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How high-resolution DEM based on airborne LiDAR helped to reinterpret landforms – examples from the Sudetes, SW Poland

Piotr Migoń, Marek Kasprzak, Andrzej Traczyk

Institute of Geography and Regional Development, University of Wrocław, Poland, piotr.migon@uni.wroc.pl

Abstract: The paper reviews recent advances in landform mapping and interpretation in the mountainous terrain of the Sudetes (SW Poland), possible due to the availability of high-resolution airborne LiDAR data. They are particularly useful in the recognition of minor landforms and their spatial patterns in the montane forest belt and in the dwarf pine zone in the most elevated parts of the Sudetes. The use of LiDAR data has allowed to both re-evaluate landforms known before, especially their extent and cross-relationships, as well as to discover surface features that have escaped attention before. The examples discussed include glacial and periglacial landforms in the Karkonosze, morphological signatures of mass movements in the Stołowe Mountains, fluvial features and morphotectonic analysis in the Izerskie Mountains. Although LiDAR immensely increases the scope for landform recognition and mapping, image interpretation should be verified in the field. Despite theoretical capability of LiDAR-derived models to show even landforms 1–2 m in length, 4–6 m seems the more realistic threshold size unless surface features are distinctly linear and continue over long distances.

Key words: LiDAR, DEM, geomorphometry, geomorphological mapping, Sudetes

Introduction

In recent years we observe rapid developments in acquisition techniques of high-quality data on Earth surface topography (Wilson, Bishop 2013). Among these new sources of data is airborne laser scanning (ALS – Wasklewicz *et al.* 2013), also known as LiDAR (Light Detection and Ranging), which provides high resolution information about the configuration of land surface and hence, is used to build detailed digital elevation models. LiDAR data are used for many purposes in geomorphology, but are particularly useful in geomorphological mapping (Höfle, Rutzinger 2011, Bishop 2013, Napieralski *et al.* 2013). The advantages of LiDAR include its ability to penetrate through forest canopies and to detect minor topographic features, which proves invaluable in mapping densely forested terrain, even if the ground is accessible physically and can be walked on. Recent examples of successful utilization of LiDAR data for mapping landforms include the recognition of subtle geomorphic signatures of landslides (Van Den Eeckhaut *et al.* 2007), tectonic features (Kondo *et al.* 2008, Lin *et al.* 2013), and fluvial landforms on floodplains (Notebaert *et al.* 2009).

In Poland the use of airborne LiDAR data for geomorphological purposes, especially landform mapping, has so far been very limited. They helped in landslide mapping in the Carpathians (Borkowski *et al.* 2011, Wojciechowski *et al.* 2012) and enriched our understanding of landform inventory and evolution in the vicinity of Mt Kasprowy Wierch, Tatra Mts (Wójcik *et al.* 2013). In the Sudetes, SW Poland, LiDAR-derived DEMs were first used to update geological maps for the Karkonosze Mts (Knapik *et al.* 2009) and the Stołowe Mountains (Wojewoda *et al.* 2011), and somehow parallel, in geomorphology, to re-evaluate and refine existing geomorphological maps (e.g. Traczyk 2009), extending to terrains never subject to detailed geomorphological analysis. Applications of LiDAR data have been manifold, from visual interpretation of shaded relief maps, through topographic profiling, to regional geomorphometric analysis (Kasprzak, Traczyk 2011, Traczyk, Kasprzak 2012). The purpose of this paper is to review selected examples of how the availability of LiDAR data helped to re-interpret landforms and patterns of their evolution. It is intended partly as a review/summary paper, in which we will refer to materials previously published in local journals, and almost exclusively in Polish. However, we also use this opportunity to comment on certain limitations in using LiDAR data, and to discuss research challenges and perspectives.

Study area – potential for LiDAR-based studies in geomorphology

General characteristics

The Sudetes are a part of a belt of middle-altitude mountains and uplands (Germ. *Mittelgebirge*) that stretches across Central Europe, from France through Germany, Czech Republic, to Poland. Among them, the Sudetes are the highest range, peaking at 1602 m a.s.l., but most of the area is located at lower elevations, between 500 and 1,000 m a.s.l. (Fig. 1) In terms of regional geomorphological landscape, the Sudetes are most appropriately classified as a relatively recent (late Neogene – Quaternary) horst-and-graben structure superimposed on a bedrock-controlled landscape that developed through long-term denudation during the entire Cenozoic (Demek 1975, Jahn 1980, Placek, Migoń 2007, Placek 2009, Migoń 2011). Among the rock-controlled landscapes the most characteristic are hilly topographies on granites and granodiorites, with a multitude of rock outcrops of various size – domes, tors, and boulders (Czudek *et al.* 1964, Migoń 1996), and tableland and cuesta landscapes on sedimentary rocks, mainly sandstones, with continuous cliff lines, towers, canyons, rock labyrinths, and hoodoo rocks (Vítek 1979, Pulinowa 1989, Migoń, Placek 2007).

While the gross geomorphic features are the outcome of protracted landscape evolution (Jahn 1980), the majority of medium-scale landforms are products of Pleistocene morphogenesis under cold climatic conditions. In the most elevated parts of the Sudetes local glaciers existed and left their morphological imprint in the form of cirques and moraines (Traczyk 1990, Engel 2007, Engel *et al.* 2011), whereas bedrock cliffs, block fields, mid-slope benches (cryoplanation terraces), superimposed solifluction sheets, and relict patterned ground are the testimony of periglacial environment (Martini 1969, Czudek 1997, Traczyk, Migoń 2003, Křížek *et al.* 2010). Landform inventory for the Sudetes includes also features resulting from mass movement, such as debris flows (Pilous 1973, Migoń, Parzóch 2008) and landslides of various types (Migoń *et al.* 2002, 2010).

The altitude of most individual mountain ranges within the Sudetes is not sufficiently high for them to rise above the tree line, which runs at 1,200–1,250 m a.s.l. (Treml *et al.* 2006), and the natural land cover is predominantly forest. In the Sudetes, very small areas in the Karkonosze Mts and Hrubý Jeseník Mts are located in the subalpine zone, with dwarf pine stands and grasslands; otherwise the mountains are densely forested, unless the forest was

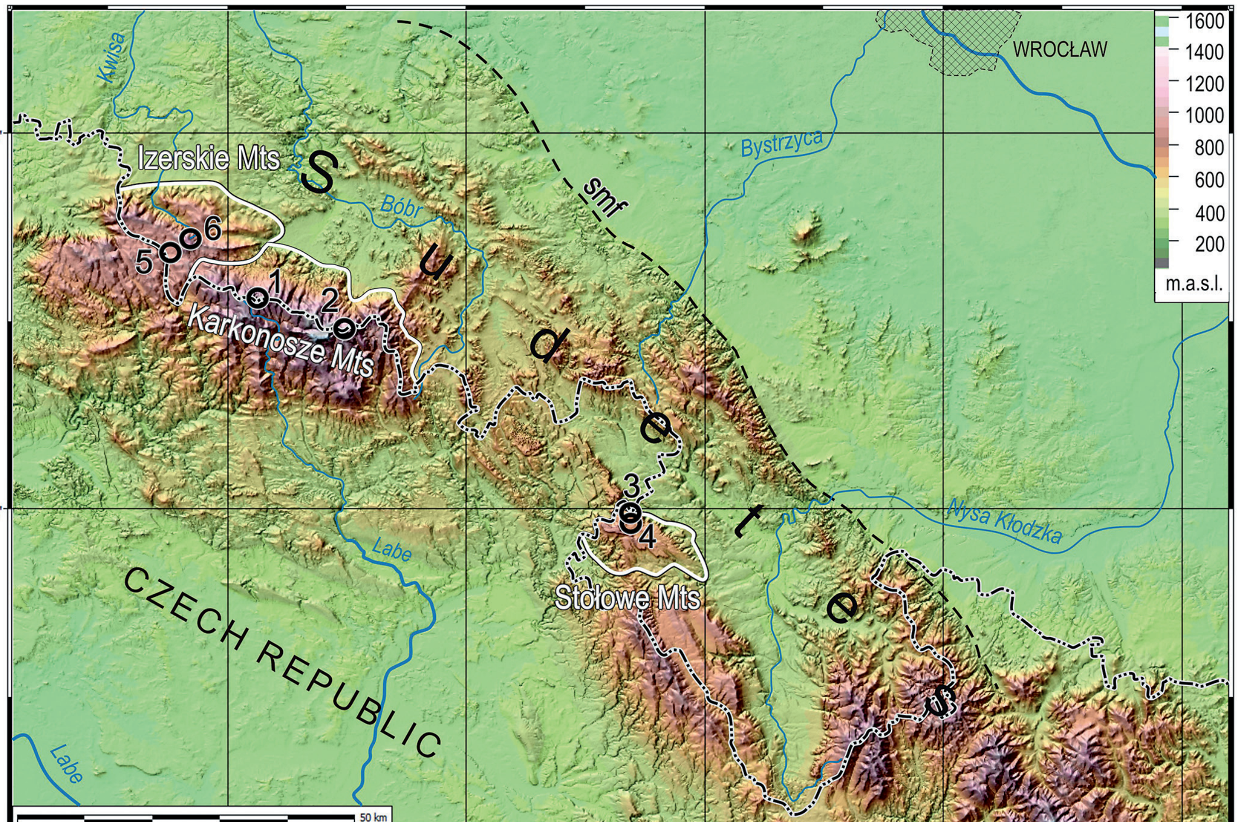


Fig. 1. Location of mountain terrains studied using LiDAR data within the Sudetes. White solid lines indicate the spatial coverage of LiDAR. smf – Sudetic Marginal Fault

Study areas referred to in detail: 1 – Śnieżne Kotły glacial cirques, 2 – Mt Śnieżka, 3 – Biała Skała escarpment, 4 – Mt Szczeliniec Wielki, 5 – Izera valley, 6 – Mt Wysoka Kopa cleared by humans to make room for agricultural and pastoral development. The widespread occurrence of forest cover bears on the efficacy of geomorphological mapping and limited usefulness of traditional data sources about local topography, such as topographic maps and aerial photographs.

History of research

The Sudetes have a long history of geomorphological research, the beginnings of which date back to the 1880s and involved mapping glacial landforms and deposits in the Karkonosze Mts (then Germ. Riesengebirge) (Partsch 1882). Soon after, in the early 20th century, further research topics emerged such as relationships between geology and relief (Cloos 1925, Berg 1927), cold-climate legacy in the most elevated parts of the Sudetes (Flohr 1934, Büdel 1937), the origin of river gorges (Berg 1928, Zeuner 1928), and landform evolution history recorded in planation surfaces (Ouvrier 1933). These research directions were continued by Polish geomorphologists after 1945 and significant advances have been made in several fields. In the Karkonosze Mts the extent of Pleistocene glaciers and the relative chronology of glaciations were established (Traczyk 1989, Chmal, Traczyk 1999), while the focus on cover deposits and residual mid-slope landforms helped to understand the patterns of hillslope evolution in the periglacial environment (Jahn 1969, Traczyk 1995, Żurawek 1999, Traczyk, Migoń 2003). In granite areas the diversity of residual granite morphology was appreciated, including its association with the phenomenon of deep weathering of granite (Jahn 1962, Migoń 1996, 1997). In the sandstone tableland of the Stołowe Mts a significant role of structural control on landforms and processes was demonstrated (Pulinowa 1989). Finally, the impact of Quaternary tectonics on the evolution of fluvial and terrace systems, particularly along the mountain front of the Sudetes, was revealed (Krzyszkowski, Pijet 1993, Krzyszkowski *et al.* 2000).

Most of those research exercises were based on field landform mapping, occasionally aided by an interpretation of aerial photographs. Landform distribution sketches at scales from c. 1:5,000 to 1:25,000 accompanied research papers, but these cartographic attachments were inevitably rather coarse, with insufficient detail and the obvious lack of georeferencing. Often the occurrence of individual landforms was marked by symbols placed in approximate locations, and mapping boundaries of terrain (geomorphic) units lacked objective, quantitative background. Geomorphometric approach to characterize landforms was used sporadically and typically at a regional rather than local scale (Sroka 1997, Krzyszkowski, Olejnik 1998, Badura *et al.* 2003). The advent of digital elevation models in the early 2000s allowed for regional analysis of various morphometric parameters and indices (Placek *et al.* 2007, Migoń *et al.* 2009) but the horizontal resolution of the source data (25 × 25 m, 30 × 40 m) was too low to capture details of hillslope or valley floor morphology.

Potential for LiDAR-based studies

Airborne high-resolution LiDAR data about surface topography are an invaluable source of information for geomorphology, which otherwise is extremely difficult, or impossible to extract. In the mountainous terrain of the Sudetes, due to dense forest cover and undergrowth, medium and small-size landforms often escape attention during field mapping and the existing topographic maps, despite their apparently fine scale (1:10,000; 1:25,000), usually fail to reveal them. Likewise, widely and freely available DEMs such as SRTM–3 or ASTER GDEM are too coarse for mapping elementary landforms (Fig. 2). Errors associated with the use of GPS in measuring both height and position of single objects can also be substantial. A clear picture of spatial distribution of elementary landforms (e.g. gullies, tors) and certain topographic features (e.g. slope breaks) is even more problematic to obtain. Identical comments are valid for the dwarf pine belt above the tree line, where many interesting geomorphic features (block slopes, solifluction lobes, rock glaciers, moraines) are located.

Data sources and methods

LiDAR data used in geomorphological research in the Sudetes were acquired through airborne laser scanning that involved scanning point density of 2–7 points per

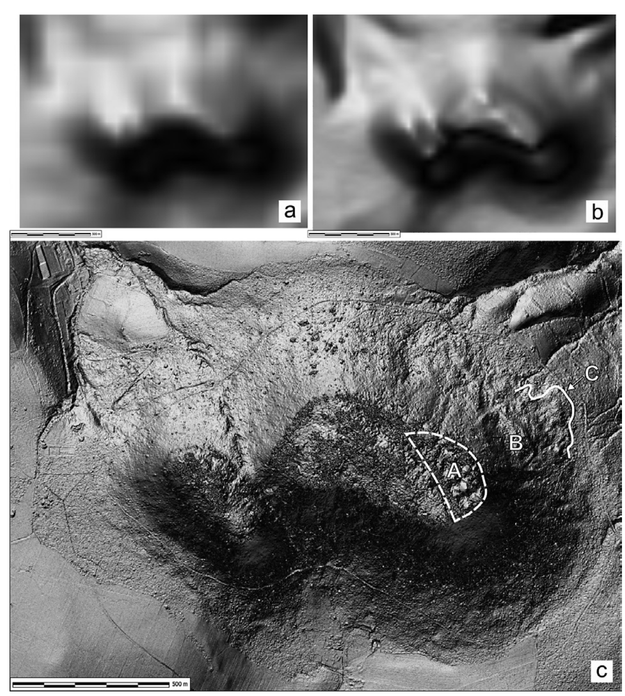


Fig. 2. Shaded relief models of Mt Szczeliniec Wielki (Stołowe Mountains) in three different resolutions, from different data sources

a – SRTM–2 (c. 60 × 90 m), b – DTED–2 (c. 30 × 35 m), c – LiDAR (0.6 × 0.6 m)

A – sagged eastern corner of the mesa, B – head scarp of the landslide, C – landslide toe

1 m^2 and measurement accuracy 0.15–0.25 m. Rough data were models of 'bare Earth' type and contained information about altitude of the topographic surface at a point, recorded as sectional .LAS or .XYZ files. ASL was independently commissioned by several state institutions to enrich their Geographic Information Systems and help current land management. These included the Karkonosze National Park, the Góry Stołowe National Park, and Świeradów Forest Inspectorate. The resolution of digital elevation models used in geomorphological analysis was, depending on specific research targets, from 0.6 × 0.6 m to 5 × 5 m and these very fine models proved invaluable in landform recognition. Modelling of geomorphometric parameters for larger areas required resolution change to 10 × 10 m and 30 × 30 m.

Further work involved the use of various software within GIS environment. Data preparation was performed using Global Mapper (conversion of file formats, change of cartographic reference system, model re-interpolation, generation of contour lines). For terrain visualization and quantitative analysis of surface topography, Open Source software/GIS packages such as SAGA GIS and MicroDEM were applied. Both have been found particularly suitable for geomorphometric analyses due to abundance of tools to handle raster digital models.

Basic and derivate land-surface (e.g. primary and secondary) parameters were widely used in the analytical studies. Among the basic parameters, elevation and slope are used most often. More in-depth interpretation was possible due to the implementation of such derivate parameters as Relief, Convergence Index (CI), Topographic Wetness Index (TWI), and Topographic Position Index (TPI) (Wilson, Galant 2000, Conrad 2001, Guth 2003, 2009, Olaya, 2004, Sørensen *et al.* 2005, MacMillian, Shary 2009, Olaya, Conrad 2009). In addition, algorithms to automatically detect relief lineaments (Topographic Grain) were used (Guth 2009).

Karkonosze Mountains – glacial and periglacial landforms revisited

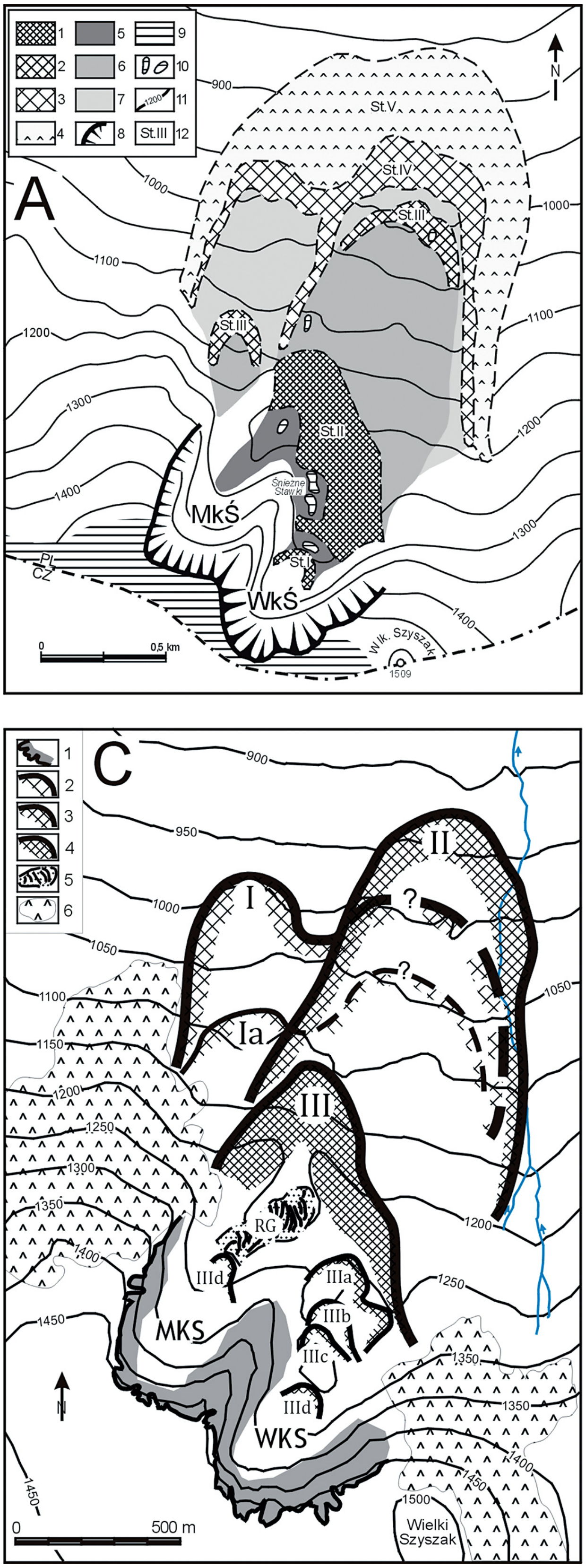
The Karkonosze Mountains, the highest mountain massif within the Sudetes, are the area for which LiDAR data were made available at earliest, in the late 2000s. The spatial pattern of major landforms has long been known and usually explained in terms of differential uplift of an old surface of low relief followed by bedrock-controlled fluvial erosion, locally enhanced by glacial action (Berg 1927, Sekyra 1964). Gross relief features were adequately revealed by the existing small-scale topographic maps (1:50,000; 1:25,000), but the coarseness of contour line presentation seriously limited our ability to identify and map assemblages of minor landforms of glacial and particularly, periglacial origin, often hidden by forest stands and dwarf pine communities. It was somehow paradoxical that despite an extensive research focused on cold-climate geomorphic legacy (e.g. Sekyra 1961, Jahn 1963, 1968), attempts of systematic geomorphological mapping of periglacial features (frost-riven cliffs, solifluction tongues, sorted circles and stripes) have not been made until the 1990s. On a few landform maps from that time their occurrence was indicated schematically and symbolically, without precise location (Cielińska 1961, Sekyra 1964).

The availability of LiDAR data, along with ortophotomaps and advances in GIS techniques, has opened new opportunities for landform mapping. The prime example of using this opportunity is the recent research on glacial depositional terrain on the northern slope of the Karkonosze. Both the Łomnica valley and the forefield of Śnieżne Kotły (= Snowy) cirques were investigated in 1980s and 1990s, through field mapping and interpretation of aerial photographs at 1:15,000 and 1:16,000 scale, resulting in maps showing the extent of glaciated terrain as a whole, as well as the course of individual moraine ridges and the presence of selected landforms of non-glacial origin (Traczyk 1989, Chmal, Traczyk 1999; Fig. 3A).

The maps from the late 20th century were subject to verification using DEM and shaded relief images derived from LiDAR data, by means of on-screen vectorization technique (Traczyk 2009, Traczyk, Woronko 2010). Findings from the new picture for the Śnieżne Kotły area (Fig. 3B) include the following:

- in the younger phase of glaciation the extent of glaciers was probably larger than before and the older moraine ramparts may have been overridden by ice tongues, which extended further to the north-east (Fig. 3C). Today, these older ridges appear to emerge from below the younger depositional terrain. Before, it was suggested that every more recent glacial advance was of shorter extent.
- a relict system of meltwater channels was recognized behind the most distant moraine complex.
- an arcuate hollow within the outer moraine rampart, along with a hummocky ground further downslope, is interpreted as a relict landslide (slump) on the steep flank of the moraine. Widespread landsliding on flanks of terminal moraines is a phenomenon known from many glacierized terrains.
- an apparently chaotic suite of humps, ridges and closed depressions in the floor of the Mały Śnieżny Kocioł cirque resembles landform assemblages left by the decay of a rock glacier. It would have been a glacier-derived rock glacier, formed in the period of advanced deglaciation.

High-resolution elevation data helped in detailed mapping of periglacial landforms too. The effects of research in the western part of the Karkonosze have been reported elsewhere (Traczyk 2007), while Fig. 4 presents the results of periglacial landform mapping on the eastern slope of Mt Śnieżka. The analysis of dense contour map allowed to delimit the extent of mid-slope benches, cryoplanation flats, snowpatch hollows and debris lobes indicating solifluction processes. The previously available ortophotomap, despite its very high



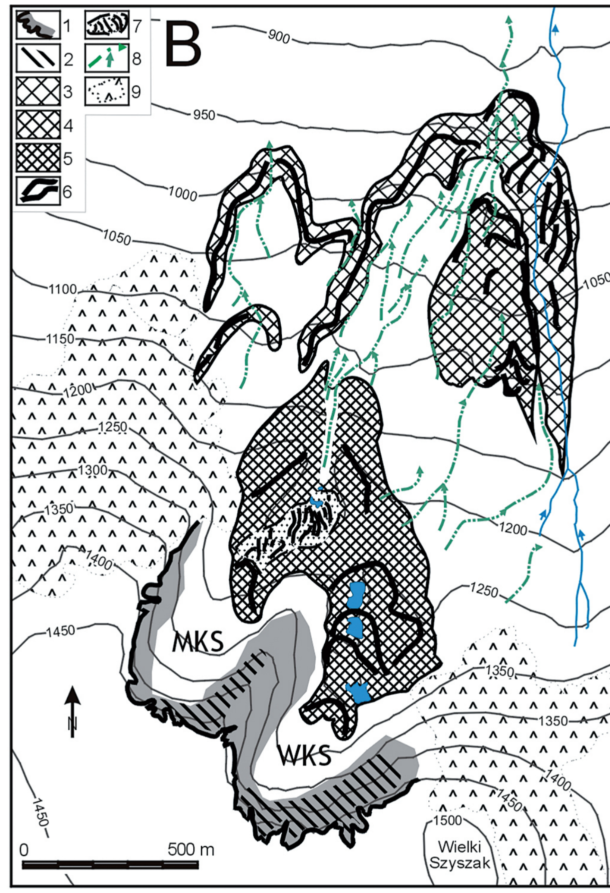


Fig. 3. Past and updated interpretation of the glacial morphology in the front of Śnieżne Kotły cirques

A: Moraine succession after Chmal, Traczyk (1999, modified): 1, 2, 3 – moraine ridges of zones I, II, III (compare with Fig. 3C), 4 – glacial deposition zone from the oldest (?) glaciation of the Śnieżne Kotły, 5, 6, 7 –glacial accumulation domain of zones I, II, III, respectively, 8 – edges of glacial cirques, 9 – summit planation surface, 10 – lakes, 11 – contours every 50 m, 12 – glacial stages after Chmal, Traczyk (1999)

B: Glacial morphology of the Śnieżne Kotły on the basis of topographic maps analysis and LiDAR data (after Traczyk 2009): 1 – edges and cirque walls, 2 – rock slopes within cirque walls, 3 – moraines from the oldest glaciation phase, 4 – moraines from the younger phase of glaciation, 5 –moraines from the youngest phase of glaciation, 6 – crests of moraine ridges, 7 – ridge and hollows morphology (rock glacier?), 8 – ancient melt-water channels, 9 – debris–blocky periglacial slope cover

C: Reinterpretation of glacier extent based on Fig. 3B and DEM analysis: 1 – cirque walls, 2, 3, 4 – successive phases of glaciation (I, II, III) and re-cessional phases (Ia, IIIa – IIId), 5 – probable rock glacier, 6 – block fields. MKS – Mały Kocioł Śnieżny cirque, WKS – Wielki Kocioł Śnieżny cirque

resolution of 0.15 × 0.15 m, proved inadequate to carry out this exercise because of the effect of vegetation and the occurrence of various anthropic landforms resulting from the long history of human presence in the summit part of Mt Śnieżka.

Stołowe Mountains – patterns of mass movement revealed

The uniqueness of the Stołowe Montains as the only elevated tableland on sedimentary formations in Poland

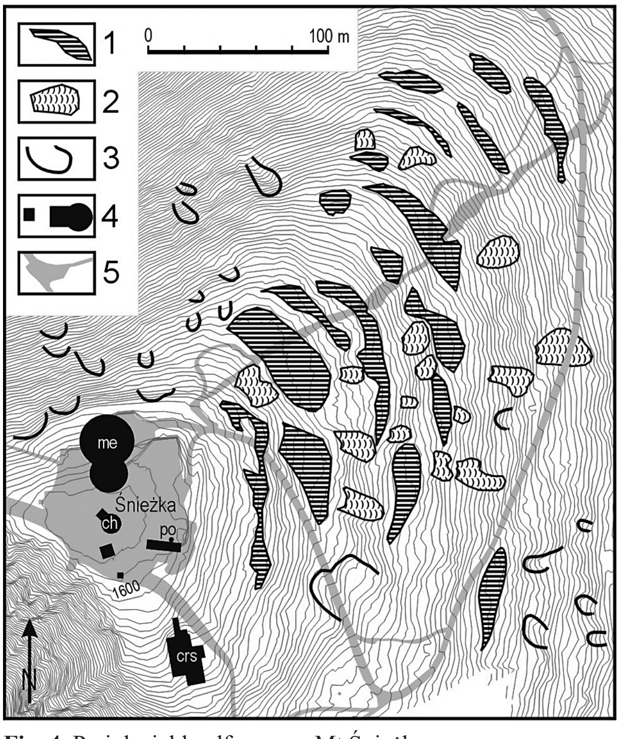


Fig. 4. Periglacial landforms on Mt Śnieżka
1 – cryoplanation terraces, 2 – solifluction lobes, 3 – nivation hollows, 4 – buildings, 5 – roads; me – meteorological station, ch – chapel, po – post office, crs – cable car station. Contour lines every 1 m

(Fig. 5) has long been recognized (Czeppe 1952), but the first comprehensive study of their geomorphology was attempted in the 1970/80s (Pulinowa 1989). Long-term escarpment retreat was widely accepted as one of principal means of landscape evolution but the specific mechanisms involved remained elusive. Sandstone-capped escarpments were explained in terms of a classical model of a concave slope, with free face, debris slope, and wash slope occurring in a downslope succession (Dumanowski 1961).

A new digital elevation model based on LiDAR data has revealed that the surface topography of the middle and toe slopes below the sandstone precipices is significantly more complex than assumed before (Migoń, Kasprzak 2011, 2012, Migoń *et al.* 2011, Kasprzak 2013). Detailed slope profiles are not consistently concave but contain alternating benches and steeper sections, often terminating in distinct bulges in the lower slope. Hence, the topography is wavy rather than planar, with superimposed large sandstone boulders, some as big as 5–6 m. The steps (risers) are rarely straight; more commonly, they follow sinuous courses, locally with lobes projecting downslope alternating with embayments. Such a topographic pattern has been described in detail below the spur of Biała Skała within the northern escarpment (Migoń, Kasprzak 2012),

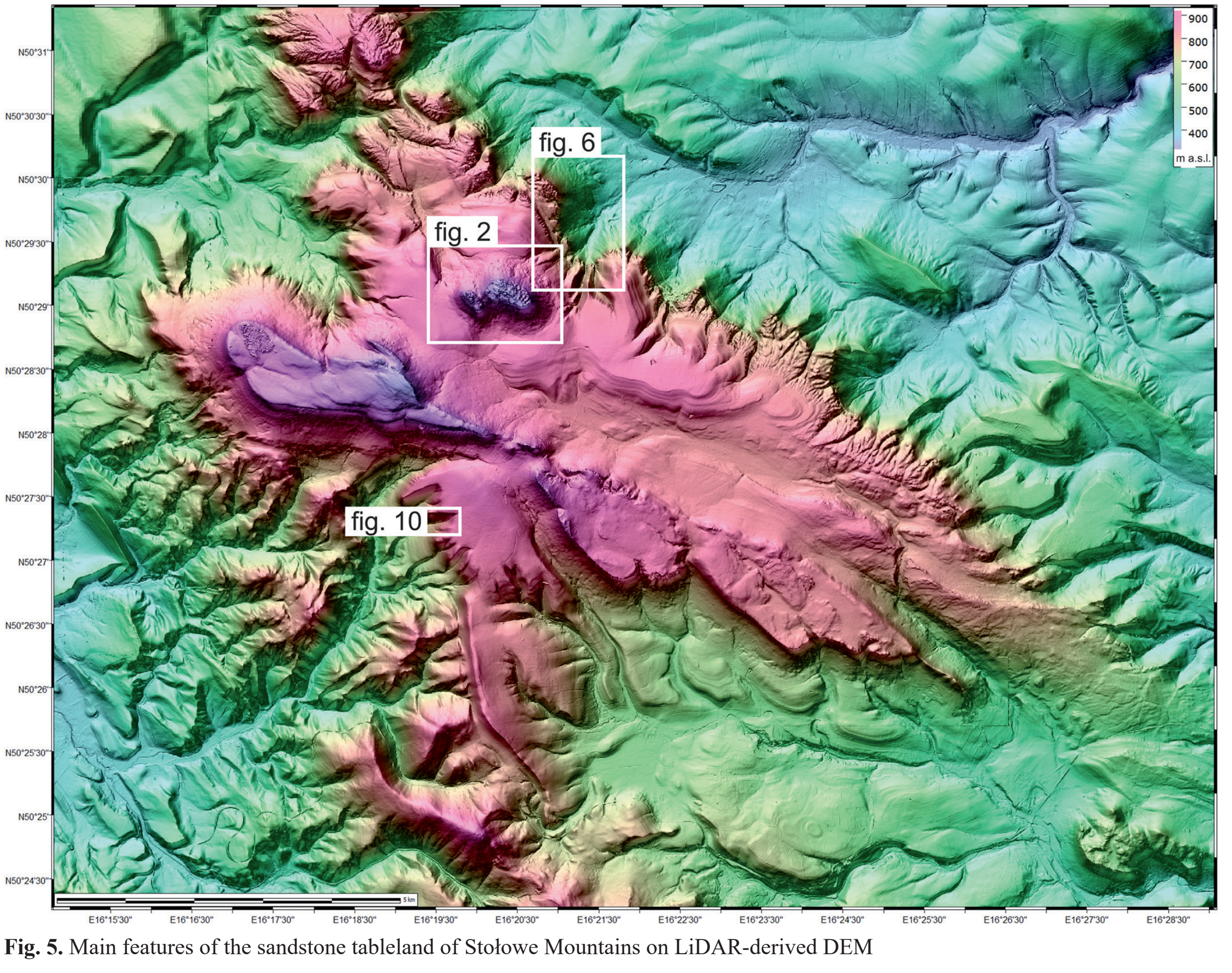


Fig. 5. Main features of the sandstone tableland of Stołowe Mountains on LiDAR-derived DEM

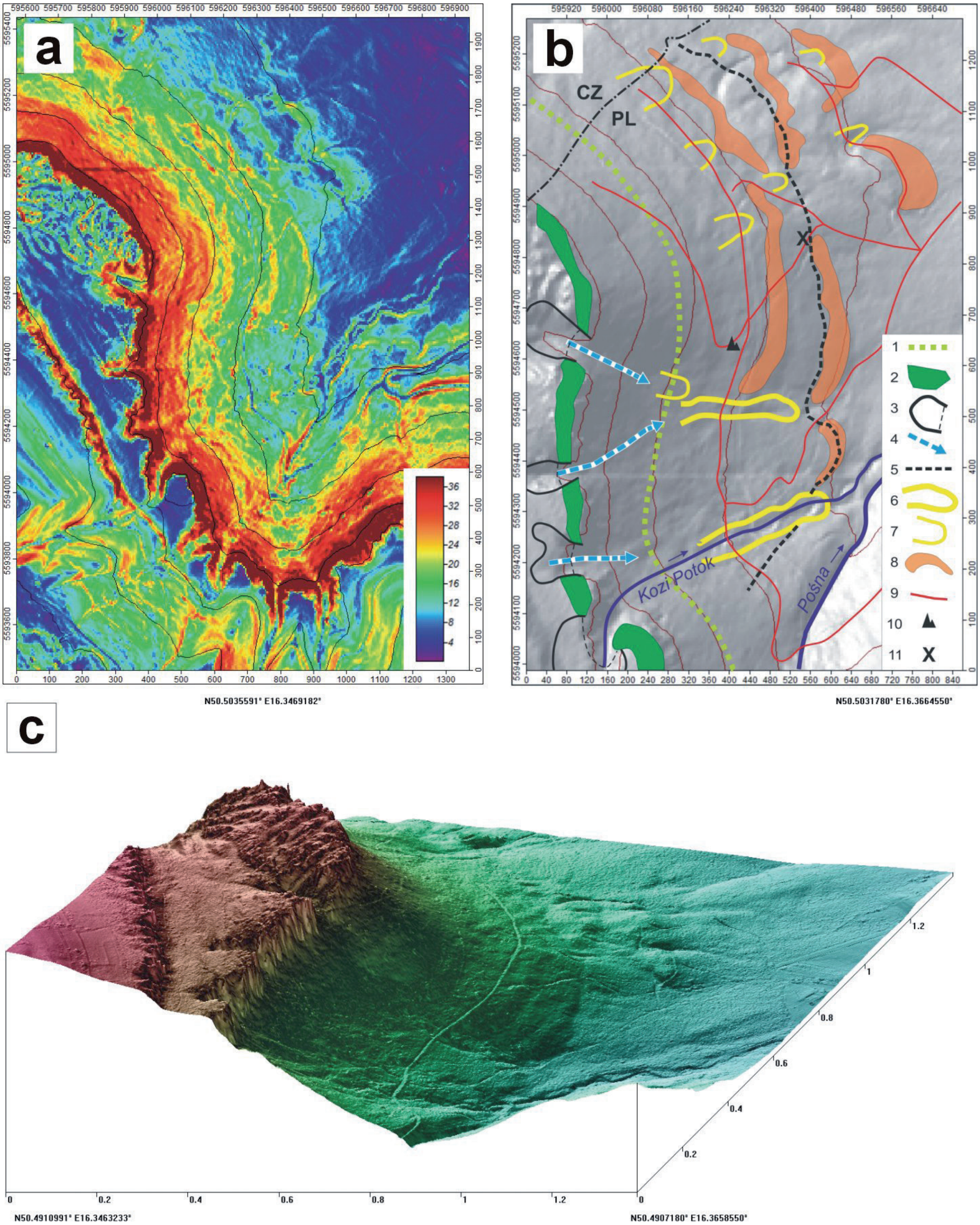


Fig. 6. Escarpment topography affected by mass, Biała Skała, Stołowe Mountains

a – slope map in degrees derived from 1 × 1 m LiDAR DEM, b – geomorphological interpretation, c – visualization (a, b – after Migoń, Kasprzak 2012)
Explanation to b: 1 – Permian/Cretaceous boundary, 2 – sandstone rock faces, 3 – hanging valleys, 4 – drainage lines, without permanent streams, 5 – lower boundary of continuous block cover, 6 – boulder streams, 7 – minor boulder lobes, 8 – landslide frontal scarps, 9 – roads, 10 – isolated rock outcrop, 11 – colluvium outcrop

but it occurs elsewhere too. DEM analysis supported by subsequent field inspection has led us to the interpretation of this landform assemblage as a series of overlapping shallow translational landslides and earth flows (Fig. 6). Hillslope instability was initiated within the lower slope segment, underlain by Permian sedimentary formations

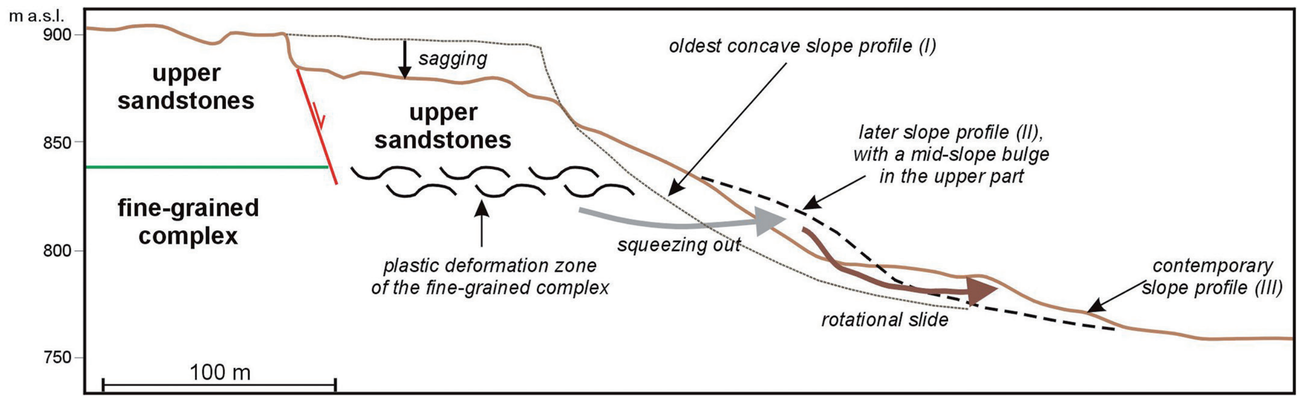


Fig. 7. Interpretation of the mass movement sequence on the eastern slopes of Mt Szczeliniec Wielki (after Migoń, Kasprzak 2011, modified)

(conglomerates, sandstones, mudstones), and propagated upslope, into the Cretaceous. The presence of large sandstone boulders far away from the caprock needs not to be explained by long run-out rock falls but can be plausibly explained by their passive transport atop sliding masses, as on a conveyor belt.

LiDAR proved also immensely useful to decipher the style and probable succession of mass movements on the slope of the mesa of Mt Szczeliniec Wielki (919 m), the highest peak in the Stołowe Mountains. Dumanowski (1961) and Pulinowa (1989) pointed to the north-eastern sector of the mesa as subject to the most widespread deformation, but were unable to provide map details. Ongoing instability along the mesa rim has been confirmed by precise geodetic surveying (Košťák, Cacoń 1988, Cacoń *et al.* 2010). DEM of 1 × 1 m resolution revealed a range of specific topographic features (Fig. 2c) which together combine into a coherent story (Migoń, Kasprzak 2011). First, the north-eastern corner of the mesa, accounting for c. 1/6 of its total surface, is lowered by 15–20 m. A straight topographic step separates the downthrown part from the main plateau. Furthermore, within this lowered portion the sandstone cap is no longer one rock mass. It has broken down into a chaos of huge blocks, more than 10 m long and high, with large caverns between and below them. Second, a distinct arcuate scarp occurs in the mid-slope immediately below the NE part of the mesa, with slope inclination up to 45–48°, whereas the adjacent slope is only 20–30°. Third, in the lower slope sector a series of lobate risers up to 8 m high, covered with large sandstone blocks, extends along c. 300 m perpendicular to the slope.

This geomorphic pattern has been interpreted as follows (Fig. 7). Subsurface denudation at the sandstone/mudstone and marl boundary, both physical and chemical (Pulinowa 1989), resulted in the removal of support for the sandstone cap and sagging of the north-eastern part of the mesa. This induced deformation of the underlying fine-grained formations which were squeezed out, leading to slope steepening, apparently beyond the limits of stability. In consequence, the oversteepened mid-slope failed leaving an arcuate scarp, interpreted as a head scarp of a rotational slide which transformed into an earth slide below. Topography suggests that minor slides of this type occurred next to the main slide. Displaced rock masses came to rest at the footslope (Migoń, Kasprzak 2011).

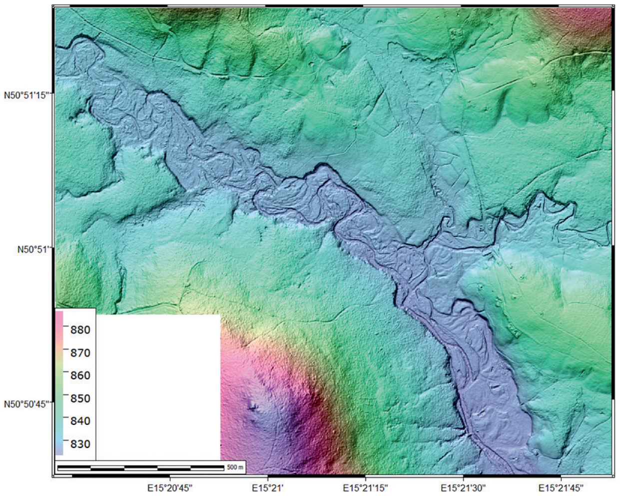


Fig. 8. Shaded relief model of the Izera valley, Izerskie Mountains

Izerskie Mountains

Izerskie Mountains, built of granite in the southern part and gneiss in the northern part, are located in the western part of the Sudetes. Gross topographic features include parallel ridges of WNW– ESE extension, separated from one another by fault-controlled valleys (Oberc 1975, Migoń, Potocki 1996). Specific morphology has developed in the central part of the uplifted block, where a large intramontane basin at c. 830 m a.s.l. exists, with a nearly level floor occupied by peat bogs and the wide meandering valley of the Izera river. Until recently, geomorphology of the Izerskie Mountains has remained relatively under-researched and poorly understood. LiDAR data, covering the highest parts of the mountain terrain, were first used to detect forest health conditions and damage inflicted by flooding (Strzeliński

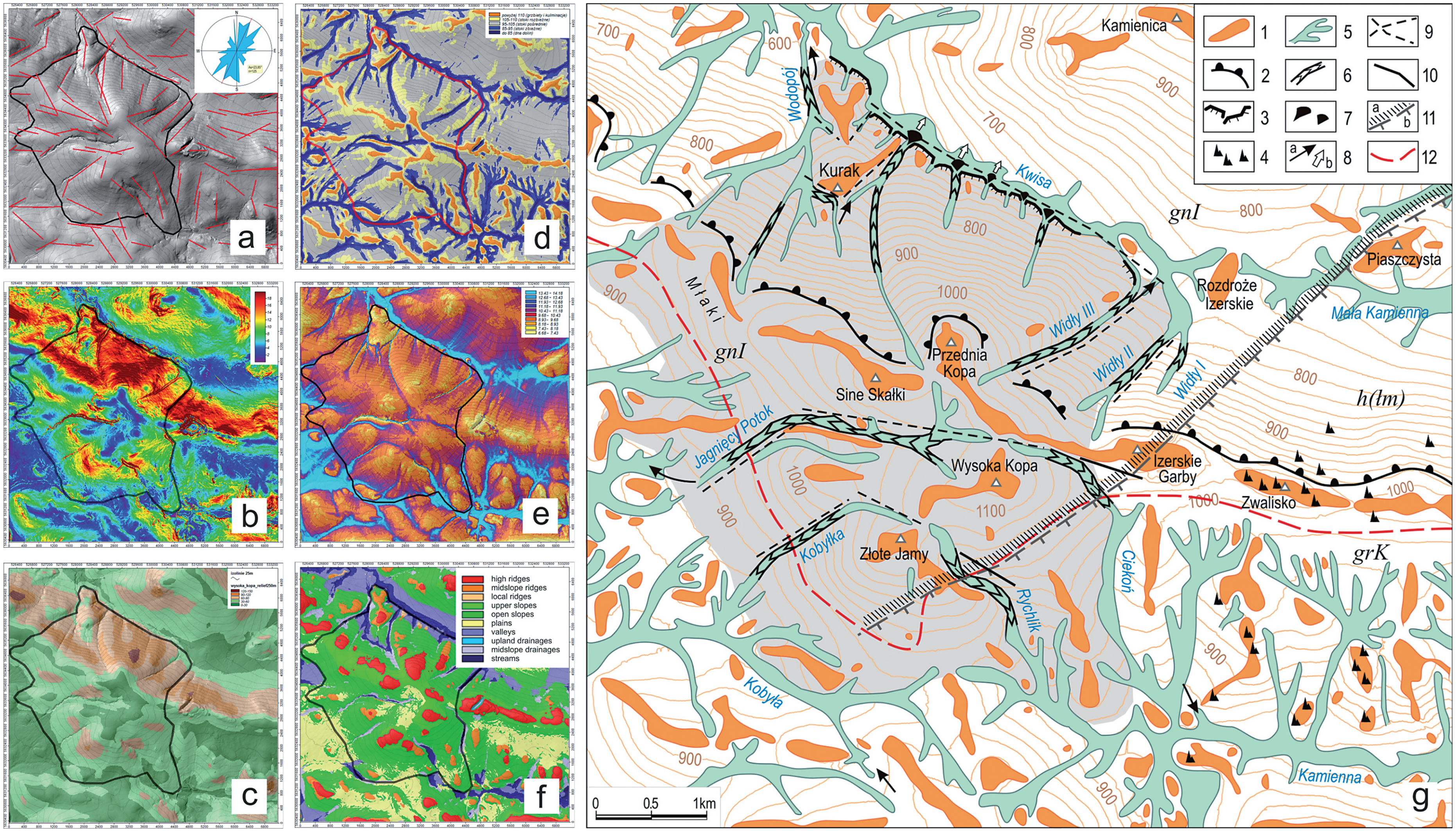


Fig. 9. Results of relief parametrization and interpretation of the highest part of the Izerskie Mountains

a) automatically drawn relief lineaments (MicroDEM topographic grain function), b) slope, c) relief, d) curvature index, e) SAGA wetness index, f) Topographic Position Index, g) geomorphological interpretation

1 – ridges and residual hills, 2 – convex slope break, 3 – fault-generated escarpments, 4 – tors, 5 – valley floors, 6 – fluvial incisions, 7 – alluvial fans, 8 – suspected former flow courses (a) and direction of lateral migration of Kwisa channel (b), 9 – presumed fault of geomorphological significance, 10 – faults mapped on the Detailed Geological Map of the Sudetes 1:25,000, 11 – quartz vein (a) and Rozdroże Izerskie Thrust (b), 12 – granite/metamorphic rock boundary: grK – granite, h(łm) – hornfels and schist, gnI – gneiss and older granite

et al. 2008). Later, very high resolution of bare Earth digital elevation models allowed for detailed mapping of fluvial morphology along the Izera river (Fig. 8) and the recognition of unit reaches with dissimilar erosional and depositional channel features and terrace systems (Kasprzak, Traczyk 2010). In particular, active and abandoned channels of the Izera river and its tributaries, as well as gravel bars, can be recognized, and an opportunity emerges to map the extent of palaeomeanders and their spatial relationships. LiDAR models helped in precise recording of morphometric parameters of meanders, which vary from 13.4 m to 58.5 m, their downstream change, the height of bank undercutting, and the width of terrace levels. Digital elevation models analysed in conjunction with ortophotomaps from different years helped to record and quantify changes in gravel bar dimensions and channel migration. As a final effect, reaches typified by different morphodynamic conditions were recognized (Kasprzak, Traczyk 2010).

Spatial analysis of parameters derived from LiDAR-based elevation models have also allowed us to recognize local relief lineaments (topolineaments) and locate 1st order watercourses, suspect to reflect minor tectonic zones and then subject to statistical analysis of predominant directions (Traczyk, Kasprzak 2012). Further components of the analysis included characterization of slope asymmetry, recognition of slope breaks, evaluation of slope shapes, and automatic classification of landforms. To detect possible fault-controlled topographic features an analysis of Topographic Wetness Index parameter has proved particularly useful. It helped to recognize linear depressions connecting headwater valleys with saddles within water divides, indicating that fluvial erosion exploits zones of structural weakness. These topographic concavities are often perpendicular to one another, further suggesting bedrock control. Other landforms to note are convex elevations and deeply incised V-shaped valleys dissecting mid-slopes, which may be interpreted as the fluvial response to ongoing uplift (Fig. 9).

Limitations, challenges and perspectives for future research

Although it is evident that LiDAR-based digital elevation models have substantially increased our ability to recognize landforms and their spatial patterns in the forested terrain, one should not be uncritical towards LiDAR. Confrontation of image analysis (shaded relief models, slope gradient maps) with ground check during field surveys has revealed several limitations of LiDAR data. In a difficult terrain, steep and covered by dense forest stands, topographic details are not adequately captured even if the preset density of measured points is 3–4 per 1 m^2. For instance, in the Stołowe Mountains LiDAR-derived models failed to return clusters of large (3–4 m long) sandstone boulders in a deeply incised ravine below Mt Rogowa Kopa (Fig. 10), whereas boulders of similar size can be identified elsewhere, on a flat ground. Surface morphology of the sagged eastern portion of the mesa of Mt Szczeliniec Wielki (see section 5) has not been returned either. Thus, the absence of minor elements of relief in specific places on LiDAR images is not necessarily the evidence of absence in reality and hence, conclusions about landform spatial distribution may not be correct. In the Karkonosze Mountains too, 4–6 m appears as a size threshold limit for safe identification of individual landforms, which leaves granite residual boulders, details of blockslopes, minor erosional landforms and minor anthropic elements below the limit. On the other hand, linear features usually appear very clearly even if the depth and width are of the order of 1–2 m (e.g. drainage ditches, risers of agricultural terraces, minor erosional incisions, crests of moraine ramparts). In areas above the timberline and stripped of forest orthophotomaps are indispensable and interactive tools to draw topographic profiles prove most useful. In the dwarf pine belt, which includes significant portions of the flat summit surface, artifacts left after removal (filtering out) of dwarf pine stands may be of similar size and shape as some minor relief features observed on peat bog surfaces (Klementowski 2008). An important comment here is that the accuracy of LiDAR

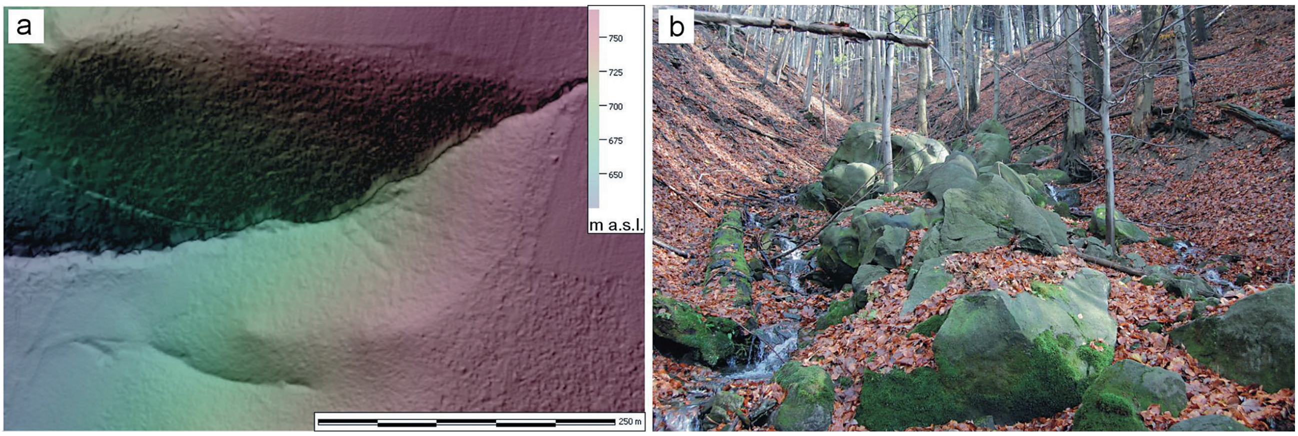


Fig. 10. Comparison of shaded relief model based on LiDAR data for a deeply incised valley and a ground photograph; the cluster of big sandstone boulders, despite their size, is not visible on the LiDAR image

data in all our exercises was beyond our control, as databases were acquired from external sources.

Our experience also tells us that an increased resolution does not necessarily mean more information. Submetric resolution proves very helpful in the recognition of minor landforms and their relation to local bedrock controls, but introduces too much information noise if more regional patterns are the focus of research. For relief parametrization we usually re-interpolate elevation models to 10 × 10 m resolution or less. This data preparation allows us to remove small surface features which are not relevant to the scope of the analysis (e.g. single boulders, minor steps in slope morphology, model imperfections, mainly in forest areas), makes it possible to reduce the size of a dataset and speeds up geomorphometric calculations to obtain a synthetic result of landform parameterization at a regional scale. An issue closely related to the volume of data is computational power of PCs which may not be sufficient to handle large datasets effectively. For example, the size of DEM (.ASC file) in 1 × 1 m resolution (1,612 columns, 1,350 rows) used to create Fig. 9 is 16,350 kB, while the reduction of resolution to 5 × 5 m (322 columns, 270 rows) yielded a 704 kB file, and further reduction to 10 × 10 m (161 columns, 135 rows) only a 176 kB file. Thus, the size of files decreases exponentially.

Perspectives for further research using airborne LiDAR are very promising. Since early 2013, LiDAR data are widely available at reasonable cost, due to the implementation of ISOK programme. Although the coverage of the territory will not long be complete, critical areas such as mountainous terrains, large river valleys and major cities are or will soon be covered. This opens new opportunities for landform recognition, especially in difficult terrains such as the Sudetes, and may generate new interest in regional geomorphological mapping. Likewise, LiDAR data will be an invaluable addition to the geomorphological toolkit in a range of specific problems.

Conclusions

The long history of geomorphological research in the Sudetes, within which landform mapping was an important component, might generate an impression that any contribution to landform recognition would be minor. This has proved incorrect. The arrival of high-resolution LiDAR data, which can be used to create detailed digital elevation models and to carry out advanced geomorphometric analysis, has opened new avenues of research and provided solid basis to re-evaluate landforms known before. The ability of LiDAR to remove vegetation before further analysis is particularly useful in densely forested terrains such as the Sudetes. Recent advances arising from the use of LiDAR include landform-based reinterpretation of local glacial history in the Karkonosze Mountains, refinement of periglacial landform inventories, deciphering patterns of mass movements along sandstone capped escarpments in the Stołowe Mountains, recognition of complex fluvial morphology of mountain valleys, and new morphotectonic interpretations. However, as far as possible, image interpretation should be verified in the field. Despite theoretical capability of LiDAR-derived models to show even landforms 1–2 m in length/height, 4–6 m seems the more realistic threshold size unless these landforms are distinctly linear and continue over long distances. Thus, the absence of certain surface features on LiDAR images should not be automatically explained that they do not exist.

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