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Morphological insights into tunnel valley formation and associated landforms: A case study from western Poland

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Abstract: The genesis of tunnel valleys, key subglacial drainage features, is a subject of debate, with significant implications for understanding past ice-sheet dynamics. This study examines two neighbouring tunnel valleys along the Poznań Phase margin of the Scandinavian Ice Sheet in western Poland. Geomorphological mapping and digital terrain analysis reveal contrasting morphologies shaped by subglacial hydrological processes. Observed features, including glacial curvilineations, outwash fans, eskers, and washboard moraines, highlight interactions between episodic high-energy meltwater discharges and sustained drainage. The results support a hybrid model of formation, emphasizing the complexity of tunnel valley genesis during deglaciation.

Keywords: geomorphological mapping, glacial curvilineations, Weichselian glaciation, Scandinavian Ice Sheet, Wielkopolskie Lakeland

Introduction

Western Poland has been repeatedly covered by expansive Quaternary ice sheets, with the most recent event being the advance of the Scandinavian Ice Sheet during the Last Glacial Maximum (LGM) of the Weichselian glaciation, which reached as far south as the Leszno/Brandenburg Phase (~25–21 ka BP, Marks 2012, Tylmann, Uścinowicz 2022). The focus of this study are two neighbouring tunnel valleys (Fig. 1) situated along the subsequent recessive margin of the Poznań/Frankfurt Phase (~17 ka BP; Kozarski 1995, cf. 21–19 cal ka BP – Marks 2023).

Tunnel valleys are among the most prominent subglacial landforms associated with paleo-ice sheets. They are widespread in palaeo-ice sheet beds and are characterized by linear, deep hollows with undulating longitudinal profiles. These features, typically oriented parallel to the direction of ice flow, vary greatly in scale, ranging from several to hundreds of kilometres in length, hundreds of metres to several kilometres in width, and depths from a few metres to over a hundred metres (Piotrowski 1994, Jørgensen, Sandersen 2006, Kehew et al. 2012, Breuer et al. 2023, Kirkham et al. 2024). These valleys are recognized as integral components of the subglacial hydrological system, serving as drainage pathways for significant volumes of water and sediment. However, uncertainties persist regarding the timing, mechanisms, and conditions of their formation, particularly their relationship to ice sheet dynamics and basal thermal regimes (Livingstone, Clark 2016, Lelandais et al. 2018, Bellwald et al. 2024).

Their genesis remains debated, with two primary models proposed: sudden, catastrophic outburst flood erosion and gradual, steady-state erosion driven by subglacial meltwater drainage. Catastrophic outburst flood models attribute their genesis to high-energy drainage events capable of rapidly carving valleys into subglacial substrates (Piotrowski 1994, Ó Cofaigh 1996, Kehew et al. 2012, Livingstone, Clark 2016, Breuer et al. 2023, Kirkham et al. 2024). In contrast, steady-state models propose a more gradual formation of tunnel valleys through sustained meltwater flow over hundreds to thousands of years, influenced by seasonal surface melting and basal ice melt (van der Vegt et al. 2012, Kirkham et al. 2024). This mechanism aligns with the presence of regularly spaced valleys and their association with ice-margin retreat, reflecting the self-organization of subglacial hydrological systems (Livingstone, Clark, 2016). Recent seismic studies indicate that these processes can coexist, with steady-state mechanisms forming valley networks that are periodically modified by ep-

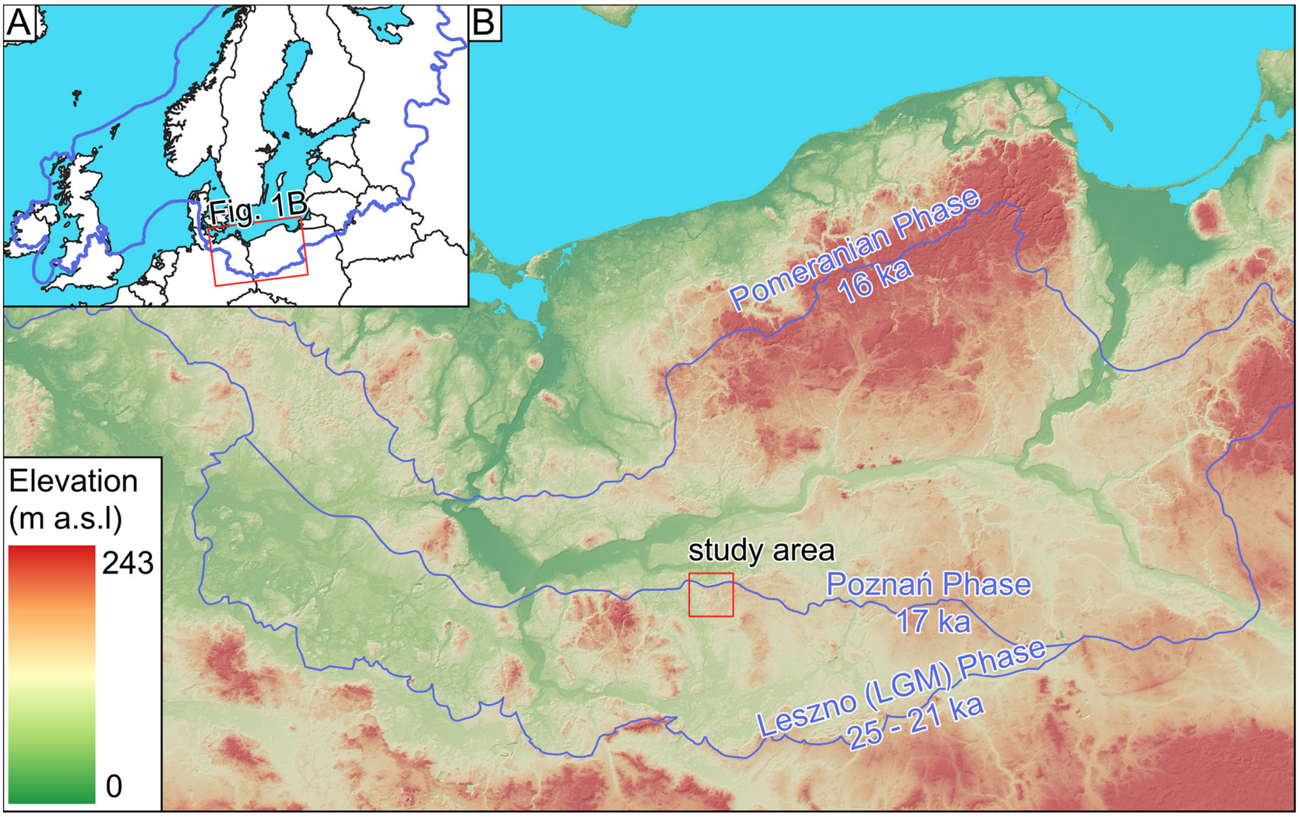

Fig. 1. Study area, A. LGM of the Scandinavian Ice Sheet in Europe. B. Main marginal standstills: Leszno/Brandenburg phase (LGM for western Poland), Poznań/Frankfurt (LGM for eastern Poland), and Pomeranian (Kozarski 1995, Marks 2012, cf. Tylmann, Uścinowicz 2022, cf Marks 2023)

isodic high-energy events (Kirkham et al. 2024). The identification of associated features like glacial curvilineations (GCL) and eskers further highlights the dynamics of subglacial hydrology. GCL swarms, typically aligned parallel to valley walls and concentrated in specific zones, indicate episodes of high-pressure, turbulent meltwater flow (Lesemann et al. 2010, Adamczyk et al. 2022, Hermanowski, Piotrowski 2023, Weckwerth et al. 2024). Their distribution near valley widenings and ice margins underscores the episodic nature of drainage events.

Regional studies, particularly in northern Europe, emphasize the geomorphological and sedimentological records of tunnel valley systems as critical for understanding ice-sheet dynamics. The reworking of pre-existing sediments within subglacial troughs demonstrates the interplay between successive glaciations and meltwater processes (Bartkowski 1959, 1967, Romanek 2009). Moreover, terminal moraines and outwash deposits associated with tunnel valleys highlight the linkage between subglacial drainage pathways and ice-marginal stabilization during retreat phases (Klimko 1973, Kasprzak, Kozarski 1989, Kozarski 1995). These observations have significantly refined reconstructions of ice-sheet behaviour and subglacial hydrology during the Late Pleistocene.

The southern sector of the Scandinavian Ice Sheet, particularly in western Poland, presents a dynamic landscape shaped by episodic meltwater drainage and progressive ice retreat. Tunnel valleys in this region were often incised during phases of Late Pleistocene deglaciation, forming in association with subglacial meltwater routing under high hydraulic pressures (Kehew et al. 2012, Szuman et al. 2021). These valleys exhibit evidence of both gradual erosion and catastrophic floods, processes intricately linked to ice margin dynamics and the evolution of subglacial drainage systems (Kirkham et al. 2024, Weckwerth et al. 2024). Subglacial meltwater flow, often confined to high-pressure conduits, carved valleys with undulating longitudinal profiles, reflecting hydraulic gradients controlled by ice surface topography rather than bedrock relief (Kehew et al. 2012). Their formation was influenced by interactions between subglacial meltwater storage, periodic drainage events, and the reorganization of subglacial hydraulic networks as the ice sheet thinned and retreated.

This study focuses on two neighbouring tunnel valleys along the Poznań Phase margin (ca 70 km west of Poznań), where their morphological characteristics suggest divergent formation pathways that resulted in distinct topographies. Subglacial drainage reorganization, driven by changes in basal water pressure and ice sheet geometry, may have played a pivotal role in this divergence (Kehew et al. 2012, Dewald et al. 2022). This study seeks to address the question: what are the causes of the significant morphological diversity observed in these two tunnel valleys and their associated landforms? By examining the contrasting morphologies and associated landforms, this research aims to contribute to the ongoing debate on tunnel valley genesis and the processes responsible for their development.

Study Area

The study area is located in the Wielkopolskie Lakeland (315.5; Solon et al. 2018), more specifically in mesoregions Nowotomyska Plain (315.50) and Poznań Lakeland (315.51). It is near the southern margin of the Scandinavian Ice Sheet during the Poznań Phase – MIS2 (Marine Isotope Stage 2) (Fig. 1), which took place approximately 17 ka BP (21–19 cal ka BP – Marks 2023). It encompasses two tunnel valleys (Fig. 2) separated by only ~7 km – referred to as the eastern and western valleys – whose distinct morphologies provide a basis for examining the processes behind their formation. These valleys are deeply incised into the moraine plateau (95–105 m a.s.l.), situated between the Toruń-Eberswalde Marginal Spillway to the north and the Warsaw-Berlin Marginal Spillway to the south. The incisions locally reach deposits from older (Sanian 2 – MIS12) glaciations.

To the west of the study area lies the Pszczew Ice Stream zone, identified by Szuman et al. (2021) as part of the B2.2.a flow unit, characterized by streamlined bedforms indicative of rapid ice flow from the northwest (Fig. 1b). In contrast, the study area itself is part of an inter-stream zone, associated with slower ice movement (Szuman et al. 2021). This inter-stream position likely contributed to the variability in subglacial conditions and the resultant landform assemblages.

Geologically, the western tunnel valley is part of the Zbąszyń Trough (Romanek 2009), which features deep subglacial troughs formed during successive glaciations. These valleys predominantly follow a meridional orientation and dissect the clay-rich deposits of the Sanian 2 glaciation (Romanek 2009). The eastern tunnel valley is associated with the marginal zone of the Poznań Phase of the Weichselian glaciation (Kasprzak, Kozarski 1989). It forms part of a broader network of subglacial channels that drained meltwater under the ice sheet during its retreat (Romanek 2009). Importantly, beneath the Weichselian sediments, evidence of older tunnel valleys associated with the two advances during Sanian 1 and Sanian 2 glaciations – MIS16 and MIS12, respectively (Romanek 2009) has been identified. These deeply incised features cut into the substratum and were later filled with redeposited material from earlier glaciations, including Paleogene and Neogene sediments (Bartkowski 1956, 1967).

Both tunnel valleys display steep-walled, flat-bottomed depressions – the western tunnel valley reaches depths of 20–30 meters and retains isolated terminal moraine accumulations along its margins. Its floor is partially filled with glaciofluvial sands and gravels (Romanek 2009, Złonkiewicz 2012), and areas of peat bogs occupy the lowest points. Similarly, the eastern tunnel valley features eskers and kames along its edges, indicative of crevasse-fill deposits formed during the late stages of deglaciation (Bartkowski 1967).

Terminal moraine chains, up to 30 m high and 1.5 km long, mark the stationary phases of the ice sheet during the Poznań phase (Kozarski 1965). Outwash fans, including a remarkably well-preserved fan near the eastern tunnel valley outlet, exhibit coarse sediments deposited by proglacial meltwater streams under high discharge conditions. In some locations, the deep older tunnel valleys, initially formed during the Sanian 2 glaciations – MIS12, were reused and modified by later meltwater flows, demonstrating the multi-phase evolution of subglacial hydrology in this region (Romanek 2009, Złonkiewicz 2012).

The surface geology is dominated by glaciofluvial sands and gravels, with localized deposits of till from the Weichselian glaciation. The latter is notably thin (2–10 m; Złonkiewicz 2012), suggesting strong erosional processes and a prevalence of meltwater activity. Weichselian till covers thick (20–30 m) series of glacial deposits from earlier (Sanian 1 and Sanian 2) glaciations (Romanek 2009, Złonkiewicz 2012). Aeolian activity during the late Pleistocene and early Holocene has further modified the region, forming small dunes and windblown sand fields, especially on sandur terraces (Kozarski, 1995).

The tunnel valleys served as key drainage pathways during the retreat of the ice sheet (Romanek 2009, Złonkiewicz 2012). Meltwater initially flowed southward and southwestward, exiting the study area into the Zbąszyń Trough and the Czarna Woda valley, before eventually redirecting northward into the Obra River valley as deglaciation progressed. This dynamic drainage evolution highlights the complex interaction of ice dynamics, sedimentation, and meltwater processes in shaping the landscape (Bartkowski 1967, Romanek 2009).

Although the tunnel valleys do not lie directly behind the primary margin of the Poznań Phase as defined by Marks (2012), the area exhibits a complex geomorphological record. This includes evidence of multiple smaller-scale ice sheet margins, whose extents and relationships to the Poznań Phase can be inferred from the arrangement of landforms and

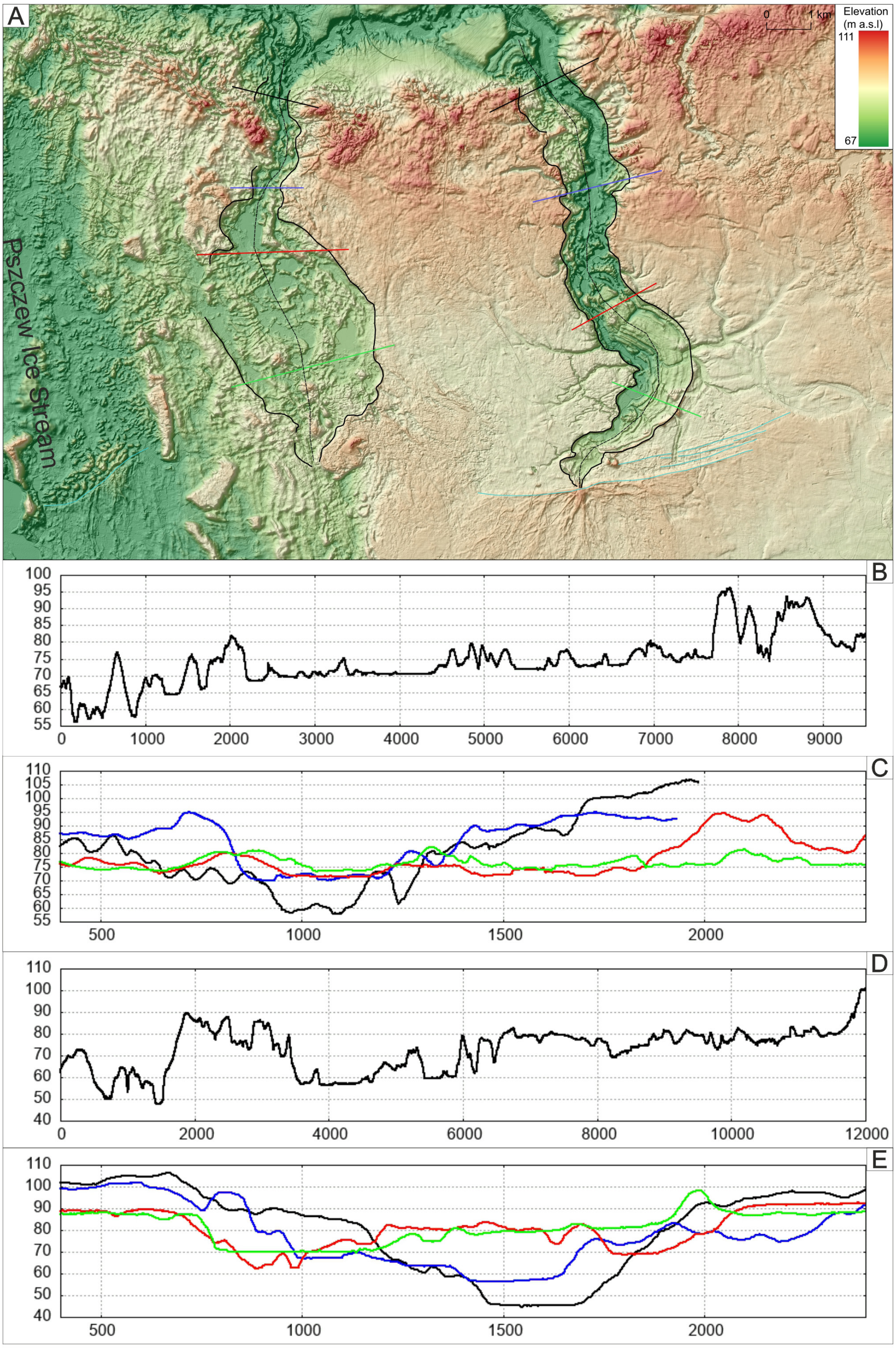

Fig. 2. Tunnel valleys, A. Tunnel valleys under investigation: western and eastern. Longitudinal profile lines (black dashed lines) and cross-profile lines (solid lines N to S, respectively: black, blue, red and green). Teal solid lines show the southern – most ice margin (as for the depicted area). Note the lower-lying Pszczew Ice Stream to the west (B2.2.a – Szuman et al. 2021). B. Longitudinal profile of the western tunnel valley. C. Cross – profiles of the western tunnel valley (colours as in Fig. 2A). D. Longitudinal profile of the eastern tunnel valley. E. Cross – profiles of the eastern tunnel valley (colours as in Fig. 2A)

features depicted in Figure 3. The juxtaposition of tunnel valleys, outwash fans, and marginal features within a relatively small region allows for a detailed analysis of ice-marginal dynamics and subglacial hydrology. Furthermore, the spatial variability in valley morphology highlights the interplay between subglacial drainage patterns and local ice sheet behaviour, offering valuable insights into paleoglacial reconstructions.

Source of data for landform interpretation

To investigate the formation and morphology of tunnel valleys in western Poland, a combination of geomorphological mapping and digital terrain analysis was employed. The methodology integrates high-resolution datasets and geospatial tools to characterize landforms associated with dynamic glacial processes.

A high-resolution Digital Elevation Model (DEM) with a spatial resolution of 1 m, generated from LiDAR point cloud data provided by the Central Geodesy and Cartography Documentation Centre (GUGiK 2017, 2019), served as the primary data source. Hillshade models were created for multiple illumination directions to enhance the interpretation of subtle topographic features. These hillshade models were generated and processed in Quantum GIS (QGIS), allowing for improved terrain visualization and detailed landform interpretation. The DEM was further analyzed by superimposing it with the hillshade models to support comprehensive topographic analysis. The DEM analysis was complemented with data from the Detailed Geological Map of Poland at a scale of 1:50,000.

Landforms were mapped manually in QGIS, with a focus on features indicative of subglacial dynamics. Key morphological parameters, including landform length, width, height, elevation above sea level, maximum incision depth, were measured and analyzed. Longitudinal and cross-profiles of the identified landforms were generated using QGIS to derive basic morphometric data. This quantitative characterization provided detailed insights into the formation and evolution of the tunnel valleys and associated landforms.

As an initial study, this research focuses solely on the morphometric characteristics of landforms, acknowledging the limitations of the adopted methodological approach. Future work incorporating sedimentological analyses is essential to provide a more comprehensive understanding of the genesis of these features, particularly the timing and environmental conditions associated with their formation.

Results

The study area reveals a diverse range of morphological features within the two tunnel valleys. Landforms such as GCL swarms, valley widenings, scours, and erosional marks (Fig. 3) were examined. These observations provide a morphological basis for interpreting the processes that shaped the valleys and their contrasting topographies (Figs 2, 3), offering insights into the mechanisms driving tunnel valley genesis.

Tunnel valleys

Both valleys are steep-walled depressions with undulating floors (Fig. 2B, C, D, E). The eastern tunnel valley reaches a relative depth of approximately 30 m and a width of 1300–1500 m, featuring notable widenings (Figs 2D, E, 3B) likely associated with increased meltwater discharge. In contrast, the western valley is shallower (Figs 2B, C, 3A), with a depth of up to 25 m and narrower widths (up to 1500 m), except in its distal part, where widenings reach up to 3600 m. In this section, crenulated margins (landform 6 in Fig. 3) indicate turbulent flow conditions during its formation.

Terraces along the valley walls suggest at least two phases of development (Fig. 2C, E), with localized incisions providing evidence of evolving subglacial conditions. The hairpin scour in the eastern valley offers additional evidence of high-energy subglacial flow. At its mouth, the extensive outwash fan of the eastern tunnel valley, with a surface ~20 meters above the valley floor, highlights significant high-energy meltwater discharge.

Associated landforms include GCL swarms, erosional marks, scours, outwash fans, eskers, and washboard moraines.

GCL (glacial curvilineation) swarms

Within the eastern tunnel valley, four GCL swarms have been identified (landform 1 in Figure 3), while only one swarm is present in the western tunnel valley. The GCL swarms in the study area are curved, quasi-linear ridge features aligned parallel to the tunnel valley sides and (partly) concentrated in zones of valley widening. In the eastern tunnel valley, the swarms consist of 3 to 6 ridges, with elevations ranging from 71–74 m a.s.l. (northernmost swarm) to 79–83 m a.s.l. (southernmost swarm). The swarm in the western tunnel valley comprises 4 ridges, reaching elevations of 71–77 m a.s.l.

The GCL swarms occur at varying elevation levels: 67 m a.s.l. (northernmost swarm), 72 m a.s.l., and 75–79 m a.s.l. (southernmost swarm) in the eastern valley, and 69 m a.s.l. in the western valley (Fig. 2C, E). These features suggest formation during episodes of elevated meltwater pressure. During such events, turbulent flow likely eroded grooves between ridges, leading to the observed GCL patterns.

Hairpin erosional mark

A prominent hairpin erosional mark (or hairpin scour) is visible in the distal portion of the eastern tunnel valley (landform 2 in Figure 3). This asymmetrical U-shaped feature is situated upstream of an obstacle (erosional remnant) and exhibits a pronounced groove extending along the valley's thalweg, with depth of incision reaching 13 m in the proximal part. The longer groove, located on the south-western side, measures 2360 m, whereas the shorter groove on the north-eastern side measures 1660 m. This asymmetry suggests prolonged activity at the tunnel valley base during its subglacial phase. The alignment of the modern Kamionka River with the longer hairpin erosional mark groove indicates subsequent fluvial reworking, subtly modifying its original morphology over time.

Scours

In the western part of the western tunnel valley, a series of scoured depressions is visible (landform 3 in Fig. 3). These scours, oriented perpendicular to the inferred ice flow direction, consist of narrow (~30 m wide), elongated (~600 m long) depressions, spaced 150–210 m apart and with a relative depth of 12–15 m. Their formation is associated here with westward-directed meltwater flow, suggesting they were created by high-energy discharge at the ice sheet margin. This configuration likely reflects an initial release of meltwater flowing westward, which subsequently redirected southward, as indicated by the orientation of later erosional features.

Outwash fans

Both tunnel valleys terminate with outwash fans or their remnants. At the mouth of the eastern tunnel valley lies a remarkably well-preserved outwash fan (4750 m long and 7500 m wide, with elevation difference N–S from 102 to 82 m a.s.l.), characterized by its nearly perfect fan shape, numerous distributary channels across its surface, (each several hundred meters long, several dozen meters wide, and with a relative height of 5 meters), and a sharp elevation change (~10 m at the mouth of the tunnel valley, lowering towards the east and west) marking the former ice margin (Fig. 3). Towards the east the morphological threshold is visible over a stretch of 4000 m, whereas towards the west the threshold becomes less pronounced and after 2500 m transitions towards the NW into a marginal zone ~400 m wide. To the north of the fan, a series of lower, subparallel ramparts are present, likely representing periodic positions of the retreating ice margin during deglaciation (Fig. 3).

In contrast, the western tunnel valley ends with erosional remnants of an outwash fan (landform 5 in Fig. 3). These remnants are located at a similar elevation (88–90 m a.s.l. on average, reaching up to 105 m a.s.l. in the probable centre of the reconstructed fan) to the eastern fan. The erosional remnants form 10 isolated terrain fragments with a relative height of approximately 13–26 meters, some of which are elongated in a N-S and NE-SW direction. Before the erosion, the outwash fan may have been 4900 meters long and 7750 meters wide. The differences in preservation between the eastern fan and the western remnants may indicate the extent of subsequent erosional modification by meltwater.

Eskers

The tunnel valleys are also associated with eskers, including narrow eskers visible along the eastern edges of both valleys (Fig. 3). The esker at the eastern margin of the western tunnel valley is 1650 m long, 80 m wide, and has a relative height of 15 m. In contrast, the esker on the eastern margin of the eastern tunnel valley is 2950 m long, 100–270 m wide, and protrudes approximately 10 m above the edges of the tunnel valley incision. Another esker is visible within the western tunnel valley, which is wider (up to 315 m) and longer (3850 m) than the eskers along the valley edges. It is interpreted as an englacial esker, distinguished by a broader crest that transitions into multiple splaying ridges near the ice margin. The morphology of these ridges – wide (~600 m) and relatively low (up to 10 m) – suggests deposition in ice-walled canyons, potentially under atmospheric pressure (Storrar et al., 2020).

Washboard moraines

Washboard moraines, identified at the forefield of the western tunnel valley (landform number 4 in Fig. 3), are quasi-regularly spaced, low ridges oriented perpendicular to the inferred ice flow direction and slightly curved down-ice. These ridges have relative heights of approximately 2–8 m, widths of 60–85 m, and spacing of 120–300 m.

Discussion

The formation of tunnel valleys and associated landforms in the study area provides critical insights into the dynamics of subglacial processes during the retreat of the Scandinavian Ice Sheet. The morphological evidence presented in this study highlights variations in subglacial hydrology, ice-sheet dynamics, and depositional environments, all of which are key to understanding paleoglacial landscapes.

Reconstruction of the sequence of events

Ice margin stabilized at position X (Fig. 3), which is the southernmost ice margin extent visible at this location.

The eastern and western tunnel valleys were initiated under subglacial conditions, with meltwater exploiting zones of weaker substrate and eroding into the soft sediments. During these early stages, the western tunnel valley was narrower and less complex than its current form. As subglacial meltwater flowed under high pressure, approaching ice overburden levels, the western valley underwent significant modification, leading to the development of steep, crenulated valley margins and localized widenings. These features reflect erosion driven by hydraulic gradients controlled by the ice surface, rather than the underlying bed topography (Kehew et al. 2012). Extensive outwash fans were deposited at the

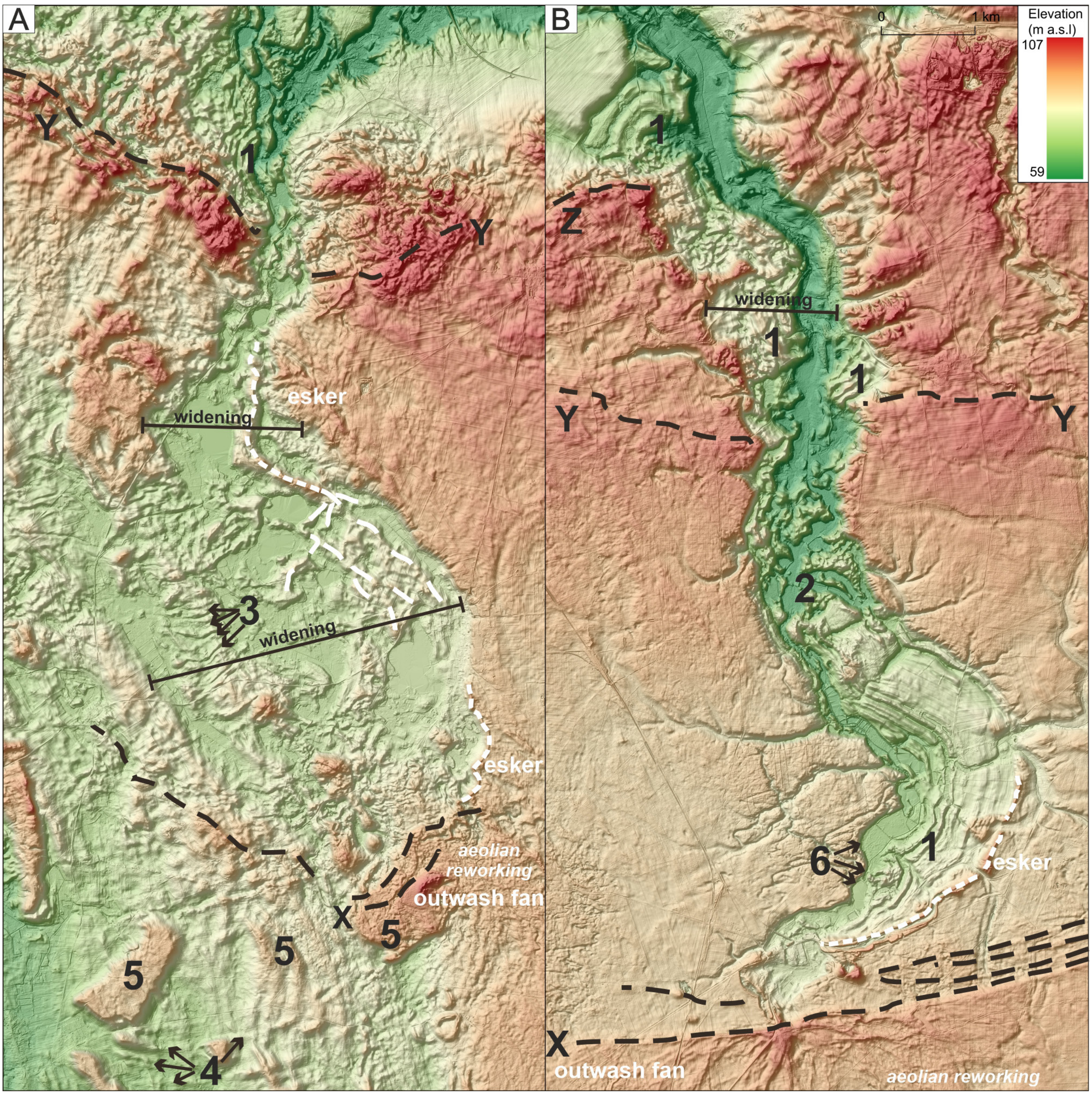

Fig. 3. Landforms identified in the study area. A – western tunnel valley, B – eastern tunnel valley; 1 – glacial curvilineations (GCL), 2 – hairpin erosional mark, 3 – scours, 4 – washboard moraine, 5 – outwash fan erosional remnants, 6 – crenulated margin; X, Y, Z – ice margin stillstands, ordered from earliest to latest

valley mouths. In the eastern tunnel valley, highly turbulent flows eroded the 3 distal GCL swarms and created a prominent hairpin scour. In the western tunnel valley, the GCL swarm was eroded, and the distal part of the valley was significantly widened, reflecting intense subglacial drainage events (Weckwerth et al. 2024). The mouth of the western tunnel valley was further widened during this stage to accommodate the release of subglacial meltwater. This flow spread across the outwash fan, leading to significant erosion and the formation of erosional remnants.

Ice thickness began to decline following intense subglacial drainage and recession was initiated. Simultaneously, narrow eskers began to form along the margins of the tunnel valleys, marking subglacial meltwater pathways and reflecting a transition from erosion-dominated phases to sediment deposition as meltwater flow diminished (Kehew et al. 2012, Kirkham et al. 2024), although it is also possible that the eskers had formed earlier.

With further retreat, an esker system developed within the western tunnel valley. The sediment forming the esker accumulated within pre-existing subglacial meltwater channels, gradually clogging these conduits and influencing subsequent flow pathways. Initially, the esker was single-crested and wide (compared to the other eskers described here), which may reflect deposition under steady meltwater flow in an ice-walled channel (Storrar et al., 2020). Toward the south (Fig. 3), the esker transitions into a multi-crested form resembling an esker system, with several ridges diverging near the ice margin. This morphological change likely reflects variations in meltwater flow as the ice sheet retreated, with meltwater pathways becoming less confined and more distributed in proximity to the margin (Russell et al. 2001). The development of the multi-crested section aligns with interpretations from Storrar et al. (2020), who describe esker systems forming under dynamic subglacial conditions during ice retreat. In this case, the observed transition from a single- to multi-crested esker highlights the evolving relationship between channel geometry, meltwater discharge, and sediment deposition, as (sub)glacial hydrology adjusted to the retreating ice margin.

Ice margin at positions Y and Z

The receding ice margin briefly stabilized at position Y before continuing its retreat. As the margin reached position Z (Fig. 3), additional GCL swarm (northernmost swarm in the eastern tunnel valley) was formed and subsequently eroded within the valley widenings just up-ice of the ice margin. Rising subglacial meltwater pressure and turbulent flow drove their formation. The erosion of these features highlights the dynamic adjustments of the subglacial hydrological system to variations in meltwater discharge and ice-margin position.

Portions of the valleys became occupied by stagnant ice, which eventually thawed, leaving behind debris deposits that further complicated the valley floor's morphology. Aeolian reworking reshaped fine-grained sediment deposits along outwash surfaces and between the tunnel valleys.

The sequence of events highlights the interplay between gradual processes, such as steady-state meltwater input, and episodic turbulent flow events that punctuated valley formation.

Glacial curvilineations

The morphologies of GCLs found in the study area suggest strong association with elevated subglacial meltwater pressure and turbulent flow conditions (Lesemann et al. 2010, 2014, Wysota et al. 2020, Adamczyk et al. 2022, Hermanowski, Piotrowski 2023, Weckwerth et al. 2024). Their presence at varying elevation levels, proximal to the ice margin and within tunnel valley widenings, indicates multiple phases of formation tied to fluctuating hydrological regimes during ice retreat.

Two competing hypotheses address the formation of GCLs. The first links their genesis to erosional remnants of longitudinal vortices formed during catastrophic outburst floods (Lesemann et al. 2010, 2014, Adamczyk et al. 2022, Hermanowski, Piotrowski 2023, Weckwerth et al. 2024). However, the abrupt curvature and alignment of GCLs with tunnel valley edges challenge this interpretation, as such abrupt changes in direction would likely disrupt vortex formation (Livingstone, Clark, 2016). The alternative hypothesis suggests GCLs result from retrogressive rotational slope failures triggered by tunnel valley incision (Clark, Livingstone 2018, Kirkham et al. 2024).

Our results provide insight into the GCLs formation but do not conclusively confirm either hypothesis. In this study, the distribution and morphological characteristics of GCLs, such as their presence within valley widenings and alignment parallel to valley sides, are interpreted as indicative of formation under turbulent flow conditions. Hairpin scours, typically formed by horseshoe vortices generated around obstacles during high-energy flow events (Shaw 1994), lend additional support to the hypothesis of longitudinal vortices and turbulent subglacial hydrology as key mechanisms in GCL genesis. These findings, while not definitive, suggest a stronger link to subglacial hydrological processes than to gravitational slope failures. Further structural and sedimentological analyses are necessary to fully resolve the mechanisms behind GCL genesis.

Associated ice-marginal landforms

The association between tunnel valleys and ice-marginal landforms, such as outwash fans and washboard moraines, provides insights into the dynamics of subglacial meltwater flow during ice retreat. In the eastern tunnel valley, a well-preserved outwash fan reflects significant glacial steady-state discharge event, including meltwater and sediment-laden flows. Its sharp elevation gradient (ice-lobe contact sedimentary scarp, according to Kasprzak, Kozarski 1989) and distributary channel network suggest deposition during high-energy flow conditions, that are further underscored by sedimentological evidence: Kasprzak, Kozarski (1989) report great variations in fluvioglacial deposits in the proximal part of the outwash fan, where the sub-surface outwash series contains very coarse deposit (>30 cm in diameter). In contrast, in the western tunnel valley, multiple furrows extending from the former ice margin towards the south, along with erosional remnants of an outwash fan (described as kames by Bartkowski, 1967), indicate episodic flooding accompanied by significant episodes of erosion, and a transition into a multi-channelized flow regime. The differences in preservation between the eastern fan and the western remnants may indicate the extent of subsequent erosional modification by meltwater. The western tunnel valley appears to be located in an interlobate position, suggesting that higher volumes of meltwater were present during its formation. The outwash fan at the mouth of the eastern tunnel valley likely began deposition slightly earlier, as evidenced by remnants of the outwash fan associated with the western tunnel valley overlapping it. However, the temporal difference in deposition between the two fans may not be substantial, as these processes could have occurred rapidly and with some degree of overlap.

As Weckwerth et al. (2024) suggest, the widening of subglacial flood routes and the exploitation of weaker substrate zones by meltwater flows mark a transition from sheet-like drainage patterns to progressively more channelized pathways. This evolution is influenced by spatial variations in topography, such as the interlobate setting, and sedimentary conditions. The multichannelized flow observed at the mouth of the western tunnel valley exemplifies these adjustments, demonstrating the interplay between meltwater pressure, substrate properties, and the shifting position of the ice margin. The partial erosion of the associated outwash fan further highlights the variability of meltwater flow conditions and the ability of the glacial hydrological system to adapt to changing discharge regimes during deglaciation.

The quasi-regularly spaced transverse ridges in the forefield of the western tunnel valley align with descriptions of washboard moraine (Livingstone, Clark 2016). Their association with the outwash fan supports an origin tied to ice-margin stabilization during the gradual retreat. Alternatively, their curvature toward the tunnel valley might suggest a subglacial origin (crevasse-squeeze) related to differential ice velocities or stress near the valley (Cline et al. 2015, Ankerstjerne et al. 2015). Based on the morphological characteristics and surficial geology (sand and gravel – interpreted as sandur deposits by Złonkiewicz 2012) the authors hypothesise the proglacial (marginal) origin rather than subglacial (crevasse-squeeze). However, without sedimentological data, it is purely speculative.

Mechanisms of tunnel valley formation

The formation of tunnel valleys remains a topic of debate, with hypotheses emphasizing episodic high-energy outburst floods versus steady-state processes involving sustained seasonal meltwater inputs (Ó Cofaigh 1996, Kehew et al. 2012, van der Vegt et al. 2012, Livingstone, Clark 2016, Kirkham et al. 2024).

The morphological evidence strongly indicates that episodic high-energy drainage events played a significant role in valley formation. Features such as GCL swarms, valley widenings, and the prominent outwash fan at the mouth of the eastern tunnel valley reflect phases of intensified subglacial flow.

A hybrid model of tunnel valley formation emerges, wherein steady-state processes establish initial pathways, and episodic events, such as supraglacial lake drainages or meltwater surges, punctuate and reshape these pathways. This interpretation aligns with Livingstone and Clark's (2016) observation that tunnel valleys exhibit incremental growth during ice retreat, driven by both gradual and episodic processes.

Future studies incorporating sedimentological and geochronological data are essential to refine our understanding of tunnel valley genesis, particularly regarding the timing and interplay of formative processes.

Conclusion

The contrasting morphologies of two neighbouring tunnel valleys in western Poland were investigated to address the processes responsible for their formation. The findings highlight the complexity of subglacial hydrology during the retreat of the Scandinavian Ice Sheet, supporting a hybrid model of tunnel valley genesis. In this model, steady-state processes established initial pathways, while episodic high-energy events, modified and reshaped these features.

The observed morphological diversity between the two valleys, reflected in landforms associations, including GCL swarms, eskers, and ice-marginal features, reveal dynamic interactions between meltwater flow, substrate properties, and ice-margin dynamics. These findings underscore the complexity of tunnel valley formation and highlight the role of sustained subglacial hydrology punctuated by episodic turbulent flow events.

Beyond addressing tunnel valley morphology, this study expands the array of recognized subglacial landforms in the region, including the mapping of GCL swarms, hairpin erosional mark, esker system, and washboard moraines. These findings contribute to the broader understanding of subglacial drainage mechanisms and their dynamic evolution under varying conditions.

While this paper focuses on morphological analysis, a more comprehensive understanding of the tunnel valleys' formation, together with the associated landforms, requires additional data on their sedimentary infill. Future research should prioritize sedimentological and geochronological analyses to validate the proposed sequence of events. Such integrative studies will provide critical insights into the timing, processes, and environmental conditions associated with tunnel valley evolution, ultimately advancing models of their formation and improving reconstructions of ice-sheet dynamics.

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