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GEOMORPHOLOGY OF THE SOWIE MOUNTAINS (SUDETES, SW POLAND) – LANDFORM PATTERNS AND ANTHROPOGENIC IMPACT

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Abstract

The Sowie Mountains in the central part of the Sudetes range are an under-researched area in terms of geomorphology, despite their potential representativeness for a large number of terrains within the Bohemian Massif, built of metamorphic bedrock. Apart from providing an overview of past work, the paper summarizes the main topographic features of the massif using visualizations of the digital terrain model, and outlines the wide range of anthropogenic impacts on relief. Characteristic landforms of the Sowie Mountains include fault-generated lithology-controlled escarpments, ridge-and-valley topography near the escarpments, water-divide flats, gneissic tors, agrarian terraces and various landforms related to former mining and military use.

Key words

mountain fronts • planation surfaces • drainage network • crags • glaciation • anthropic landforms • digital terrain models • geomorphometry • Sudetes

Introduction

The Sudetes are a topographically complex mountain range in Central Europe, which owe their present-day appearance to the long-term interactions between rock-controlled denudation, spanning the entire Cenozoic, and more recent, Neogene to Quaternary differential uplift (Migoń, 2011; Placek, 2011; Szymanowski et al., 2019). Consequent to that is the subdivision of the Sudetes into a few tens of distinctive geomorphic/physiographic sub-regions, different from one another in terms of altitudinal relationships, geology, major landforms, vegetation patterns, and land use (Solon et al., 2018; Richling et al., 2021). The Sowie Mountains (*Owl Mountains*) are one such sub-region, located in the central part of the Sudetes, next to their fault-generated north-eastern border (Fig. 1). With the highest peak exceeding 1000 m a.s.l. (Mt. Wielka Sowa, 1015 m), they rise prominently in relation to both the foreland of the Sudetes, beyond the faulted margin, and less elevated hills and basins to the south-west. However, despite this distinctive physiographic setting the Sowie Mountains have been rather neglected as an object of geomorphic research, at least in comparison with some other mountain massifs within the Sudetes, such as the Karkonosze Mountains, the Stołowe Mountains tableland, or Hrubý Jeseník. Most of research carried out to date was focused on geomorphic evidence of faulting along the north-eastern border of the massif (see below), whereas other topics were addressed in only a handful of papers. Moreover, the majority of these studies predates the moment when high-resolution digital terrain data became available.

This paper intends to partially fill the gap and aims to offer an overview of geomorphology of the Sowie Mountains, based on both critical review of the rather limited range of publications available and new data about the relief and its transformation due to various forms of human impact. This approach is reflected in the structure of the paper, which systematically presents various aspects of geomorphology of the massif rather than solves one narrowly defined research problem. After outlining the state-of-the-art, we will show geomorphometric characteristics of the massif, discuss the pattern and origin of major landforms, address the legacy of the Pleistocene and contemporary geomorphic processes, and review a multitude of human–landform interactions reflected in the geomorphic record, many of which are documented here for the first time. It is worth noting in this context that the Sowie Mountains are one but many sub-regions of the Sudetes and the entire Bohemian Massif, whose geological structure is made mostly of medium-grade metamorphic rocks (such as gneiss dominating in the study area). Therefore, this study can become both a starting point for further detailed research in the Sowie Mountains as well as a useful reference source for any geomorphological work carried out in those other areas.

Sources and methods

This study synthesizes information obtained from four main sources. First, it uses the existing literature considering it as the background information, but subject to critical appraisal given the length of time since the publication of some of these papers and the emergence of new topographic databases. Second, old (pre-1945) topographic maps at 1:25,000 scale and other historical sources proved useful to assess the magnitude of landscape change due to human impact. Third, the high-resolution LiDAR-based digital terrain model (DTM) was used to both identify and map specific landform assemblages, as well as to perform morphometric study at the whole massif-scale. Fourth, field work was carried out in selected localities and involved geomorphological analysis and mapping, subsequently compared against the picture revealed by the LiDAR DTM.

The LiDAR-based DTM of 1 m × 1 m spatial resolution, with a mean elevation error up to 0.15 m (Kurczyński et al., 2015), is accessible from the Polish Centre of Geodetic and Cartographic Documentation (www.geoportal.gov.pl; access date 8 March 2022). Shaded relief generated from DTM of original resolution was used for assessment of spatial distribution of anthropogenic landforms. Basic geomorphometric characteristics of the study area were calculated with use of resampled DTM – lower resolution of 10 m × 10 m was used in order to eliminate possible influence of minor anthropogenic disturbances in cartographic presentation of regional scale. The set of indices included local relief (relief energy) (within 1 km radius), slope and valley depth. Geomorphometric analysis was conducted with use of ArcGIS 10.8 software, except valley depth which was calculated in SAGA-GIS 8.1.1.

Geological background

The Sowie Mountains, understood as a geographical unit, are part of the Sowie Mountains Block (SMB) that occupies c. 600 km^2

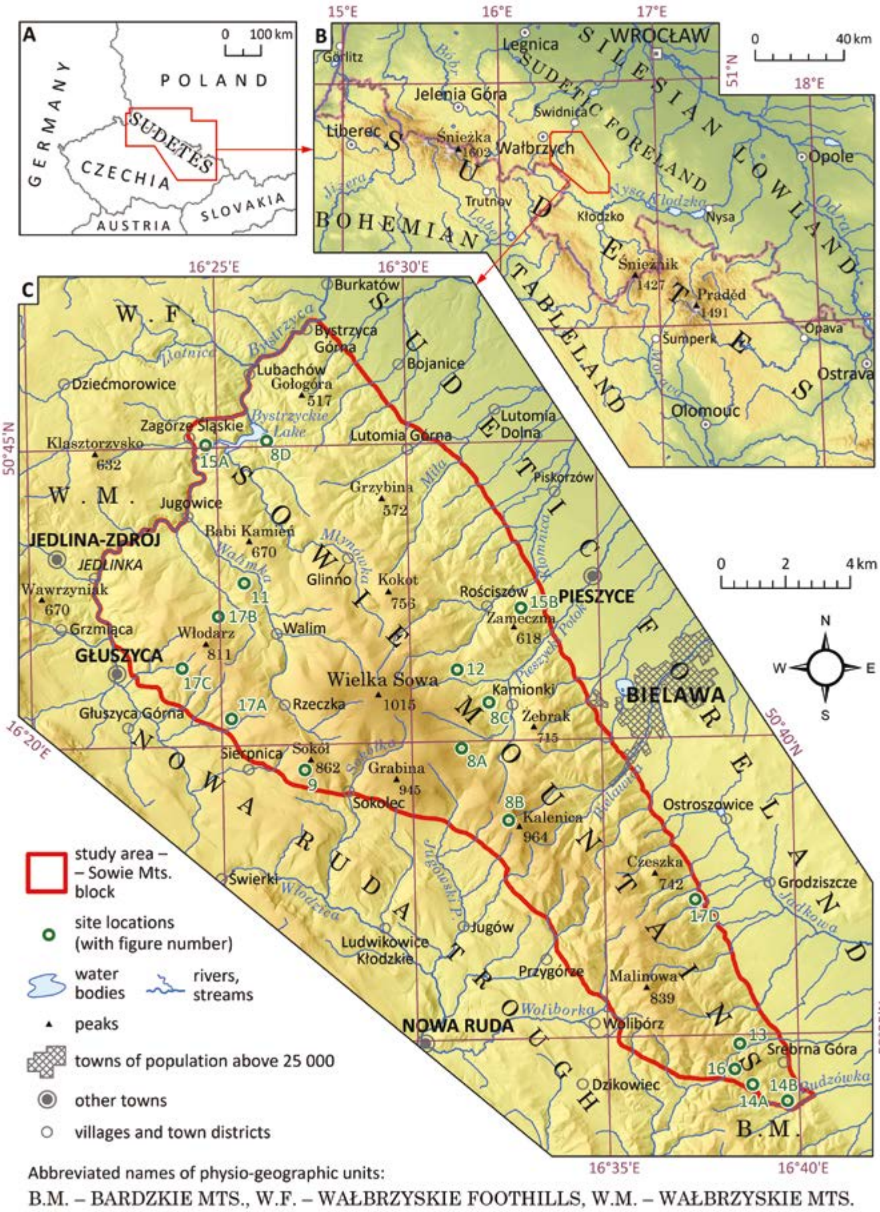

Figure 1. Study area

and is almost homogeneous in terms of geology (Fig. 2). Only the western part of the SMB coincides with the present-day Sowie Mountains, whereas the other half occurs in the Sudetic Foreland, in downfaulted position (see below). The SMB is mainly built of Early Palaeozoic gneiss, with subordinate occurrences of amphibolites, granulites, quartzites and serpentinites (Grocholski, 1967; Żelaźniewicz, 1990). Locally, minor intrusions of rhyolites and kersantites, as well as veins of aplites and pegmatites occur, testifying to the impact of Variscan and post-Variscan magmatism (Grocholski, 1962). Within the gneissic complex various structural variants occur, but their distribution does not show any clear relationship to the contemporary morphology of the massif. The only more extensive, younger lithological unit in the SMB are Lower Carboniferous clastic deposits, predominantly conglomerates (Łapot, 1986). They are present in the central and northern part of the area as a series of disconnected patches of various size and inconsistent relationship to topography, even though their boundaries are delimited by faults. Thus, to the east of Mt. Wielka Sowa conglomerates occur within a triangular intramontane depression (Kamionki Basin), whereas to the east of the Młynówka river they occupy a water divide position (Fig. 2).

Morphological boundaries of the Sowie Mountains are clearly fault-controlled. However, they are fundamentally different as far as the relationship to regional geology is concerned (Różycka et al., 2021). The SE boundary coincides with the eastern extension of the Intra-Sudetic Fault, which is an old Variscan structure and a regionally important dividing line between different terranes that amalgamated during the Variscan orogeny (Aleksandrowski & Mazur, 2002). As such,

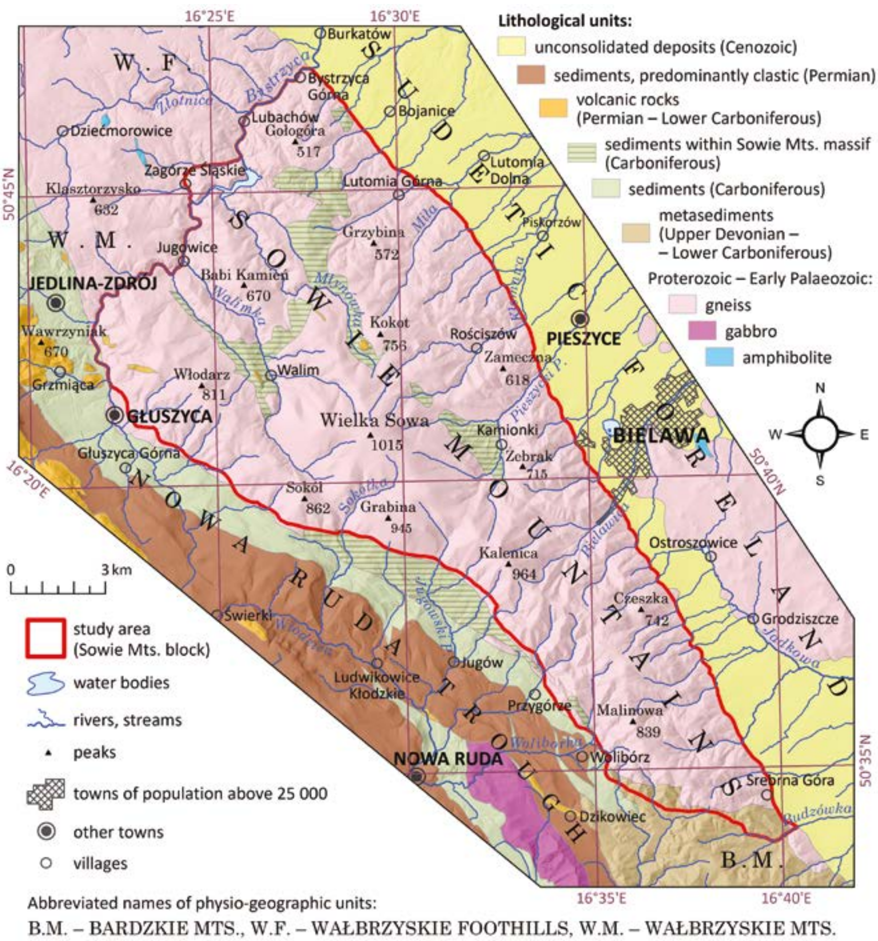

Figure 2. Geology of the Sowie Mountains and adjacent areas (based on data in Grocholski, 1967 and Żelaźniewicz, 1990)

the fault line also coincides with an important lithological boundary, separating gneisses from various sedimentary formations of the adjacent Intra-Sudetic Synclinorium, and the mountain front itself seems to be primarily lithologically-controlled (Różycka et al., 2021). By contrast, the NW boundary is part of the mountain front of the entire Sudetes, which developed along the Sudetic Marginal Fault (SMF). The SMF cuts the gneissic block into two halves, so that the escarpment does not have any lithological background and is a purely morphotectonic feature (Krzyszkowski et al., 1995; Badura et al., 2003, 2007; Różycka et al., 2021).

Past research – an overview

Geomorphology of the Sowie Mountains was relatively seldom addressed in academic publications, resulting in very incomplete knowledge and limited appraisal of major geomorphic features of the massif. Apparently the first systematic geomorphological study was presented by Arnold (1938) who sought to identify the evidence of periglacial mass wasting, mainly in hillslope and piedmont deposits. Dumanowski (1961) focused on hillslope and valley floor geomorphology of the north-eastern escarpment and included various observations on Quaternary deposits from the foreland zone. Following the once dominant conceptual model of cyclic pediplanation, he also attempted to identify relicts of planation surfaces and used them to build tentative denudation chronology. However, poor quality of cartographic materials available at that time did not allow one to carry out rigorous analysis, whereas the suggested age bracketing of surfaces was purely speculative, so that the proposed chronology is only of historical interest. An unusual addition to the general geomorphology of the Sowie Mountains was offered by Klimaszewski (1995), who converted his old field notes and sketches from the late 1940s into a paper published more than 40 years later. Although very outdated in terms of presentation and lacking any reference to later research, it includes some valid observations. Among them is the general morphological subdivision of the Sowie Mountains into a proper mountainous section in the southern and central part, with a relatively narrow axial ridge and deeply incised valleys, and a dissected upland in the north, with more extensive undulating surfaces in water-divide positions and elevations up to 750 m a.s.l. (Fig. 1). This subdivision was ascribed to non-uniform uplift in the Cenozoic. More recently, Aramowicz et al. (2006) used thermochronology to constrain long-term uplift and erosion, suggesting rapid cooling in the last 5-7 Ma and hence, substantial denudation of the order of two kilometres within this time-interval. However, serious doubts were expressed regarding the correctness of this conclusion and various procedural flaws were suspected (see Migoń & Danišík, 2012), leaving the room for further research.

A distinctive line of research developed in the 1990s, focused on the neotectonic activity of the Sudetic Marginal Fault as reflected by various morphological indicators (Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Krzyszkowski et al., 1995; Krzyszkowski & Biernat, 1998; Krzyszkowski & Olejnik, 1998). Among them were knickpoints in longitudinal stream profiles, valley cross-sectional shapes, fluvial terrace architecture, especially terrace truncation at the fault line, and stream deflections. Morphometric analysis was carried out, but it was based on manual handling of rather poor-quality topographic maps. Mid-slope and ridge-top "flats" were mapped and connected across the valleys, to support the concept of non-uniform uplift along a series of faults parallel to the SMF (Krzyszkowski & Olejnik, 1998). Again, this approach suffered from insufficient quality of background cartographic materials. Nevertheless, a consensus emerged that the SMF in the Sowie Mountain sector is a moderately active structure, especially in the southern part, and the amount of uplift in the latest Middle and Late Pleistocene was estimated for 10-25 m. The advent of digital terrain models allowed for a new look at the problem of SMF activity and various morphometric indices were computed, lending support to the hypothesis that the SMF is a continuously active structure (Badura et al., 2003, 2007). However, these studies were based on manual digitalization of contours from 1:10,000 topographic maps and hence, the findings were recently subject to re-appraisal using high-resolution LiDAR elevation data (Różycka et al., 2021). LiDAR data were also used to calculate identical indices for the SW front of the Sowie Mountains, never investigated before (Różycka et al., 2021), and have become input data for geostatistical analysis of relief variability within the frontal zone (Szymanowski et al., 2021).

Other themes were rarely explored. Krzyszkowski & Biernat (1998) focused on the Bystrzyca river valley beyond the mountain front and identified various stages of its evolution related to neotectonic uplift and glaciation. Descriptive characteristics of selected gneissic and conglomerate crags (tors) were provided by Migoń (2004) and Migoń & Latocha (2005). Kowalski (2018) identified two lithologically-controlled landslides on Mt. Ostrzew, developed at the contact between magmatic and weak sedimentary rocks. Not much is known about contemporary geomorphic processes, with only two site-specific studies of soil displacements available (Jońca, 1966; Laskowski, 1993). Likewise, despite long history of human occupation and diversity of human impact, detailed geomorphological works addressed only limited areas and topics, such as agrarian terraces (Latocha & Urbanowicz, 2010). However, the historical and popular science publications, especially on mining legacy and military constructions, are abundant (see below).

Geomorphometric characteristics and major landforms

The subdivision of the Sowie Mountains into two main parts advocated by Klimaszewski (1995) on the basis of hypsometry and qualitative relief analysis is broadly confirmed by the results of morphometric analysis (Fig. 3 to 5). It is most evident on the local relief map (Fig. 3), which clearly differentiates the southern and northern part, with the dividing line connecting the towns of Walim and Bielawa. However, closer inspection of these maps suggests that the morphological structure of the massif is more complex. The southern part can be further resolved into the central part, with the highest elevations of Mt. Wielka Sowa and Mt. Kalenica, and the south-eastern part, beyond the line connecting Bielawa and the village of Przygórze. In the former, local relief commonly exceeds 400 m, but a patch of relatively low value (< 200 m) is evident between Mt. Wielka Sowa and Mt. Grabina. The highest values typify the steep slopes facing to the north-east, between Mt. Wielka Sowa and Mt. Kalenica. In the SE part the values are lower, around 300 m, consistent with lower altitudes (< 850 m a.s.l.) of this part of the massif. By contrast, local relief in the northern part only locally exceeds 300 m and the 150-250 m range is typical. In contrast to the more southerly areas, the mountain front zone is not associated with local relief values higher than those in the hinterland.

The distinctiveness of the south-eastern part also emerges from the slope map (Fig. 4) and is mainly revealed by the paucity of low-angle surfaces (< 10°), but the percentage of steep slopes (> 25°) is also the highest within the massif. The most elevated part around Mt. Wielka Sowa does not coincide with particularly steep slopes, but hosts a fairly extensive area of near-planar relief (< 10°), including nearly level terrain. A few streams originate within this high-elevation surface, continuing within much deeper valleys further downstream (Fig. 5). The northern part, in turn, is dominated by moderately steep slopes, with wide tracts of gently sloping terrain in both interfluve positions and along some streams. The steepness of terrain and the depth of fluvial incision (Fig. 5) rise towards the trunk valley of Bystrzyca river, with the former being particularly high in the gorge-like reach of the Bystrzyca river downstream of the village of Zagórze.

The Sokół – Włodarz ridge in the western part of the massif has individual characteristics. In terms of altitude (around 800 m a.s.l.)

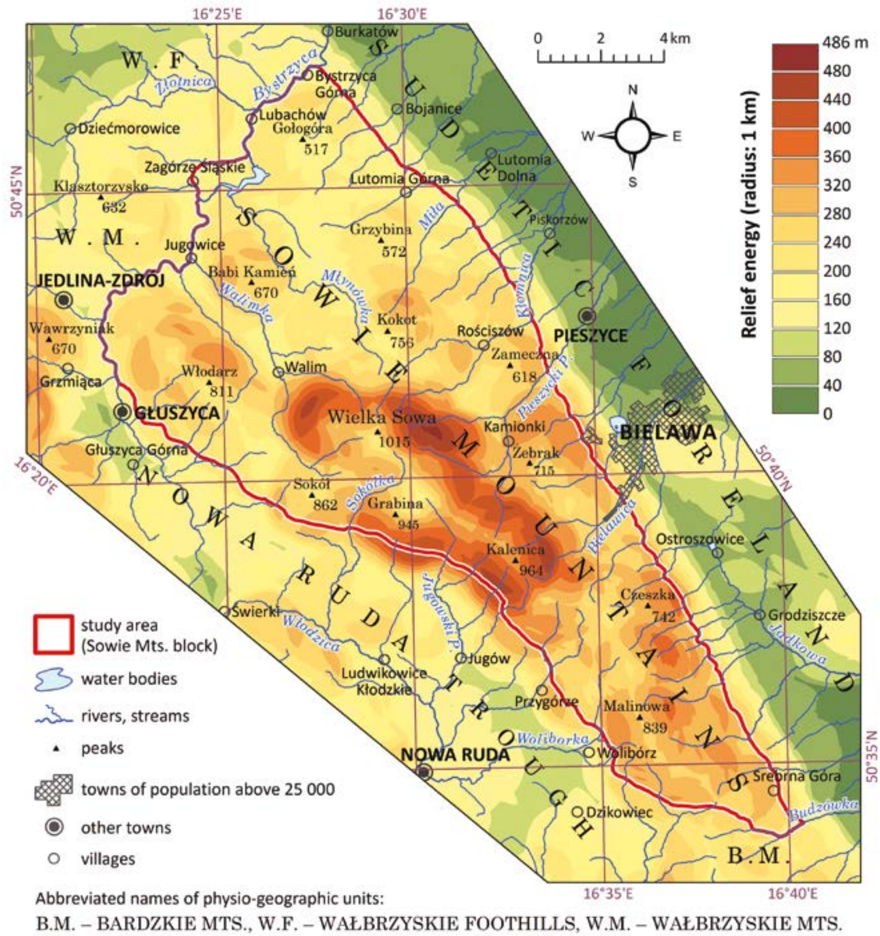

Figure 3. Local relief (relief energy) map of the Sowie Mountains and adjacent areas

it is close to the south-eastern part, but local relief is lower (Fig. 3) and slopes are clearly not so steep (Fig. 4). Ridge-top flats occupy sizeable areas and fluvial dissection is moderate. However, it is difficult to consider it as part of the northern dissected upland, as altitudes are higher and incision is less advanced (Fig. 5).

Marginal escarpments

Marginal escarpments that define the morphological boundaries of the Sowie Mountains (Fig. 6A) have been recently comprehensively analysed by Różycka et al. (2021) and Szymanowski et al. (2021), who applied various methods of relief parametrization using a re-sampled high-resolution LiDAR DTM. The main findings emerging from these studies are the following. First, some morphometric characteristics are similar for both mountain fronts, such as sinuosity of the mountain/foreland junction and the mean slope. Geomorphological similarities are most evident in the south-eastern part of the massif, where it turns into a rather narrow ridge and the mountain fronts are closest to each other. Second, complex relief presentation by geostatistical means (madograms) revealed that the NE escarpment shows less relief variability

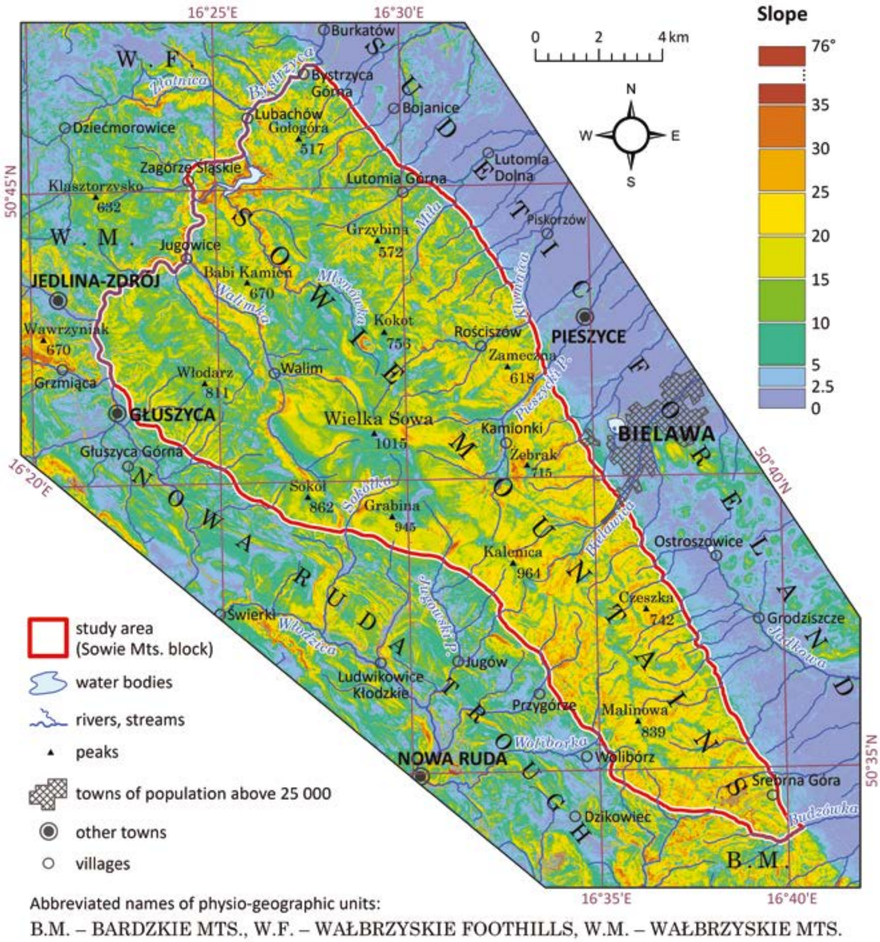

Figure 4. Slope map of the Sowie Mountains and adjacent areas

along the front than its SW counterpart. Third, most stream profiles show steepening (knickpoints) at the base of the NE escarpment, whereas the picture for the SW front is inconsistent. Fourth, combined morphometric indices for drainage basins incised into both escarpments show dissimilarity between the fronts, with more homogeneity found for the NE front. Taken together, these similarities and differences were interpreted to indicate different origins of two fronts. Given indisputable tectonic origin of the NE front (Krzyszkowski et al., 1995; Badura et al., 2003, 2007), it was suggested that the SW front is a fault-line feature, that is a denudational landform that owes its origin to rock resistance contrasts along respective sides of an old fault (Różycka et al., 2021). Minor uplift could not be excluded, especially along the Mt. Wielka Sowa sector, but it did not leave clear geomorphic evidence. Morphological similarities between the two fronts were ascribed to the same lithology of the footwall, as gneiss is exposed in both.

These morphometry-based studies also revealed considerable along-front variability. The NE escarpment shows different characteristics in its south-eastern versus north-western sector, consistent with the

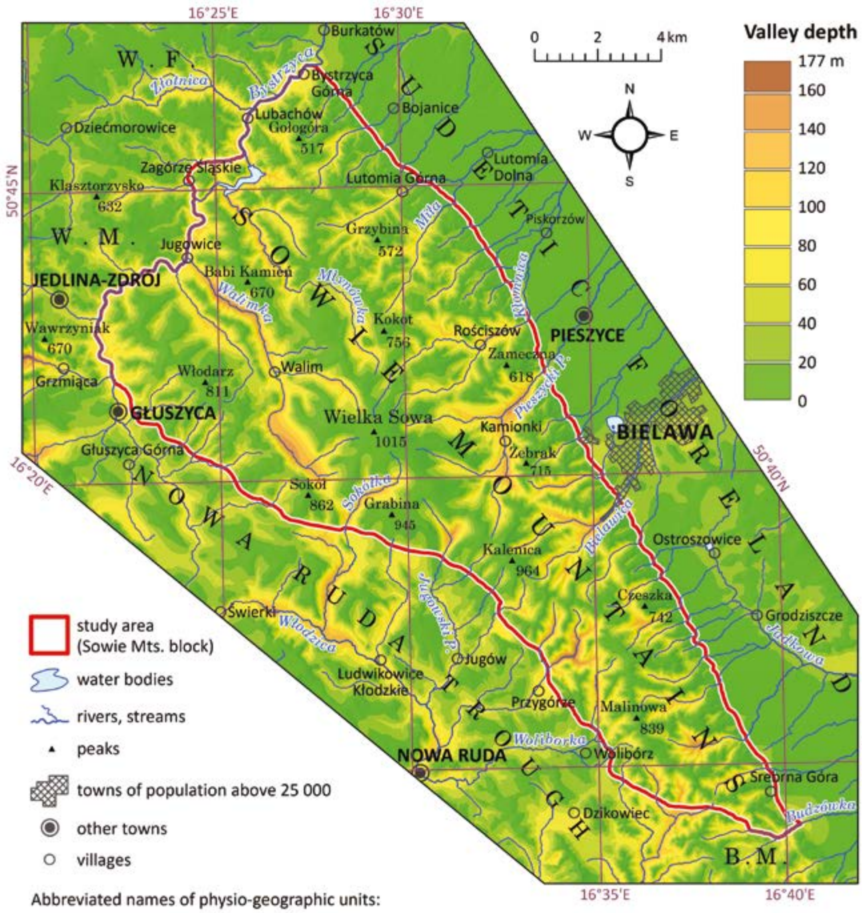

Figure 5. Valley depth map of the Sowie Mountains and adjacent areas

subdivision of the Sowie Mountains into the mountainous (S) and upland (N) part. Altogether, they were interpreted as the evidence of fault segmentation, with more uplift and resultant erosion in the south, in agreement with the previous suggestions (Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Krzyszkowski et al., 1995; Krzyszkowski & Olejnik, 1998). By contrast, the picture for the SW escarpment is generally internally inconsistent, with much more variability in the altitude variability of the frontal zone, drainage basin characteristics, and stream longitudinal profiles. This is ascribed to the role played by various local factors.

Low-angle surfaces ('planation surfaces')

The high-resolution LiDAR DTM allows one to have a new look at the old problem of relict planation surfaces in the mountainous areas, as the model identifies low-angle surfaces (< 5°) in an objective way. The slope map (Fig. 4) shows that the distribution pattern of such surfaces in the Sowie Mountains is non-uniform. They are essentially absent in the south-eastern part, except a few small patches along the main ridge and some of the branching divides. In the central part they occupy around 80 ha around

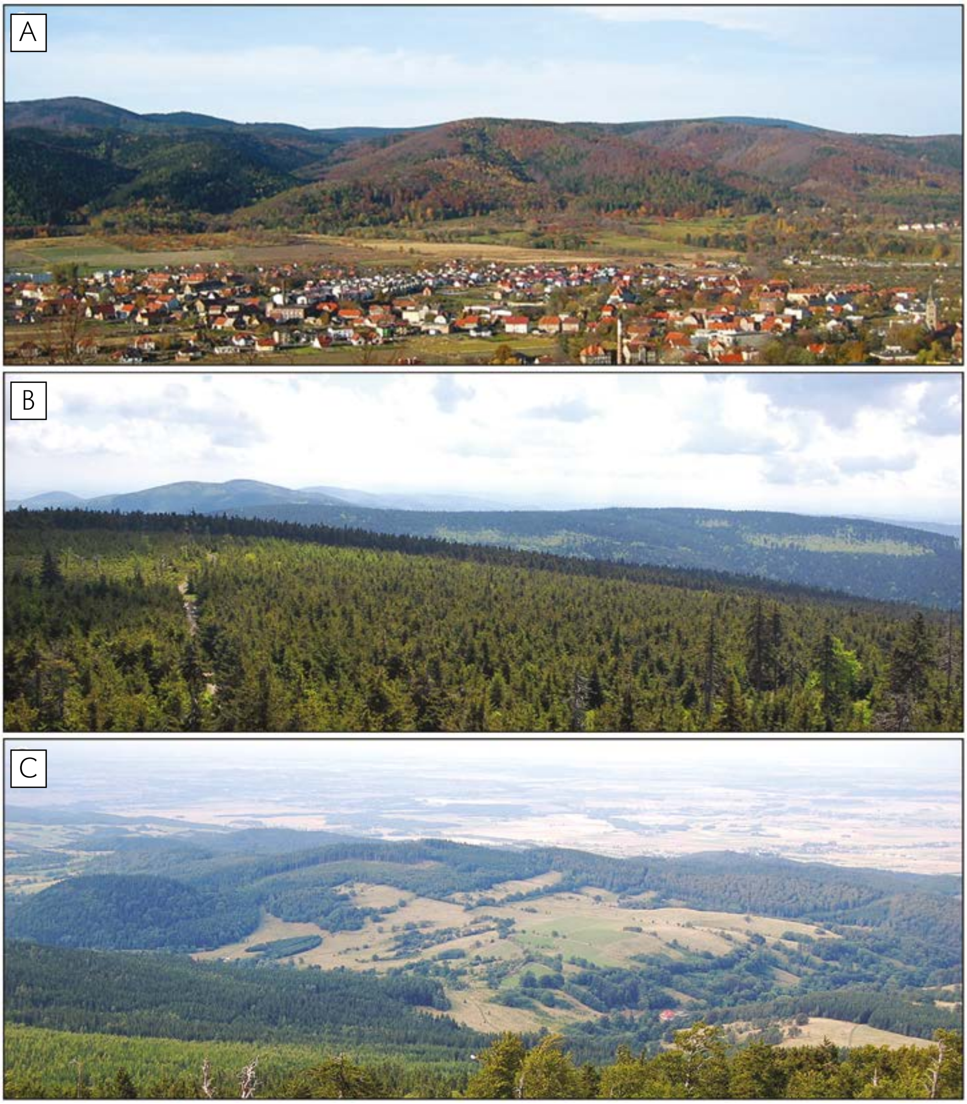

Figure 6. Large-scale geomorphic elements of the Sowie Mountains. A – NE mountain front above the town of Bielawa, B – low-relief surfaces ("planation surfaces") in the most elevated part of the Sowie Mountains (view from the tower on Mt. Wielka Sowa), C – view from Mt. Wielka Sowa towards rolling interfluve surfaces in the northern part of the massif (Sudetic Foreland in the background)

Mt. Wielka Sowa and Mt. Grabina, within the 900-1015 m a.s.l. altitude belt (Fig. 6B). They also occur along the Sokół – Włodarz ridge, mostly at 700-800 m a.s.l., over an area of c. 200 ha. The third area of their occurrence is the largest and occurs in the southern part of the northern upland unit, to the north-east of Walim, at 550-750 m a.s.l. This area is also most complex geomorphologically, including both planar divide ridges, long low-angle slopes, and broad shallow trough valleys (Fig. 6C). Towards the east (the NE mountain front) this surface becomes more fragmented, whereas in the south, these rolling interfluve surfaces abruptly terminate against the northern slopes of Mt. Wielka Sowa, with the corresponding altitude rise of 250-300 m (Fig. 3).

Beside water-divide positions, wide low-slope surfaces are also present along some valleys and three such areas stand out. Two form a NW–SE striking intramontane corridor to the north-east of the Sokół – Włodarz ridge, although they occur along two different rivers and have different positions in respect to them, resulting in highly asymmetric valley cross-sections (Fig. 4). The third area coincides with part of the intramontane Kamionki Basin of triangular shape. Low-angle surfaces have developed along two streams, along the eastern and northern limits of this basin.

The tentative interpretation of these low-angle surfaces is the following. The most plausible relict, pre-uplift landscape occurs to the east of Walim, but given its altitude range, it can be hardly considered as a remnant of one nearly flat surface. Rather, it represents an undulated terrain, equivalent to that present in the fore-mountain part of the gneissic massif (see Dumanowski, 1961; Migoń, 1999), with occasional more prominent hills due to local lithological control (Mt. Ostrzew with its magmatic cap). Subsequent erosion, concurrent with uplift, resulted in fragmentation of this landscape, although the wave of headward erosion of the Młynówka river from the north-west is yet to reach the headwater sections (Fig. 4). The planar surface around Mt. Wielka Sowa used to be considered as a remnant of the Palaeogene planation surface, claimed to be widespread in the Sudetes (Walczak, 1972), but this view cannot be confirmed because of lack of relevant evidence. However, given even conservative rates of long-term denudation of the Sudetes inferred from the thermochronological record (Migoń & Danišík, 2012; Sobczyk et al., 2015), the survival of intact surfaces > 30 Ma old is unlikely. Rather the summit surface predates the Late Miocene–Pliocene uplift of the Sudetes and is much younger than thought, with possible additional contribution from Pleistocene cryoplanation. In the same way, the age of the Sokół – Włodarz ridge remains unconstrained, but it may be an equivalent of the mountain-top surface, located some 200 m lower. The Kamionki Basin, located close to the faulted NE margin of the Sowie Mountains within the footwall, owes its origin to the preferential denudation of Carboniferous conglomerates, which led to exhumation of its old fault-controlled boundaries in the east and north. The trough to the east of the Sokół – Włodarz ridge has uncertain origin. Its northern sector contains Carboniferous sediments, but they are lacking in the southern sector (Fig. 2). Thus, several interpretations are possible. It could be an old graben, currently subject to excavation, complete in the south and ongoing in the north. Alternatively, it may be a narrow graben (or half-graben) downfaulted in the Cenozoic, along intra-mountain faults parallel to the Sudetic Marginal Fault. The absence of low relief surfaces in the southernmost part of the massif is due to most advanced erosion, expanding headward from the very clear boundary escarpments. In contrast to Krzyszkowski & Olejnik (1998), Różycka et al. (2021) using LiDAR DTM could not identify any staircases of flat surfaces along secondary interfluves, which would suggest phase-wise uplift or separation of the footwall into a series of narrow, front-parallel blocks.

Drainage network

The drainage network of the Sowie Mountains can be resolved into three separate areas, delimited by the main water divides. Two of these areas are distinctively associated with the marginal escarpments and consist of streams draining straight to the Sudetic Foreland in the north-east and to the Nowa Ruda Trough in the south-west. These streams are short and their catchments are small, especially on the south-western side (the largest one is 5 km^2, the mean area is 1.15 km^2). Streams draining the NE front have larger catchments (the mean size 2.61 km^2), but only two occupy more than 10 km^2. The third area is located in the north-western part of the Sowie Mountains and includes the right-side tributaries of the Bystrzyca river. The longest of these streams, Walimka, is 12.4 km long and has the sources below the summit surface of Mt. Wielka Sowa. In its upper reach it flows within an intramontane trough, but then leaves it and cuts a short gorge upstream of the town of Walim, followed by a deeply incised section between Walim and Jugowice (Figs. 4, 5).

The valley of Bystrzyca river is traditionally considered as the NW limit of the Sowie Mountains, even though the spatial distribution of morphometric variables such as local relief (Fig. 3) and slope (Fig. 4) suggests geomorphic continuity towards the Wałbrzyskie Foothills. Moreover, the gneissic bedrock continues towards the north-west. Therefore, the Bystrzyca river is the only river that originates on the south-western side of the Sowie Mountains and crosses the mountain block to reach the Sudetic Foreland (Fig. 1), and it does so in the least elevated part of the gneissic massif. The 14.7 km-long reach between the town of Jedlina-Zdrój and the Sudetic Foreland is likely antecedent in respect to the Neogene-Quaternary uplift. The regional drainage pattern does not suggest that any other river may have crossed the area of the contemporary Sowie Mountains, allowing one to infer a long-lasting elevated position of the gneissic massif, even prior to the regional uplift. This proposal is consistent with the finding that gneisses are among the most resistant rocks in the Sudetes, capable to sustain terrain elevations (Placek & Migoń, 2007; Placek, 2011).

Neotectonic uplift of the Sowie Mountains triggered a wave of headward erosion, initiated at the NE faulted margin, where the base level (mountain/foreland junction) is 100-150 m lower than on the SW side. Streams are eroding backward, undercutting the main ridge and shifting the divide westward. This tendency is confirmed by some morphometric characteristics of catchments such as increasing elongation, reduced circularity and lower average value of hypsometric integral (Różycka et al., 2021). Moreover, this is consistent with contrasts in chi-index, with higher values on the SW side indicative of more aggressive headward erosion on the NE side of the divide (Jancewicz et al., 2022).

Glacial and periglacial imprint

In the Pleistocene, the Sowie Mountains were modelled by geomorphic processes typical for cold climates (glacial and periglacial). The altitude of the mountains proved too low to allow for mountain glaciation to develop, even though anomalously low positions of cirques and moraines, below 1000 m a.s.l., are known from elsewhere in the Sudetes: the Karkonosze Mountains (Pilous, 2019) and Jizerské Mountains (Engel et al., 2017). LiDAR DTM does not reveal any comparable landforms on the lee-side of the main ridge (such as gently sloping or flat floors of valley head amphitheatres and depositional ridges). However, valley heads located in the lee-sides of Mt. Wielka Sowa and Mt. Kalenica, i.e. the most elevated parts of the massif, are steeper than others, which may suggest remodelling by persistent snow patches and their role as nivation hollows.

Although the higher parts of the Sowie Mountains were shaped only by non-glacial, cold-climate processes, the lower parts were covered by the Scandinavian ice-sheet. However, neither is the geographical extent of ice coverage known, nor it is agreed when or how many times was the ice sheet present. Patches of till were mapped up to the altitude of 500 m a.s.l. in the northernmost part of the massif and scattered erratic boulders were also found approximately up to that height limit (Finckh, 1923; Teisseyre & Sawicki, 1958; Gawroński, 1961; Krzyszkowski & Pijet, 1993b). The presence of ice did not necessarily mean any substantial modification of relief and in fact, no reports of glacial erosion have ever appeared. The southern sector of the mountain front, in turn, lacks any glacial deposits and must have acted as a powerful topographic barrier to the ice masses. Even if the lowest slopes were under ice, the geomorphic impact of continental glaciation was negligible.

The only part of the region that experienced important landform change conditioned by glaciation was the antecedent valley of the Bystrzyca river, whose contemporary course differs in several reaches from the preglacial one (Krzyszkowski & Biernat, 1998). The old valley was filled by glacigenic deposits (lacustrine, outwash and till) and not everywhere exhumed during deglaciation. New narrow reaches were incised in the gneissic bedrock, whereas old valley floors are hanging ~20 m above (Fig. 7). The longest postglacial reach is located downstream of the village of Zagórze Śląskie and is nearly 2 km long, representing one of the finest examples of glaci-epigenetic gorges in the Sudetes.

Periglacial processes probably did not differ much from those inferred for other medium-altitude massifs in the Sudetes (Traczyk, 1996; Czudek, 1997; Traczyk & Migoń, 2003), leaving similar sedimentary and geomorphic record that comprises widespread hillslope cover deposits produced by solifluction and surface wash, rock cliffs and crags in more massive bedrock compartments, small and largely forested block fields (e.g., at Mt. Kalenica), and possibly nivation hollows (Fig. 8). The complexity of periglacial hillslope deposits, which include stratified sands and gravels, boulder-rich solifluction loams and sandy loams with scattered boulders was documented by Traczyk (1996), although at one locality in Glinno only. The largest crags (tors) occur in the summit part of Mt. Kalenica, where they are up to 10 m high, whereas an isolated rock spur to the south of the summit is nearly 15 m high (Migoń & Latocha, 2005). Blocky talus attesting to joint-guided mechanical breakdown of gneiss is ubiquitous around the crags. Interestingly, the summit surface of Mt. Wielka Sowa lacks any bedrock outcrops and is nearly featureless, but whether this

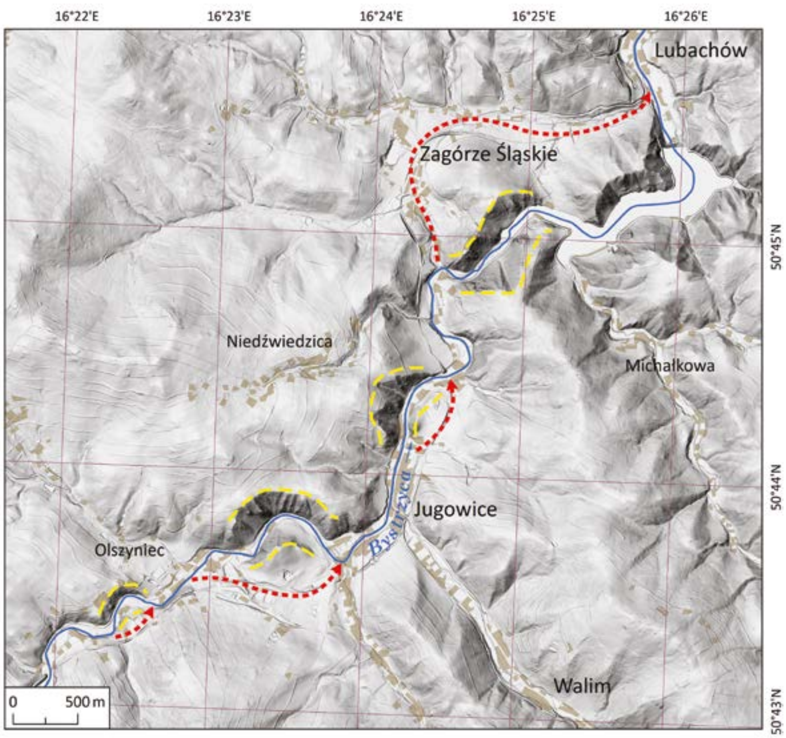

Figure 7. Hydrographic changes in the Bystrzyca valley conditioned by inland glaciation. Red lines with arrows show abandoned reaches of the preglacial valley, yellow broken lines indicate younger, postglacial reaches.

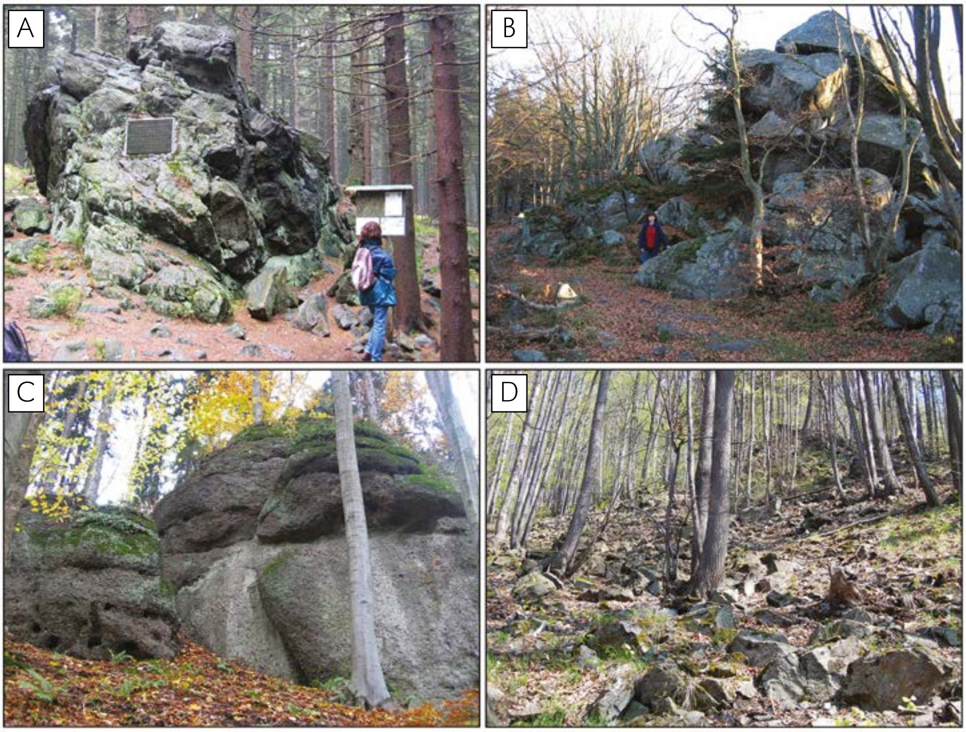

Figure 8. Rock landforms in the Sowie Mountains. A – solitary gneissic tor on the main ridge, to the south of Mt. Wielka Sowa, B – the largest gneissic tor within the tor group on Mt. Kalenica, C – conglomerate crags above Kamionki, D – blocky accumulations on steep slopes of the Bystrzyca valley, near Zagórze Śląskie

is the result of long-term cryoplanation, cannot be determined.

Contemporary geomorphic processes

As indicated in the overview of past research, contemporary geomorphic processes have never been systematically studied in the Sowie Mountains. Likewise, no studies of results of extreme fluvial events have been undertaken, although the Bystrzyca river does have a record of historical floods (Kasprzak, 2010). However, information from other parts of the Sudetes, similar in terms of geology, relief and land cover, can be used to infer the present-day relief dynamics in the study area, which appears to be generally very low. A significant part of the Sowie Mountains is under forest and the forest domain, especially on crystalline bedrock, is characterized by low activity of hillslope denudation processes, unless severely anthropogenically disturbed (Bieroński et al., 1992; Migoń, 2017). Limited slope wash may be expected within beech stands, but otherwise dense undergrowth limits the efficacy of surface wash. Outside forested slopes, grasslands rather than arable land dominate and these are not much affected either. However, slope wash may be hypothesized to be much more important a few tens of years ago and earlier, when cultivated fields were of much larger extent and occupied fairly steep slopes (see the next section). Laskowski (1993) observed minor, centimetre-scale downslope soil displacements due to the growth and then decay of needle ice in a headwater part of the Bielawica valley, but wider significance of this process is probably marginal. On the other hand, ground disturbance due to tree uprooting by strong wind, shown elsewhere in the Sudetes as an important component of Holocene denudation (Pawlik, 2012; Pawlik et al., 2016), may be hypothesized to play a significant role, but no specific research has yet been attempted. Apart from two localized and bedrock-controlled cases at Mt. Ostrzew (Kowalski, 2018), there is no evidence of landslides in the area. It seems that human-induced landform change has been much more profound in the Sowie Mountains than alterations resulting from natural processes, as will be demonstrated in the following section of the paper.

Evidence of human impact on topography and geomorphological system

Outline of historical and economic development

Archaeological findings indicate that the area of the Sowie Mountains has been penetrated and used by humans since at least the end of the Neolithic (Gohlisch & Reisch, 1999), and perhaps even in the Palaeolithic (Bronowicki, 2006). Permanent settlement, however, developed much later. The main foundations of the contemporary settlement network were formed in the 13-14th centuries (Nowotny, 2006), following the pattern of main relief features. The settlements were concentrated along the valley floors and depressions, taking the form of "Waldhufendorfen" – this layout is still legible today. Only later did the settlement also enter the higher slopes. This took place during the second main colonization period in the Sudetes, the so-called Frederician (internal) colonization, in the second half of the 18th century (Adamska, 2016). A dozen new settlements and numerous colonies and hamlets were established in the Sowie Mountains in that period.

Over the centuries, the development of settlement and demography were subject to fluctuations, with the phases of growth interspersed by periods of regression resulting from the numerous wars in this border area (Hussite wars in the 15th century, the 30-years War in the 17th century, the Prussian-Austrian wars in the 18th century) (Pregiel & Przerwa, 2005). During World War II, military operations did not took place in this part of the Sudetes, although there are remains of military structures. However, the post-war expulsion of the indigenous German population, related to the change of the state border (Prausser & Rees, 2004), and the influx of new settlers, who were not familiar with and adapted to mountain conditions, strongly affected the type and intensity of human impact in the region. The trend of depopulation of mountain villages has intensified during this period, although it started at the end of the 19th century and was determined mainly by economic factors (Chachaj, 1978). In many places, it continues to this day (Kneć, 2020, unpublished).

In terms of the economy, agriculture and forestry were the basis of inhabitants' income for many centuries. In many places, mining of polymetallic ores was also undertaken, which lasted, intermittently, from the 14th to the 19th century (Dziekoński, 1972; Piątek & Piątek, 2000). The importance of mining is evidenced, among others, by the fact that in the year 1536 the settlement of Srebrna Góra (Silberberg) was granted the rights of a free mining town (Przerwa, 2001). From the 16th century, weaving started to play an important role in the entire Sudetes (Kęsik, 2015). In the Sowie Mountains, clusters of weaving settlements occurred in the vicinity of Głuszyca and Walim and in the region of Pieszyce and Bielawa, directly in the north-eastern foreland of the mountains. The development of weaving was strongly influenced by natural factors, mainly abundant water resources in mountain streams, necessary both to provide energy and in the production process. Slope inclination and aspect were also favorable for flax dewing, bleaching, and drying of canvases. Apart from craft, rural industry also began to develop over time, which was a characteristic feature of villages in the entire Sudetes

(Żochowska, 2014). It generated a significant impact on the natural environment, especially deforestation. Slope denudation and accumulation within valley floors followed, which is evidenced by the anthropogenic slopewash and alluvial deposits, detected in many areas in the Sudetes (Latocha, 2012). In the second half of the 19th century the importance of cottage weaving began to decline due to increasing mechanization and industrialization. Meanwhile tourism gained higher importance and many villages served as popular summer resorts (Przerwa, 2003; Dziedzic, 2013). Nowadays tourism is a very important part of the local economy, with skiing areas around Rzeczka and Sokolec as the main tourism centers. The specificity of the Sowie Mountains topography, and especially the extensive, low-angle "planation" surfaces, make even the highest parts of the mountains easily accessible, including the summit of the Mt. Wielka Sowa, with the tourist infrastructure developed at the top, e.g., a stone viewing tower dating back to the beginning of the 20th century.

Agriculture and forestry

Over the centuries, various human activities have left numerous traces in the relief. They are legible to this day, despite the fact that most of the anthropogenic landforms are relict. This applies primarily to the most spatially widespread landforms related to former agriculture, the extent of which was much larger in the past than it is nowadays. An analysis of land use changes in the north-western part of the Sowie Mountains (Walim municipality) was performed based on the comparison of cartographic materials from the 1930s and the modern ones. In this period the forest area increased by approx. 34% (from 26.8 to 35.9 km^2). At the same time, there was an over fourfold increase in the area of permanent grassland (meadows and pastures) (from 6.3 to 27.4 km^2) and an approx. fourfold decrease in arable land (from 42.2 to 11.35 km^2) (Kneć, 2020, unpublished). Agricultural terraces are the most characteristic vestige of human transformation of slopes for agriculture purposes. They occur

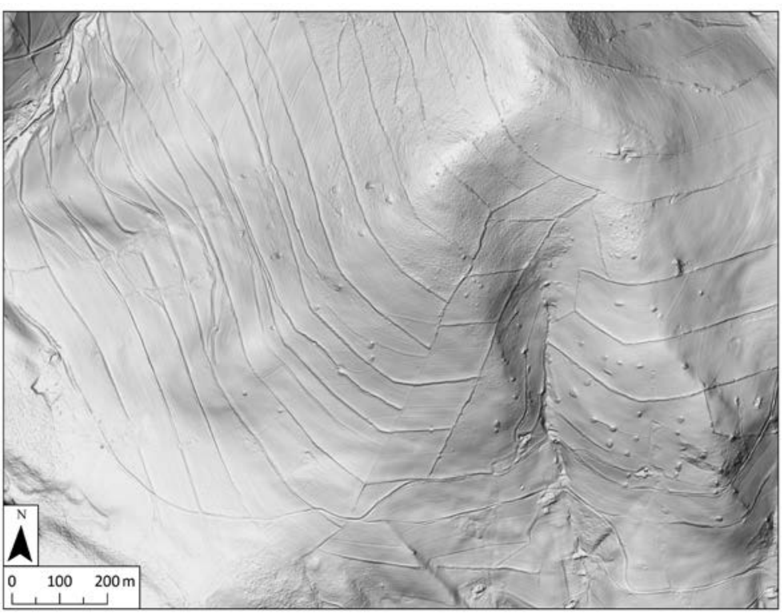

Figure 9. Agricultural terraces and stone heaps on the southern slopes of Mt. Sokół between the villages of Sierpnica and Sokolec are clearly seen on LiDAR imagery

on most of the slopes formerly used as arable land, and their largest extents are concentrated in the south-western and western parts of the study area (between villages of Sokolec, Jedlinka, Jugowice and Glinno), above the village of Jugów, and in the lower slopes along the north-eastern escarpment (villages of Lutomia Górna and Rościszów). Most of them are currently located in permanent grassland or forests. However, despite changes in land use, they are still well-visible landforms, both in the landscape and in the LiDAR imagery (Fig. 9).

The detailed geomorphic study of agricultural terraces was carried out for the village of Sierpnica (2.8 km^2, 580-862 m a.s.l.), where a set of 23 agricultural terraces located at a distance of 20-100 m from one another occurs (Fig. 10). Their lengths range from 50 to over 1000 m, the height of the risers is from 0.5 to 4 m, and the slope angle of the risers varies from 25° to 52°. The density of agricultural terrace risers in Sierpnica is 13.2 km/km^2 (Latocha & Urbanowicz, 2010). The analysis of sediments accumulated within terraces allowed to estimate the lowering of slopes once used for agriculture for 0.28 to 1.35 mm per year, depending on the topographic position and slope inclination (Latocha & Urbanowicz, 2010; Latocha, 2012).

Other remnants of agriculture are heaps of stone removed from the fields to facilitate

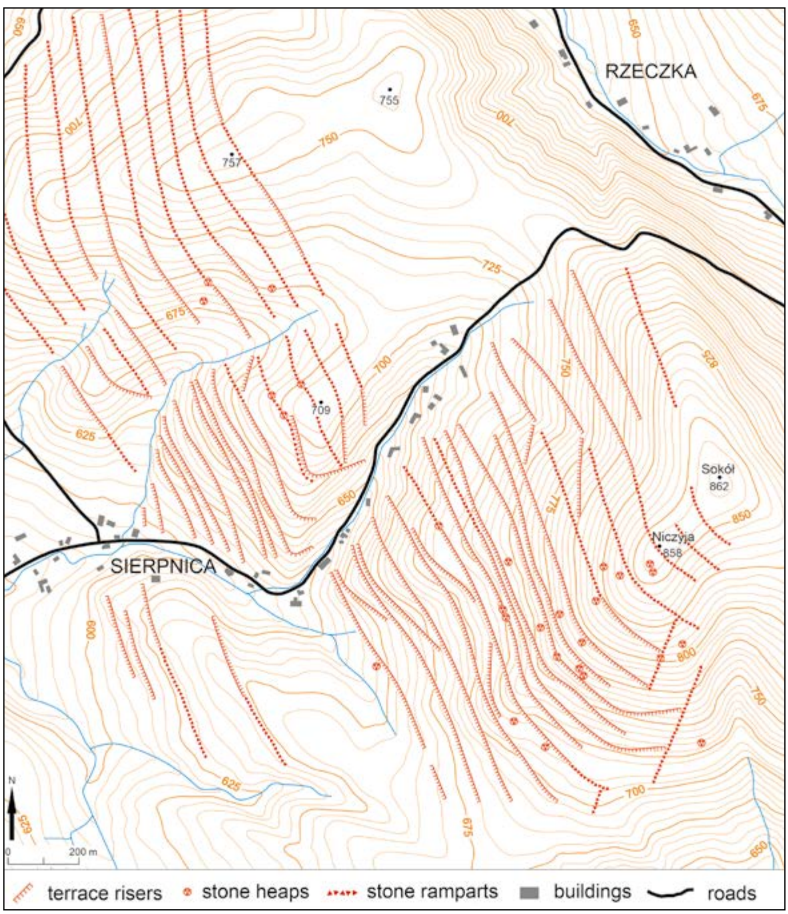

Figure 10. Agriculture-related landforms above the village of Sierpnica (Source: Latocha & Urbanowicz, 2010)

ploughing. Nowadays, they are also located in forests or within grasslands. The highest concentrations of stone heaps within former arable land occur on the slopes above Jugów and in the vicinity of Sokolec and Rzeczka (Fig. 9). The stones were also stored in the form of walls or embankments along the edges of agricultural terraces and along the balks marking property boundaries. In the first case, they represent clear linear landforms transverse to the slope, while in the second case they follow the slope. They can be thus interpreted as a long-term testimony to former land divisions, referring to the original, mainly medieval layout of villages. They form parallel strips delimiting the lands belonging to each owner (Fig. 11). The best examples of well-preserved landforms of this type are found around Walim and Rzeczka.

The slopes of the Sowie Mountains are also intensively transformed as a result of forest management. Furrows left by dragging logs downslope are up to 30 cm deep and they are further deepened by periodic water runoffs. The characteristic overdeepenings associated with the transport of logs occur both on slopes and within forest roads, which locally leads to their transformation into gullies (sunken lanes), which may be up to 2 m deep (Fig. 12).

Quarrying and mining

The intensive exploitation of mineral resources took place in the Sowie Mountains in the past. The prevailing gneisses are not currently quarried, but in the past there were numerous quarries, mainly serving local needs. Contrary to the quarries, the sites of former exploitation of Quaternary clays for brick making are not clearly visible in the landscape today.

The rich mineralization, present in the Sowie Mountains in the form of ore-bearing veins and lenses, determined local remodelling by mining activities. Mineral veins were formed mainly by quartz, feldspar, calcite and barite, which contained metal sulfides (i.e., galena, pyrite, sphalerite) with admixtures of valuable minerals such as silver, gold, cobalt and nickel (Dziekoński, 1972). Due to the limited resources, most of lodes were exhausted by the 19th century (Piątek & Piątek, 2000). Mining in the Sowie Mountains was attempted in various areas, and the traces of the past exploration and exploitation sites are still visible in the form of mostly collapsed adit entrances, pits signifying the location of shafts, tunnels, exploration and exploitation ditches, mining-related sinkholes

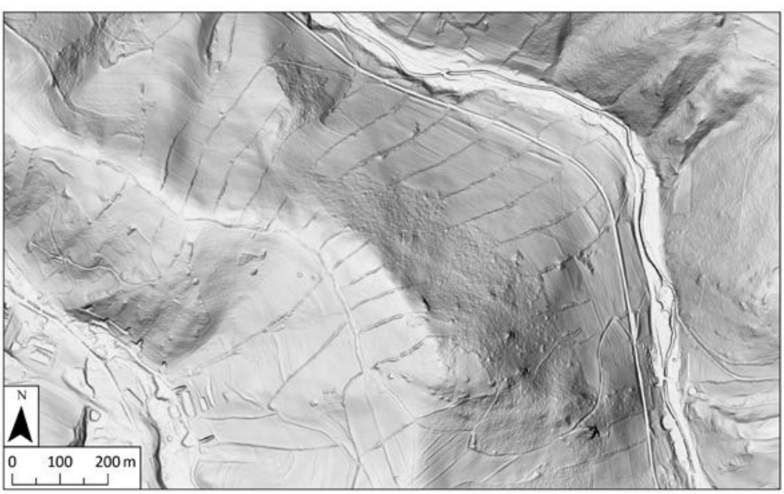

Figure 11. Stone walls along the former property borders extend up to and across the ridge between Jugowice (south-west) and Walim (north-east)

Figure 12. Road gully (sunken lane) with stone embankment, above Kamionki

and associated earth ramparts. In total, over a hundred different relicts of former metal ore mining have been identified, which concentrate in the following areas: Srebrna Góra, Bystrzyca Górna, the area of Mt. Wielka Sowa, Kamionki, Rościszów, Walim and Zagórze Śląskie (Stysz & Zagożdżon, 2020).

The best-preserved historic mining sites include the Silberloch mine near the town of Walim and the Marie Agnes mine in the village of Bystrzyca Górna. The first one dates back to the 14-15th centuries, and the second one – to the 16th century. The total length of the corridors is 77 m in Silberloch (Stysz & Zagożdżon, 2020) and 140 m in Marie Agnes. They are carved in gneisses and are 1.8 m high (on average) and approx. 1 m wide. Despite numerous detailed historical studies on mining history, as well as inventories of traces of former mining in the Sowie Mountains (i.e., Piątek & Piątek, 2000; Madziarz & Sztuk, 2005; Krzyżanowski & Wójcik, 2010), the only strictly geomorphological study is the analysis of anthropogenic relief transformation of the Chłopina catchment, at the southern end of the Sowie Mountains (Borecka, 2009, unpublished) (Fig. 13). Post-mining landforms were identified within an area of c. 2.3 km^2 and include remains of adit entrances (for both mining and drainage), collapse sinkholes, linear trains of circular and elongated hollows indicating former shafts, minor surface excavations, and heaps of waste material in both hillslope and valley floor setting.

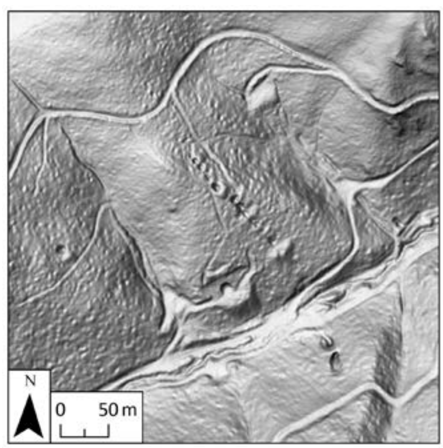

Figure 13. Geomorphic legacy of former mining activities in the Chłopina catchment

Transportation

Specific anthropogenic landforms in the Sowie Mountains are related to the transport and communication network. A very dense network of unpaved roads is associated with agriculture and forestry. Even those that are no longer in use are still visible in the relief in the form of road flats and undercut slope escarpments, or even road gullies in some sections (Fig. 12). Noteworthy are the remains of the currently closed railway lines, with viaducts and trenches. In terms of geomorphology, the most spectacular was the so-called Sowiogórska railway, completed in 1902 (Jerczyński & Przerwa, 2007). This route connected the towns on the eastern and western sides of the Sowie Mountains, mounting the Srebrna Pass just below the fortress. Due to the steep slope, the rack railway was constructed in the area of the pass (6.6 km long). In addition, the construction of the route required building of two brick viaducts and several sections of high embankments and deep trenches (up to 30 m deep) in solid rock (flysch, conglomerates, gneiss) by using explosive materials (Fig. 14). Due to difficult technical conditions of this route, unprofitability of transport and frequent rock falls within the trench, the rack railway was closed in the 1930s, and the entire line stopped operation in the 1970s (Jerczyński & Przerwa, 2007).

Within the flysch rocks in the trenches of the Sowiogórska railway, a large amount of fresh, non-vegetated weathering material

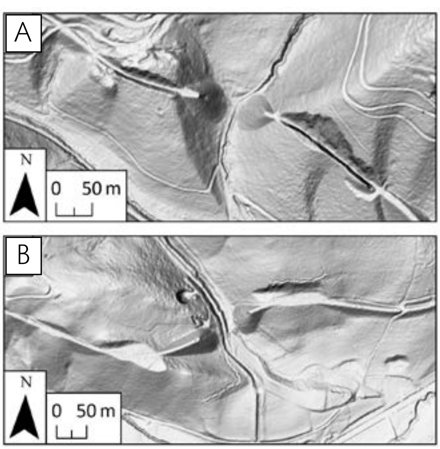

Figure 14. Trenches (A), embankments and mid-slope benches (B) indicate the line of the former Sowiogórska railway (south of Srebrna Góra)

can be found locally in the forms of cones of various sizes or chaotic accumulation of debris. The largest blocks have a diameter of 2 m. This proves constant activity of slope processes, whose intensity shows a clear relationship with the dip of rock layers (Huszcza, 2014, unpublished).

Military landscapes

The slopes of the Sowie Mountains have also been strongly remodelled by military activities. There are several remains of medieval strongholds located at the top of mountains. They were related to the former border between the Kingdom of Bohemia and the Piast duchies that ran along the Sowie Mountains and functioned until the end of the 14th century. Additionally, these strongholds guarded important trade routes that led across the mountains, through passes and valleys. One of the best-preserved buildings from this period is the Grodno Castle from the end of the 13th century, erected on the top of Mt. Choina (450 m a.s.l.), on the steep and high edge of the gorge in the Bystrzyca valley, making good use of the natural, defensive features of the topography. Other medieval strongholds are poorly preserved, but are still legible in the landscape (Fig. 15). The remains of a 13th-century stronghold on Mt. Grodzisko/Zameczna (535 m a.s.l.) above Rościszów are one of the most interesting examples, as they represent a transitional form between an early medieval stronghold and a late medieval castle. The facility was built on a plan of three circles, with the central one located on a small hill, and it covers a total area of nearly 15,000 m^2. There is a double line of embankments, 10 m wide, and a dry moat carved in the rock. The main buildings were located on a rampart (50 m in diameter and 8 m in height).

Medieval strongholds perfectly used the natural, defensive features of the topography, modifying the surface to a small, though permanent, extent. The construction of the 18th-century mountain fortress in Srebrna Góra, together with a complex of various buildings and defensive structures on the nearby slopes

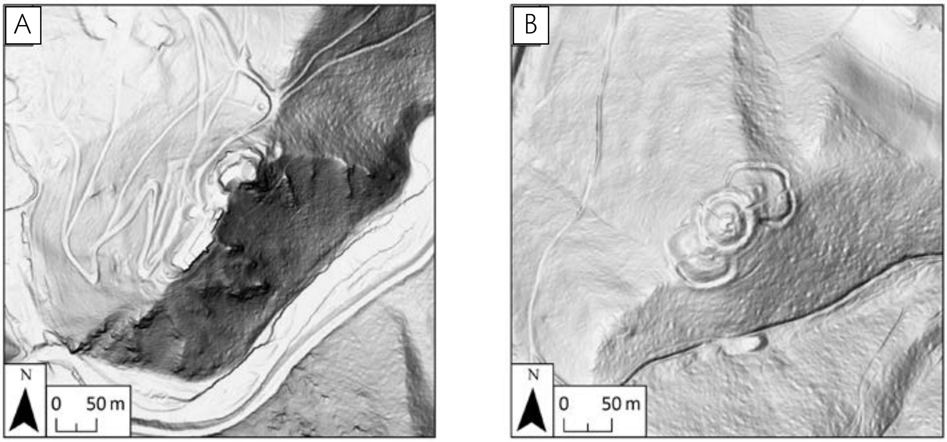

Figure 15. Medieval defensive architecture and related landform changes. A – Grodno Castle above the Bystrzyca gorge on the top of Mt. Choina. Notice also extensive slope remodelling associated with building of access road and the general asymmetry of slopes, with crags and hollows on the east-facing slope and smooth relief on the opposite one. The craggy slope is part of the postglacial gorge of the Bystrzyca river. B – remains of the Rościszów stronghold at the top of Mt. Grodzisko/Zameczna

and hills, caused a much greater interference with morphology (Podruczny & Przerwa, 2010). The fortifications were erected in the ridge part, leading to its artificial flattening, within which a complex of defensive structures was constructed – it is one of the largest (more than 100 ha) and best preserved in the country (Fig. 16). The fortress in Srebrna Góra was an important element in the system of fortifications protecting the south-western border of Silesia.

The most recent military objects are trenches from the World War II. They form linear, zigzag ditches, stretching along the north-eastern edge of the Sowie Mountains, in the lower part of the slopes, for a distance of almost 10 km in a straight line (Fig. 17). Most of them are arranged perpendicular to the slope. Overlooking the Sudetic Foreland, their location was an excellent place for defence and observation. The ditches are on average 50-70 cm deep (maximum 2 m), and their width reaches 2 m (Borecka, 2009, unpublished). They are accompanied by earth ramparts. Nowadays, the ditches are subject to filling with mineral and organic material. These landforms are currently located in the forested area.

The period of World War II is also associated with the construction of the extensive “Riese” complex, one of the largest military undertakings in the contemporary Poland, but part of Germany and supervised by the German Reich at the time of construction. It is an underground system of adits, tunnels, corridors and halls, probably planned as the main army headquarters and weapon factories, although never made fully operational (Aniszewski, 2006; Kosmaty, 2006). The works were carried out in the years 1943-45. There are six building complexes which have been so far discovered in the Sowie Mountains. Most of the work under the “Riese” project was carried out underground, but the land surface was also transformed in the form of numerous concrete and reinforced concrete structures above ground, as well as energy and transport infrastructure (e.g., Sienicka & Zagożdżon, 2010) (Fig. 17).

Hydrotechnical constructions

Due to the high risk of flooding arising from the combination of steep slopes, poorly permeable substrate and numerous watercourses, most streams and rivers were regulated

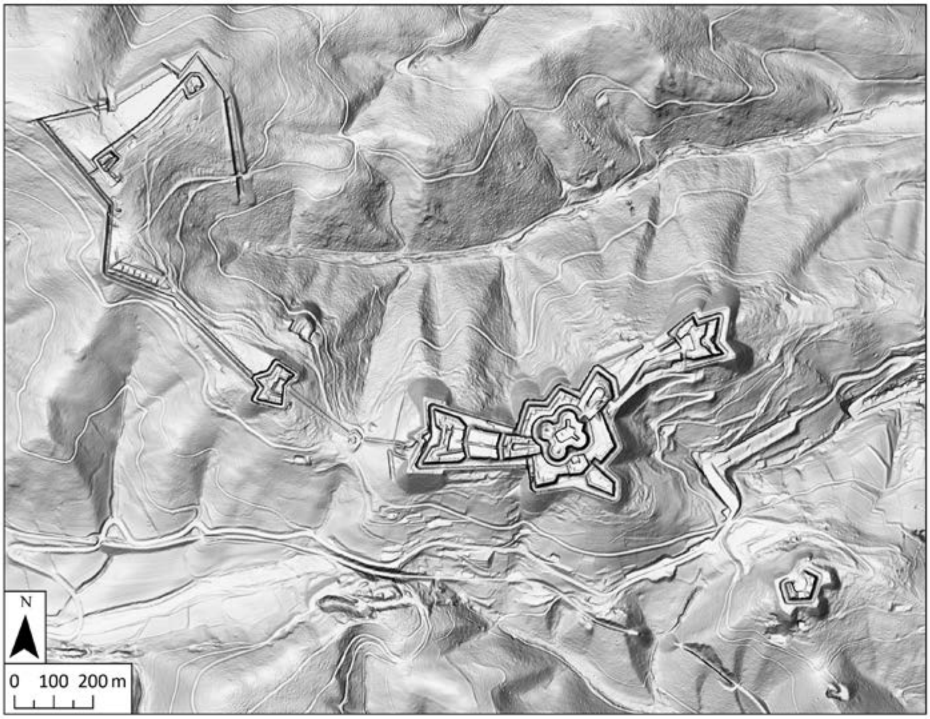

Figure 16. Remodelling of the ridge part of the Sowie Mountains by building a 18th-century fortress in Srebrna Góra

at the end of the 19th century and the beginning of the 20th century. In addition, in the years 1912-14, in the Bystrzyca valley in Lubachów, a water dam was built from local gneiss (height: 44 m, length: over 230 m, width at the base: 29 m, width of the crown: 3 m), causing the origin of a retention reservoir (Bystrzyckie Lake) with a capacity of 8 million m^3, where a hydroelectric power plant was established (Stysz & Zagożdżon, 2020). Over time, holiday and recreational centres developed around the reservoir, and its recreational function has been maintained until today.

Conclusions

Combination of an overview of previous scattered work, large-scale topographic analysis based on DTM, and examination of various types of anthropogenic impact on landforms and surface processes show that the seemingly monotonous Sowie Mountains represent considerable geomorphological diversity. Although rather overlooked in previous research, with some notable exceptions such as the efforts to decipher the history of neotectonic activity of the Sudetic Marginal Fault, they may serve as a representative example of complex relief developed upon predominant gneiss bedrock. Major landforms include prominent escarpments (mountain fronts) of apparently varied origin and interfluve areas with different degree of erosional dissection, depending on the distance from the trunk rivers or mountain/foreland junctions. The northern part of the area was overridden by an ice sheet, the result of which is a series of new reaches of the Bystrzyca river valley, whereas abandoned reaches remain filled with glacigenic and slope sediments. The impact of periglaciation is not yet fully

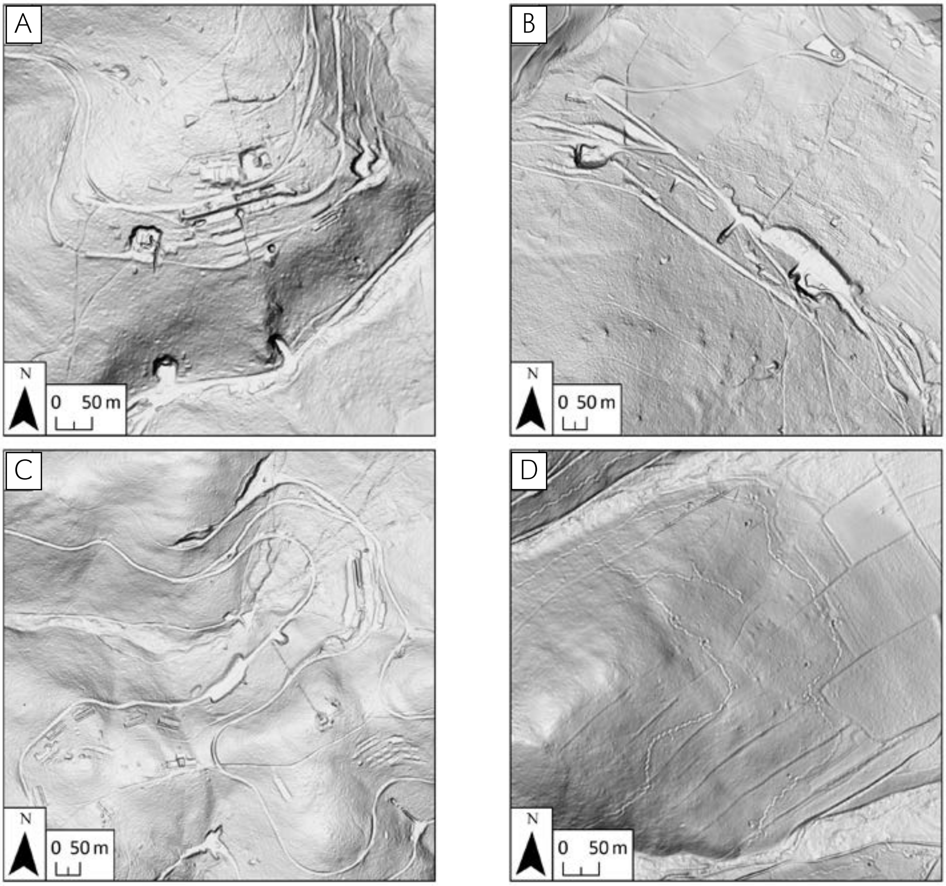

Figure 17. Relief transformation within the complexes of military facilities from World War II: A –Osówka complex, B – Włodarz complex, C – Soboń complex. D – trenches within NE slopes of the Sowie Mountains

elucidated, but tors, vegetated block fields and loamy, debris-rich solifluction mantles show the efficacy of mechanical weathering of bedrock outcrops and downslope transport. Human impact on the topography is not as spectacular in the Sowie Mountains as it is in some other regions of the Sudetes, but it is very diverse and related to many different types of human activities in the past, ranging from agriculture through forestry, mining, transportation to ground alterations arising from military use. Moreover, the area hosts evidence of some of the most spectacular landform change due to defensive constructions, exemplified by the huge Srebrna Góra fortress.

The state-of-the-art of research presented in this paper and the qualitative inventory of landforms differing in size and origin may become a good starting point for further studies. On the one hand, there remains a deficit of information regarding fluvial geomorphology and hillslope morphology of headwater parts of the valleys. Likewise, our understanding of periglacial transformation of relief and contemporary processes is selective and insufficient. Also it is recommended to continue research on anthropogenic transformation of topography, in order to refine the knowledge of geomorphological dimension of human impact, its effects on the functioning of geomorphic systems, and the durability of anthropic landforms. Finally, comparative studies with other mountain massifs and uplands underlain mainly by gneiss, rarely addressed in geomorphology from the rock control point of view but fairly widespread in the Bohemian Massif, may significantly inform attempts to separate effects of lithology, tectonics and various exogenous factors in the long-term evolution of erosional topography.

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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