the resolution and vertical exaggeration of the elevation model. Given their primary application to mountainous regions with large relief contrasts and steep slopes (Masoud & Koike, 2017; Shevyrev & Boriskina, 2025), the DTM characteristics were adapted for the low-relief study area. Specifically, resolution was reduced to 90×90 m, and 20× vertical exaggeration was applied.

All lineament types were presented as directional rose diagrams that also take into account lineament lengths.

In the second stage of the research, morphological and morphometric analyses of the pradolina and lower Drwęca valley and the southern Chełmno Moraine Plateau were conducted based on DTM-derived hypsometric maps and profiles and existing geomorphological maps (Fig. 3). To highlight morphological features, a contrasting colours scheme was applied with a small (13.5-m) interval of changes on the elevation scale (total relief difference 270 m). Additionally, histogram equalisation was applied using Surfer software. This function stretches the colour scale non-linearly to enhance contrast in the most frequent elevation ranges. Colours thus span similar numbers of elevation values (rather than equal elevation intervals), resulting in unequal spacing. This increases the colour contrast in areas characterised by the most common elevation values, making subtle differences more visible, even with a strongly skewed distribution of elevation values. To reduce the complexity of the image in areas of less relevance to the analysis, colours were made more uniform.

In the third stage of the analysis, the DTM of the study area and its surroundings was compared against the inferred course of deep basement discontinuity and the directional features of its morphology.

In the final research stage, the results of the analyses were synthesised and subjected to morphotectonic interpretation, providing the basis for the proposed model explaining the stages and mechanism by which the basins of the pradolina and lower Drwęca valley were formed (Fig. 3). The proposed model assumes that the ice-marginal valley initially followed an approximately straight course, corresponding to the present-day morphological axis of the lower Drwęca Valley.

Results

The studied basins of the pradolina and lower Drwęca valley are generally irregular and asymmetrical, except for the Rypin Basin. The Elgiszewo and Młyniec Basins are interconnected, complicating precise determination of their basic dimensions and areas (Fig. 4). The Rypin Basin is the exception, exhibiting a roughly oval shape ~8.0 km long and ~5.0 km wide. Maximum dimensions of the basins, based on coordinates of their extreme edges, are shown in Fig. 4. In addition, minimum bounding rectangles (MBRs) – the smallest axis-aligned rectangles enclosing each basin – were used to dimension them and provide a simplified description of their shape. Dimensions from these two methods differ by up to ~1.6 km, with

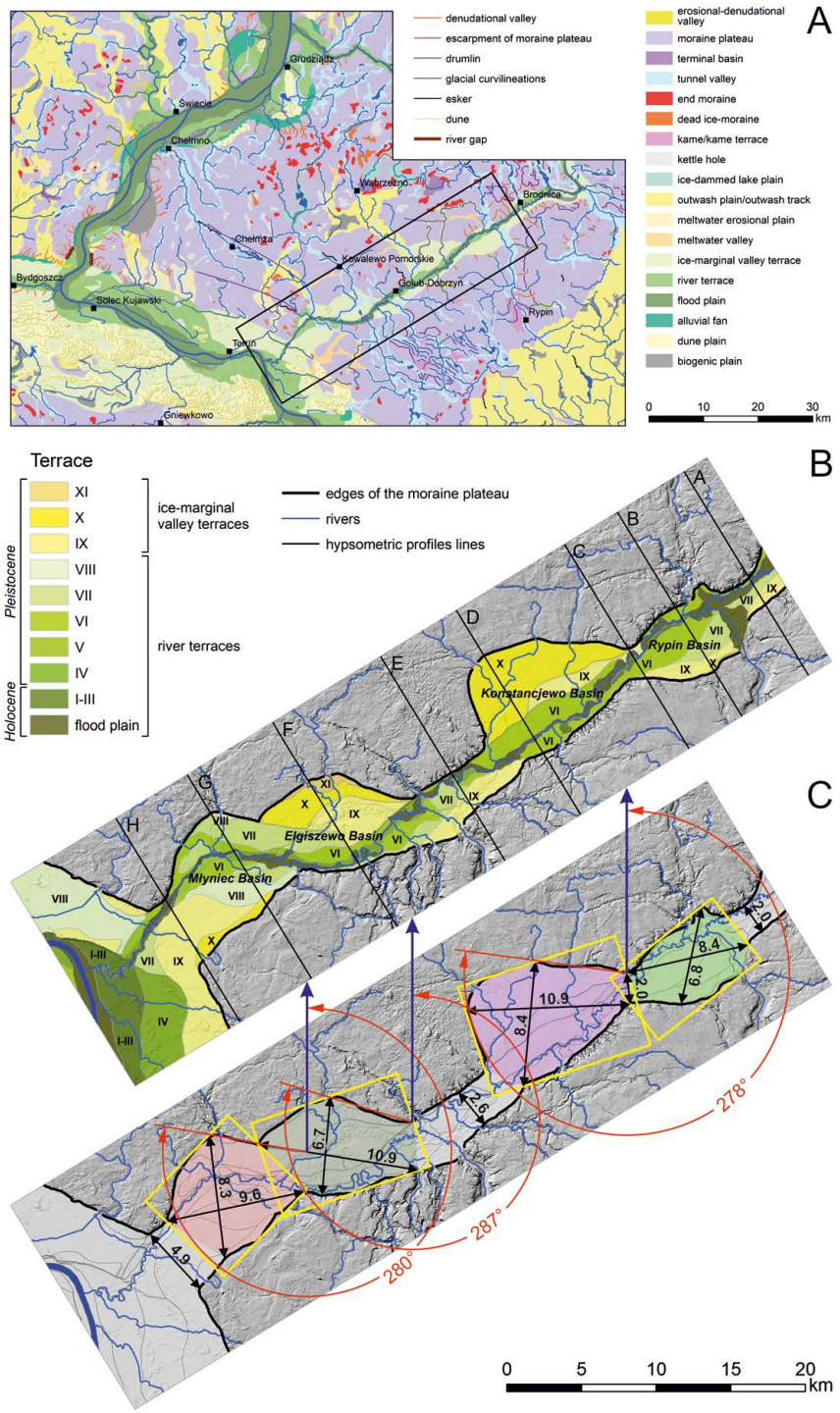


Figure 4. Geomorphology and morphometry: A – geomorphological map of the study area (based on Molewski & Weckwerth (2017), modified); B – terrace system of the pradolina and lower Drwęca valley according to Niewiarowski (1968) and a fragment of the Vistula valley according to Tomczak (1987), A to H – lines of hypsometric profiles from Fig. 5; C – selected morphometric features of the pradolina and lower Drwęca valley: azimuths of straight sections of basin edges, dimensions of basins [km] based on the extreme coordinates of their edges; yellow rectangles surrounding the basins – minimum bounding rectangles (description in text)

a maximum relative difference in average measurements of 24.8% (Tab. 1). Above the Rypin Basin, the ice-marginal valley is ~2 km wide. The narrowing between the Rypin and Konstancjewo Basins is similarly ~2 km wide. The Konstancjewo and Elgiszewo Basins are connected by an ice-marginal valley section of ~7.5 km long and minimum ~2.6 km wide. The narrowing between the combined Elgiszewo and Młyniec valleys is ~4.4 km wide. The Młyniec Basin is connected to the Toruń Basin by a short, 2.5-km-long, 4.9-km-wide section of ice-marginal valley. The basins vary in surface area and are marked in various colours on Fig. 4C (Tab. 1).

The Rypin Basin is the smallest, covering just over half the area of the largest (Konstancjewo Basin). In plan view, the Konstancjewo, Elgiszewo and Młyniec Basins are approximately similar in dimensions and shape. These basins are asymmetrical, with more pronounced development on the right flank of the ice-marginal valley. Their right-flank edges take similar lines, being rectilinear or sub-rectilinear in the initial sections (Fig. 4C). Azimuths of the directions of these sections converge (differing by ~10°), ranging from 278° to 287°. The rectilinear edges of some terraces have a similar direction, i.e. X and partly IX in the Elgiszewo Basin and VII in the Młyniec Basin. Cross-sections across the Rypin, Konstancjewo and Elgiszewo Basins are markedly asymmetrical (Fig. 5).

Alongside morphological and morphometric features of the analysed basins, other, previously unrecognised morphological features of the southern Chełmno Moraine Plateau are relevant to basin genesis (Fig. 6). The moraine plateau in this area rises to 100-110 m a.s.l. and features two stepped lower levels, which lie 10 m below (higher level) and 15 m below (lower level) the main surface, each ~6 km wide. The higher level, averaging 90 m a.s.l., is separated from the moraine plateau by a straight, ~10-m-high slope trending NW–SE (azimuth about 300°), paralleled by the Lake Chełmżyńskie tunnel valley (Niewiarowski, 1959). This slope is very poorly visible in the southeast extension of the channel, within the Chełmża outwash plain (Fig. 4A). Similar in course to this edge is the rectilinear section of the north-western edge of the Elgiszewo Basin (Fig. 6).

The lower level, averaging 85 m a.s.l., is separated from the higher level by another, approximately rectilinear slope of ~5 m high, with a very similar direction (azimuth ~295°). This edge is poorly expressed in the DTM, although in open spaces it is visible directly in the field. The course of the rectilinear section of the northwestern edge of the Młyniec Basin and the edges of terrace X and partly IX in the Elgiszewo Basin all correspond to this edge. The lower level is separated from the ice-marginal valley terrace (~70 m a.s.l.) in the Toruń Basin by a slope of up to 15 m high. In this section, the edge of the ice-marginal valley is similar in direction to the terrain step edges (azimuth ~292°). These level differences are emphasised on the DTM by a fine colour interval and the equalise function – and in the hypsometric profile by the significant

Table 1. Morphometric parameters of the basin (MBR – minimum bounding rectangles, RD_{mean} – Relative Difference with respect to the mean)

Basin	Determined based on coordinates of extremes [km]		Determined by MBR method [km]		RD_{mean} in length	RD_{mean} in width	Surface area
	length	width	length	width	[%]	[%]	[km^2]
Rypin	8.4	6.8	8.8	5.3	4.7	24.8	33.60
Konstancjewo	10.9	8.4	11.1	7.7	1.8	8.7	62.44
Elgiszewo	10.9	6.7	10.4	6.7	4.7	0.0	48.52
Młyniec	9.6	8.3	8.0	7.3	18.2	12.8	47.37

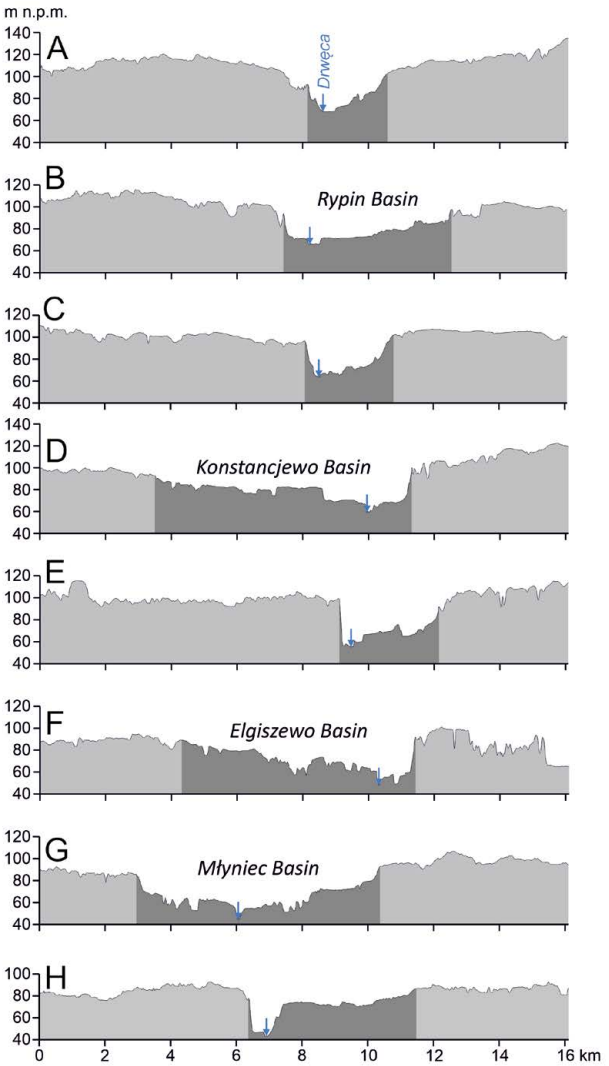


Figure 5. NW–SE-oriented transverse hypsometric profiles across the pradolina and lower Drwęca valley and its immediate surroundings (see Fig. 4B)

vertical exaggeration (of ~100x) and generalisation using the locally estimated scatterplot smoothing method (LOESS) (Fig. 6).

In the study area, the structural image of the older, tectonically disturbed basement remains obscured by the Cenozoic sediment cover (Fig. 2). As noted above, to determine the relationship between the indicated, roughly rectilinear morphological edges and the course of inferred discontinuity zones in the basement, the procedure for their identification was based on indirect premises, including the analysis of photo- and morpholineaments (Graniczny, 1989). The analysis of lineaments together with analyses of the morphological features of the ice-marginal valley and lower Drwęca valley and the adjacent Chełmno Moraine Plateau, provided the basis for the proposed interpretation of the formation and evolution of basins.

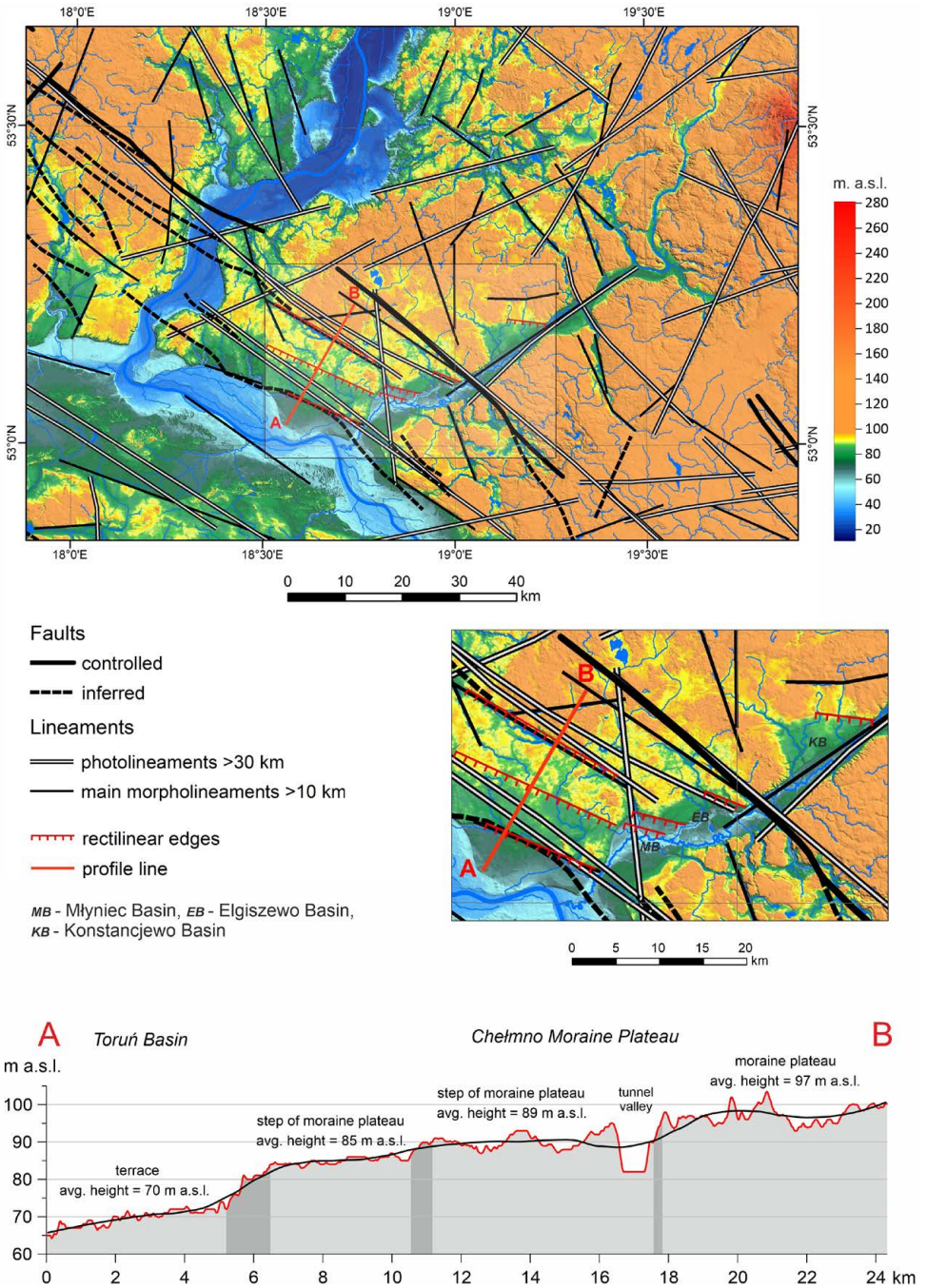


Figure 6. Rectilinear terrain edges relative to deep basement faults and main photo- and morpholineaments and hypsometric profile through terrain steps in the southern Chełmno Moraine Plateau, showing average height of the level in the profile line; black line is the profile line generalised by hypsometric locally estimated scatterplot smoothing method (LOESS)

The highest-frequency photolineaments (12% occurrence, longest > 100 km) as identified by Graniczny (1991) and Graniczny et al. (1995) are potentially most closely associated with the geological structure (Jaroszewski & Piątkowska, 1988; Piątkowska, 2003) and trend SE–NW (azimuths 305-315°) (Fig. 7). These lineaments cross the studied valley section perpendicularly and run through the southern Chełmno Moraine Plateau, where they align with the terrain edge separating the main moraine plateau surface from the higher of its two topographic levels (Fig. 6). This direction converges with the main tectonic units and disjunctions on the sub-Cenozoic surface (Fig. 2).

Multi-coverage-method DTM analysis identified three dominant morpholineament directions with (each > 8 % frequency, mostly < 30 km long). The most common morpholineament azimuths are 295-305°, 335-345° and 25° (Fig. 8A), accounting for most of the main morpholineaments (Fig. 8B). The directions of morpholineaments with azimuths in the range of 295-305° are similar to the directions of the most common and longest photolineaments (Fig. 7). They lie in, among other places, the southern part of the Chełmno Moraine Plateau, where their direction corresponds to the course of faults on the sub-Cenozoic surface (Fig. 2C). The main morpholineaments on the Chełmno Moraine Plateau have azimuths of 335-345° and correspond to the directions of faults in the top of the Silurian formations, which trend SSE–NNW (Fig. 2B).

Software-automated lineament detection yielded results that are challenging to interpret unambiguously, though they partially align with the multi-coverage method analysis results. LINDA-generated morpholineaments (Masoud & Koike, 2017) consist of multiple short segments (several to 10 km long), predominantly NE–SW trending (Fig. 9A). This direction aligns directly with, *inter alia*, the overall orientations of the pradolina and lower Drwęca valley and the Lower Vistula Valley, where many morpholineaments were generated. Some morpholineaments exhibit slight curvature, coinciding with terrain morphological edges. Despite significant differences in orientation and arrangement of LINDA-generated relative to morpholineaments determined by multi-coverage method, some of the automatically detected lineaments correspond to the courses of the main morpholineaments (Fig. 9A). Similarly, the orientation and

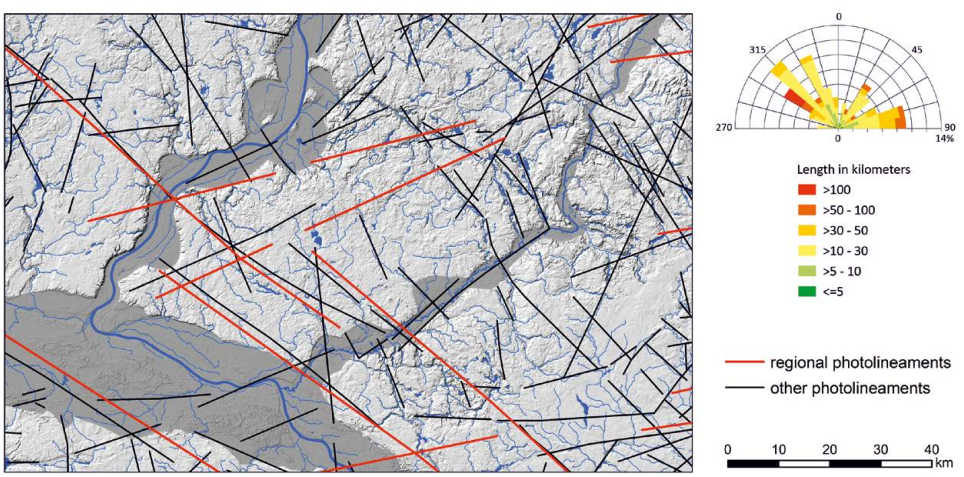


Figure 7. Photolineaments of the study area (based on Graniczny, 1991; Graniczny et al., 1995) and a rose diagram of the distribution of their directions, showing the percentage share of photolineaments of specific lengths (for photolineaments extending beyond the boundaries of the study area, lengths refer to total dimension)

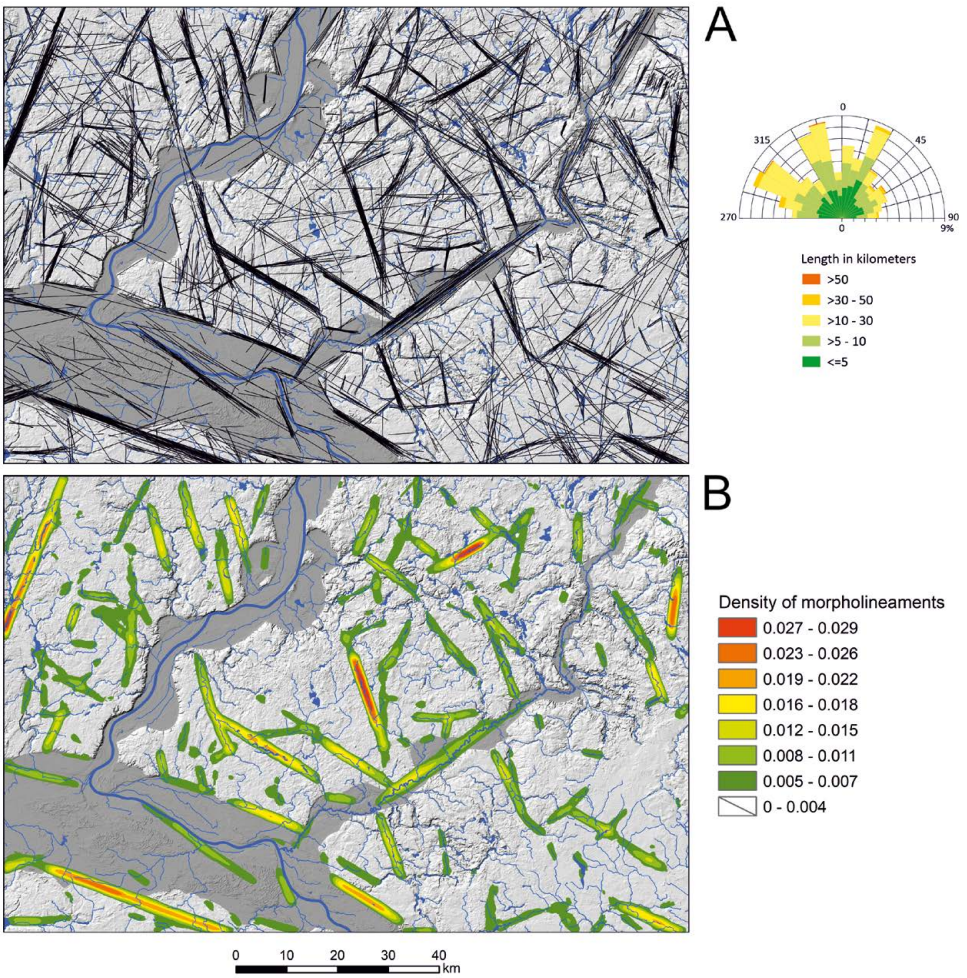


Figure 8. Visual interpretation of morpholineaments: A – map of morpholineaments of the study area made by multi-coverage method and a rose diagram of the distribution of their directions, showing the percentage share of morpholineaments with specific lengths; B – morpholineament density map, showing main morpholineaments (search radius 1 km)

arrangement of pyLEFA-generated morpholineaments (Shevyrev & Boriskina, 2025) differs radically from multi-coverage method results. This arises because pyLEFA generates so-called "second-order elements" that directly determine the main orientations of basement faults (Fig. 9B). These lines (mostly 5 to 20 km long) run only straight. Their dominant azimuths (285-305°) align with some of the most common multi-coverage-determined morpholineaments.

The analyses indicate strong convergence between dominant photo- and morpholineament directions and inferred deep tectonic faults across the southern Chełmno Moraine Plateau (Fig. 6). High lineament density implies significant tectonic activity in the deeper basement (Piątkowska, 2003). The azimuth of the individual types of lineaments crossing the southern part of the Chełmno Moraine Plateau are very similar. The azimuths of the longest photolineaments are in the range of 305-315°,

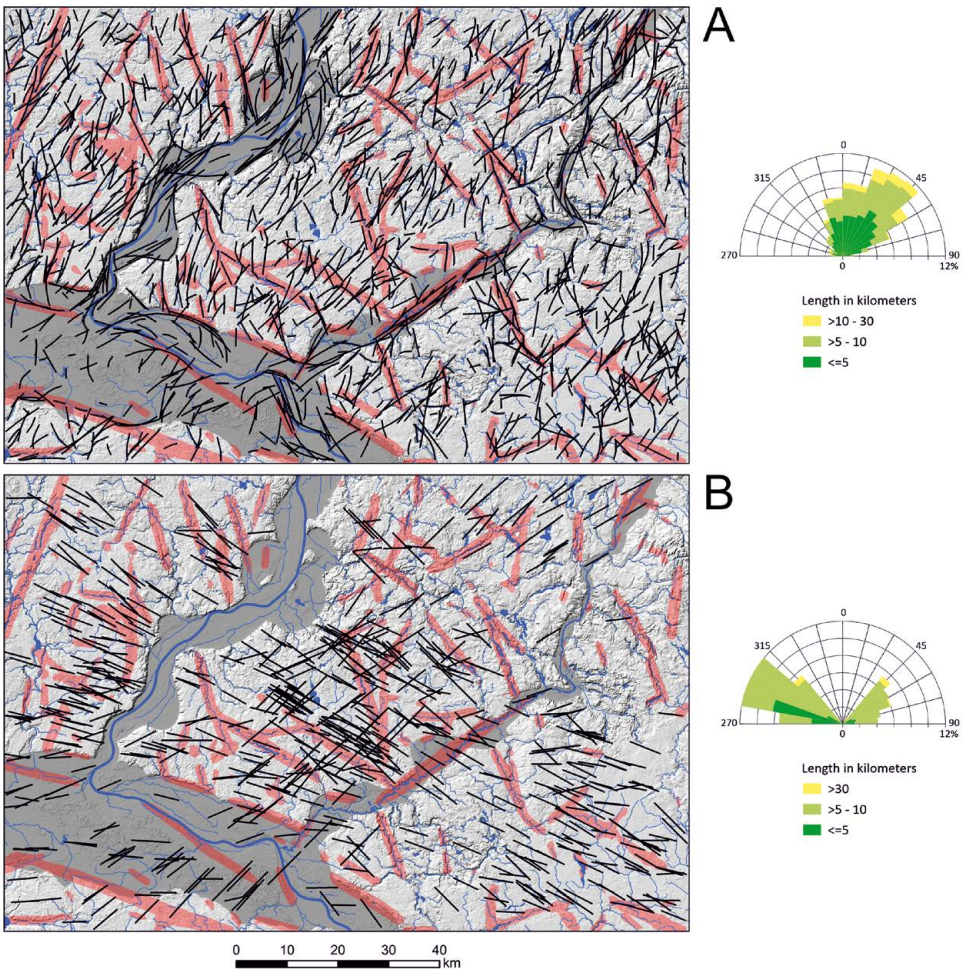


Figure 9. Automatic detection of morpholineaments: A – map of morpholineaments LINDA-generated in the (Masoud & Koike, 2017); B – map of morpholineaments pyLEFA-generated (Shevyrev & Boriskina, 2025); generated morpholineaments against background of main morpholineaments identified by multi-coverage method (see Fig. 8B)

and those of the main morpholineaments are in the range of 295-305°. The edges of the plateau terrain steps and part of the northern edge of the Toruń Basin align closely with these directions. The azimuth directions of these edges are in the range of 292-300°. In contrast, rectilinear sections of the edges of the Konstancjewo, Elgiszewo and Młyniec Basins, along with terraces in the Elgiszewo and Młyniec Basins, all trend slightly obliquely (azimuths 278-287°), i.e. ~15° less than the lineament/fault directions.

These rectilinear edges of the Elgiszewo and Młyniec Basins align with the terrain step scarps on the southern Chełmno Moraine Plateau (Fig. 6). Their formation, like that of the discussed terrain levels, was most likely initiated by fault activity in the older basement deflecting water flow in the ice-marginal valley towards the WNW (azimuths 278-287°). This ~15° discrepancy in orientation between the inferred older basement faults (photo- and morpholineament

azimuths of 295-315°) results from the original ice-marginal flow direction and the ground surface above the down-thrown fault block being lowered and (along the fault) tilted northwestwards.

This tilt redirected the main meltwater stream towards the resultant vector of the fault-block inclination vector and the valley-floor slope (Fig. 10). Once the slope caused by the deep fault had disappeared, meltwater flow reverted towards the primary ice-marginal valley depression. Progressive lateral erosion sculpted the northwestern basin edges. Similar faults activation likely influenced formation of the higher terraces in the Elgiszewo and Młyniec Basins. No equally clear spatial relationships exist between inferred basement faults and the Konstancjewo Basin. However, its morphological similarity to the Elgiszewo and Młyniec Basins implies similar neotectonic conditioning. The smallest basin (Rypin) connects directly to the Konstancjewo Basin. The assumption that neotectonic movements influenced the Konstancjewo Basin raises their potential influence on the adjacent Rypin Basin. These interpretations remain hypothetical and require further verification.

Discussion

River valleys, through their drainage patterns, orientations, and river deflections in response to tectonic structures, offer critical indicators of recent tectonic movements. This utility stems from the extreme sensitivity of streams to subtle, persistent slope changes (Chain, 1974). Nevertheless, such correspondences of landforms to tectonic structures (including the course of faults) in the Polish Lowlands are indirect, as they relate to contemporary surface forms being conditioned by very deep-seated disjunctions (Mojski, 2005).

Lateral erosion that sculpted the northwestern edges of the Konstancjewo, Elgiszewo and Młyniec Basins is here attributed to reactivation of deep basement faults. Vertical movements along these faults deflected meltwater flow through the ice-marginal valley.

River deflection – a directional change in channel or valley course – is a well-documented response to active tectonics, including in fault zones. When erosion cannot keep pace with tectonic changes, rivers deflect to follow the structural arrangement of the basement (*inter alia*, Holbrook & Schumm, 1999; Schumm et al., 2000; Burbank & Anderson, 2001). Fault–river intersections are documented globally (except Antarctica), with active faults crossing rivers at > 26,000 known sites worldwide (McEwan et al., 2023).

Numerous examples of river deflection in fault zones are documented (Woolderink, 2021, and references therein). Examples include valley deflection in the Sudetic Marginal Fault zone as an indicator of neotectonic movements (Migoń, 1994); the Lo River fault line in northern Vietnam (Cuong & Zuchiewicz, 2001); the Hunter Mountain fault zone in south-eastern California (Oswald & Wesnousky, 2002); and an active fault on the Tiber River in Rome (Marra et al., 2018). Zhang et al. (2004, 2014) documented asymmetrical valley widening due to fault-induced deflection and fault-blocks tilting on the north-eastern edge of the Tibetan Plateau.

Niewiarowski (1968) interpreted all four basins (Rypin, Konstancjewo, Elgiszewo and Młyniec) as forming at ice-marginal valley terrace levels XI, X and partly IX (Fig. 4B). The oldest terraces are, in the Elgiszewo Basin, terrace XI, and in the Rypin, Konstancjewo and Młyniec Basins, terrace X. However, in the Młyniec Basin, which, unlike the other basins lacks cross-sectional asymmetry (Fig. 4), terrace X occurs only as a narrow left-bank shelf. The right side of the basin, i.e. in its basin-like extension, hosts its oldest terrace – terrace VIII. Below this terrace is terrace VII, which begins in the Elgiszewo Basin, where it undercuts terraces X and IX. The edges of terraces X and partly IX constitute an extension of the rectilinear Młyniec Basin edge section. The direction of this edge partly corresponds to the edge of terrace VII, which is undercut by terrace VI. It cannot therefore be ruled out that the Młyniec Basin's present, asymmetrical shape was sculpted later than the

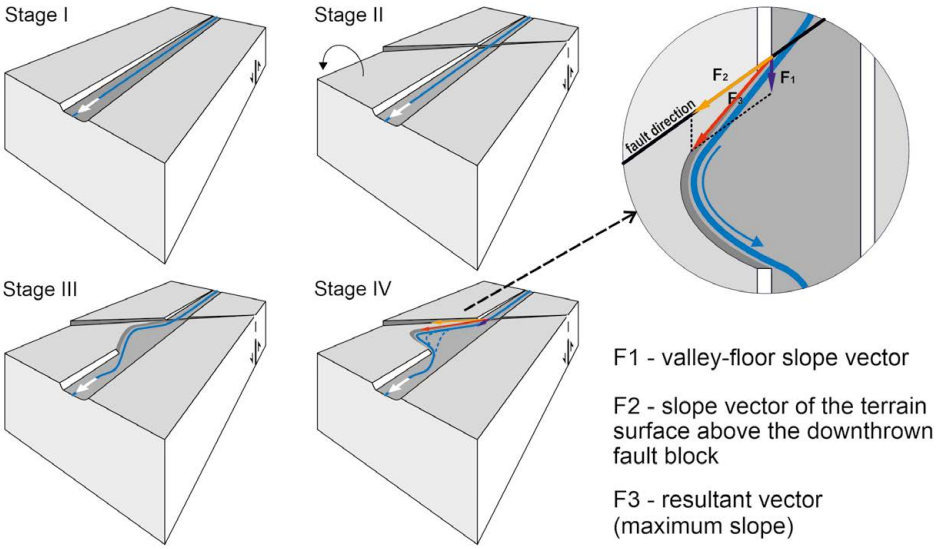


Figure 10. Sequence of models illustrating the proposed stages and mechanism of basin formation

other basins, i.e. at the level of terrace VIII, i.e. exclusively during river discharge. This interpretation, contrary to Niewiarowski (1968), implies asynchronous formation of the basins. However, terrace VIII thus provides only the oldest preserved stage for the right basin margin formation, because earlier terraces may have been eroded away.

Assumed asynchronous basins formation under inferred neotectonic conditions raises questions about the timing of basement tectonic activity.

As previously mentioned, the tunnel valley of Lake Chełmżyńskie parallels the main moraine plateau edge at a higher level. Its formation here may reflect tectonically induced crevassing in the ice sheet, implying early tectonic movements during ice sheet recession from the Chełmno Moraine Plateau. There are examples of tunnel valleys from the last glaciation and of fossil forms being linked with basement dislocations (e.g., Krüger, 1983; Dąbrowski & Mojski, 1982; Mojski & Tomczak, 1994; Molewski, 1999). However, the precise nature of these links remains unclear (Marks, 1988).

The lower moraine plateau level is separated from the higher by a slope that aligns closely with the rectilinear section of the north-western Młyniec Basin edges and with ice-marginal valley terrace edges in the Elgiszewo Basin. As previously indicated, the present shape of the Młyniec Basin may have been sculpted later than the other basins, i.e. after ice-marginal outflow ceased. Consequently, tectonic activity shaping the Młyniec Basin may post-date that which shaped the Elgiszewo and Konstancjewo Basins, i.e. occurring during the late glacial.

The inferred neotectonic origin of the terrain steps in the southern Chełmno Moraine Plateau warrants further discussion. Terrain steps (levels) within moraine plateaus are documented in the Polish Lowlands within the Weichselian glacial limit (e.g., Bartkowski, 1960; Niewiarowski & Wysota, 1986; Molewski, 1999). Explanations of their genesis vary: Bartkowski (1960) attributes moraine plateau steps in central Greater Poland through the pre-Weichselian fossil relief, reproduced in the till. Molewski (1999) ascribes a similar origin to moraine plateau steps in the northern surroundings of the Lake Gopło tunnel valley (in the eastern Wielkopolska Lakeland), considering them relict forms reproduced

in till on terraces built by proglacial meltwaters during Weichselian ice sheet advance. Niewiarowski and Wysota (1986) find no such inheritance in Brodnica Moraine Plateau levels. After considering various factors (including tectonic), they ultimately conclude they resulted from two successive Weichselian ice advances and associated glaciation/deglaciation processes.

To evaluate these competing explanations, the basement and Quaternary sediment development in the southern Chełmno Moraine Plateau were analysed in detail. Comparison against sub-Cenozoic and sub-Quaternary basement relief maps and geological cross-section analyses (Molewski & Pomianowska, 2006; Drozd & Trzepla, 2005, 2006; Molewski & Weckwerth, 2018a, 2018b) reveals no connection between the moraine plateau steps (levels) and deeper basement structures. However, imprecise dating of Quaternary sediments prohibits reliable reconstruction of the pre-Weichselian surface topography. Additionally, the sparsity of geological drillings prevents detailed recognition of the basement structure and, consequently, limits identification of potential pre-Weichselian (fossil) conditions for the formation of these levels.

I propose that the formation of these terrain steps, like the discussed basins of the pradolina and lower Drwęca valley, relates to neotectonic movements. Palaeogeographic evidence suggests these movements were glacio-isostatic, reflecting successive phases of crustal loading during glaciation in the Pleistocene and isostatic rebound during deglaciation (Liszkowski, 1975, 1993). Faults are considered to be most unstable during ice-sheet deglaciation (Gregersen & Voss, 2014), and similar movements have also been identified beyond the ice sheet's maximum extent (Štěpančíková et al., 2022).

Conclusions

The role of neotectonic movements in the development of the ice-marginal valleys and river valleys of the Polish Lowland during the Quaternary is often marginalised in favour of climatic factors and changes in the erosion base level. However, the analyses of the older basement, lineaments, morphology and morphometry conducted in this study indicate that the hypothesis of neotectonic control on the development of basins within the ice-marginal valley and lower Drwęca valley, as well as their surroundings, is supported by the observations.

The results suggest that the reactivation of deep-seated basement dislocations may have induced vertical block movements and local tilting of the land surface, thereby promoting the deflection of meltwater and river flows. The diversion of water towards the north-western margin of the valley stimulated lateral erosion, which probably contributed to the formation of the asymmetric Elgiszewo and Młyniec Basins and, presumably, also the Konstancjewo Basin.

According to the proposed scenario, the development of the basins was asynchronous, and the accompanying vertical crustal movements were glacio-isostatic in origin, occurring from the deglaciation of the Chełmno Moraine Plateau until the end of the last glaciation. The proposed model lends support to the hypothesis presented and provides an impetus for the palaeogeographical reinterpretation of adjacent areas, including the morphogenesis of the Lower Vistula Valley (west of the Drwęca Valley), with particular emphasis on its characteristic basins (see Figs 1 and 4A).

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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