S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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GEOMORPHOLOGICAL CHARACTERISTICS OF AVALANCHE TRACKS ON BABIA GÓRA MT., WESTERN CARPATHIANS

Abstract: Distribution and parameters of avalanche tracks on the slopes of asymmetric ridge of Babia Góra Mt. (1725 m a.s.l. – the highest massif in the flysch Western Carpathians) were studied in relation to slope relief, prevailing wind directions, snow cover thickness, treeline and timberline locations. The following sections of avalanche tracks were distinguished: starting zone, track zone and runout zone. The entire course of each track was described using the following parameters: the elevation [m a.s.l.], vertical drop Δh [m], maximum and mean inclination α [°], length on slope L [m]. The relationships between these parameters were analyzed on slopes of straight, concave, step-like and convex profiles. The character of starting zone (from a point or a line) and the form of avalanche track (confined or unconfined) were determined. Values of sinuosity index [%] were calculated. The longest avalanche tracks (>300 m, locally >800 m) occur on convergent slopes of different profiles with domination of straight once. 75% of avalanche tracks exceed the treeline causing lowering of the timberline by over 200 m. On divergent slopes, avalanches are not present. The most frequent are avalanche tracks of mean slope inclination in the range 26–40°. The application of LiDAR data and their linkage with field work investigations made it possible to reveal that the number of avalanche tracks on Babia Góra Mt. and their dimensions are greater than it was so far assumed. Their main concentration was determined on the steep northern slope of straight, concave or step-like profiles.

Keywords: avalanches, timberline, spruce forest, dwarf mountain pine, Babia Góra Mt., the Carpathians

INTRODUCTION

In mountain massifs, especially those elevated above timberline level, avalanches develop on slopes with windblown snow (Kłapowa 1969; Kwiatkowski 1985; McClung 2003; Sekiguchi, Masanori 2003; Sekiguchi et al. 2005; McClung, Schaerer 2006; Rączkowska et al. 2016; Voiculescu et al. 2016). The origin of avalanches depends on cumulative influence of many factors including the thickness of snow cover overlying the older snow of larger density and also weather conditions favouring snow sliding (Kłapa 1959; Kłapowa 1969; Birkeland, Mock 1996; Keylock 1997; Mock, Birkeland 2000; Esteban et al. 2005; McClung, Schaerer 2006; Rączkowska et al. 2016). In avalanche tracks, three sections may be distinguished:

a starting zone, a track zone and a runout zone, and each of them is described by the following parameters: elevation [m a.s.l.], vertical drop Δh [m], maximum and mean inclination α [°], length on slope L [m], form of longitudinal profile (convex, concave), character of starting zone (from a point or a line), form of avalanche track (confined or unconfined), sinuosity index [%] (Schweizer et al. 2003; McClung, Schaerer 2006; Eckerstorfer, Christiansen 2011, 2012; Voiculescu et al. 2016). Possibilities of avalanche development are limited in different extent by vegetation cover (thick or thin forest, dwarf mountain pine bushes, grass, rock walls or grass-free stone block fields) (Birkeland, Mock 2001; McClung, Schaerer 2006; Voiculescu et al. 2016). One of the direct effects of snow avalanche activity is lowering of a timberline (Bebi et al. 2009). Geomorphological features of slopes which are most favourable for development of avalanches are evaluated in the literature in different ways. For example, slope inclinations susceptible to avalanche development according to different authors are in the range 35–45° (Sekiguchi et al. 2005), 22–65° (Luckman 2010). There is no information concerning the most favourable slope profile for avalanche development.

In Poland, avalanches are most frequently recorded in the Tatras (2499 m a.s.l.) and in the Karkonosze Mountains (1602 m a.s.l.) (e.g. Kłapa 1959; Kwiatkowski 1985). Avalanche tracks in these massifs run along steep slopes of various length, mainly in the areas re-modelled by former glaciers. In the Polish Carpathians, avalanches are also observed on Babia Góra Mt. (1725 m a.s.l.), in smaller extend on the highest ranges of the Western Bieszczady Mountains (1346 m a.s.l.), and locally on Pilsko Mt. (1557 m a.s.l.) (Łajczak 2004, 2015). The largest number of publications on meteorological and geomorphological conditions of avalanches concerns the Tatra Mountains (e.g. Kłapa 1959; Kłapowa 1969; Gądek et al. 2016; Rączkowska et al. 2016) and the Karkonosze Mountains (e.g. Kwiatkowski 1985). Studies on avalanches on Babia Góra Mt. are less advanced. First more detailed publications on avalanches in the massif concerning the hazards of tourist trails are quite recent (Łajczak 2004, 2016; Łajczak et al. 2015). First morphometric investigations concerning the course and frequency of snow avalanche occurrence were carried out with application of dendrogeomorphological and spatial analyses using GIS tools (Czajka et al. 2015a, b). As opposed to the Tatras, where monitoring of avalanches started in the 1950s (Kłapa 1959; Kłapowa 1969), systematic observations of avalanches on Babia Góra Mt. have not been carried out.

This paper contains analyses of distribution and parameters of avalanche tracks on the slopes of Babia Góra Mt. of various exposures in relation to predominant wind directions and snow cover thickness. Main attention was paid to geomorphological analysis of avalanche tracks. The following types of slopes were taken into consideration: straight, convex, concave, step-like, and also convergent and divergent slopes.

STUDY AREA

Babia Góra Mt. (1725 m a.s.l.) is the highest massif in the flysch Western Carpathians and it is elevated about 400 m above the timberline, and from 200 to 600 m above the adjacent mountain peaks. The northern slope and the eastern part of the southern slope of this massif are located in Poland and the other part is located in Slovakia. Next to the Tatras, Babia Góra Mt. is the second highest massif in Poland, and the third in the whole Western Carpathians (including the Slovakian part) (Fig. 1A). Babia Góra Mt. with the relative altitude of 1100 m is formed as a 10 km long monoclinal and asymmetric ridge of W-E course (Fig. 1B). The ridge above 900–1000 m a.s.l. is built of resistant layers of Magurskie

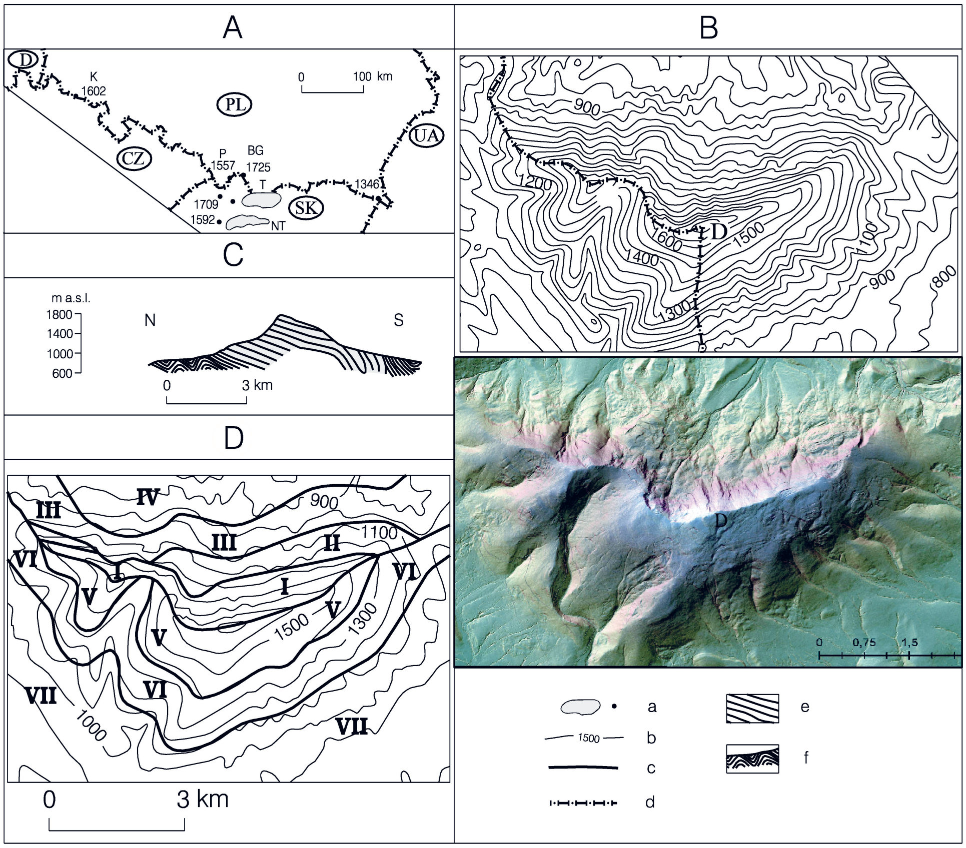


Fig. 1. Study area. A – location of Babia Góra Mt. (BG) against the background of Polish-Slovak border, B – Babia Góra Mt. in contour-line map and in elevation model from LiDAR data, C – schematic geological profile of Babia Góra Mt., D – determined parts of the massif (for explanations I–VII see the text). T – the Tatras, NT – the Low Tatras, P – the Pilsko Mt., K – the Karkonosze Mts., D – Diablak (summit of Babia Góra Mt.). a – mountain massifs where avalanches occur, b – contour-lines, c – limits of determined parts of Babia Góra Mt., d – state borders, e – Magurskie sandstone, f – Sub-Magurskie layers

sandstone dipping south whereas the lower part is built of Submagurskie layers (Fig. 1C), (Książkiewicz 1983)

The following mesoforms were determined within the northern slope of Babia Góra Mt. (Fig. 1D): I – abrupt part of the cuesta, II – foot of the clif, III – zone with headwater areas, IV – lower part of the slope dissected by valleys, and within the southern slope: V – gently sloping upper part of the slope, VI – zone with headwater areas, VII – lower part of the slope dissected by valleys. The cuesta is inclined at 40° and locally at 70°, and the area located at the foot of this abrupt is inclined at 20–30°. This slope located on the substratum of Magurskie sandstone shows a concave profile. The inclination of lower located middle zone of the slope embracing the contact of Magurskie sandstone and Sub-Magurskie layers increases to 30–40°. The southern slope of Babia Góra Mt. shows a convex profile along the section concordant to the dip of Magurskie sandstone layers. Its upper part is inclined at 20° and the middle part at 30–40°. The middle zones of the northern and southern slopes of Babia Góra Mt. are dismembered by headwater areas showing convex or straight slopes, and at the foot of the massif by river valleys. On the northern slope, the location of headwater areas does not exceed the altitude of 1100 m a.s.l. and only in its western part they reach 1350 m a.s.l. Above the headwater areas there is a 600 m high zone of the slope dismembered by landslide headwalls, corries and couloirs. On the southern slope, the headwater areas reach the altitude of 1400 m a.s.l. and in its western part they reach the axis of the massif ridge. The slopes of Babia Góra Mt. are extensively modelled by landslides which develop on Magurskie sandstone and belong to deep-seated type (Alexandrowicz 1978, 2004; Książkiewicz 1983; Łajczak 2014; Łajczak et al. 2014). In such areas ridge and slope troughs occur as well as rocky headwalls and vast distensions of block colluvia deposits. On the steep northern slope, rocky couloirs with torrential cones occur.

Babia Góra Mt. is located within five climatic vertical zones determined by values of mean air temperature (Hess 1965) (Fig. 2A): a1 – temperate warm, a2 – temperate cool, a3 – cool, a4 – very cool, a5 – temperate cold. Total precipitation increases on the northern slope from 1100 mm at the altitude 700 m a.s.l. to 1500 mm at the altitude 1200 m a.s.l. and decrease to 1200 mm at the altitude 1600 m a.s.l. On the southern slope the total precipitation is lower by 20% than on the northern slope (Obrębska-Starklowa 1963). During the period of snow cover occurrence which lasts in the vertical profile of the massif from 4 to 6 months, total precipitation makes 1/3 of the annual precipitation. Vegetation vertical zones correspond to the climatic vertical zones (Celiński, Wojterski 1978) (Fig. 2B): b1 – submontane forest, b2 – lower montane forest, b3 – upper montane forest, b4 – dwarf mountain pine zone, b5 – alpine meadows. The two highest located vegetation zones represent subalpine belt and lower located zones make up a forest belt of Babia Góra Mt. which borders to deforested and agriculturally used foot of the massif. Almost all the headwater areas

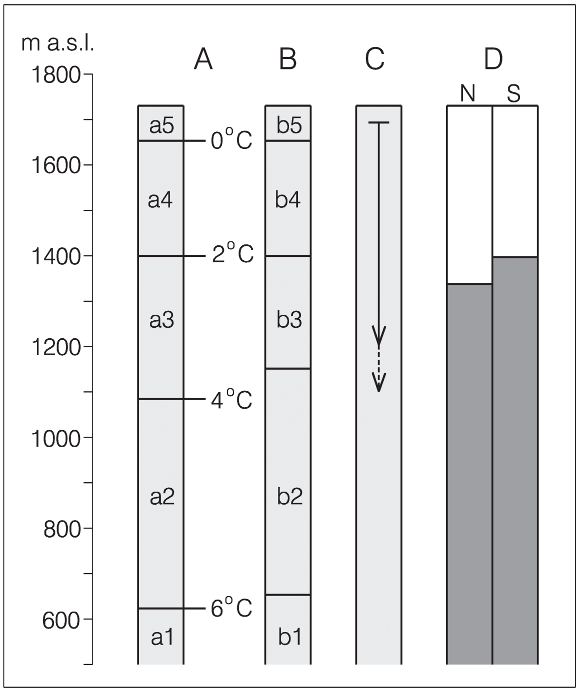


Fig. 2. Climatic vertical zones (A) and vegetation vertical zones (B) on Babia Góra Mt., C – cited in the literature altitudinal range of avalanches on the northern slope of the massif; the longest limit of avalanches is marked, D- mean altitude of a timberline on the northern and southern slopes. For explanations a1–a5 and b1–b5 see the text

on the northern slope occur within the forest belt whereas headwater areas on the southern slope are mostly located in the subalpine belt.

Mentioned in the literature avalanches on Babia Góra Mt. concern only the northern slope where they occur within the dwarf mountain pine zone and the upper part of upper montane forest, and locally reach the upper part of lower montane forest (Hudziak 1987; Łajczak 2004, 2016; Czajka et. al. 2015b) (Fig. 2C). This altitude zone of the massif comprises cool and very cool climatic belts where total precipitation during the period of snow cover occurrence reaches 500 mm. The timberline on the northern slope is located at the average altitude of 1335 m a.s.l., whereas on the southern slope it occurs 60 m higher (Fig. 2D).

METHODOLOGY

The main source of information concerning the number and extend of avalanche tracks on Mt. Babia Góra (both on the Polish and Slovak parts of the massif) are archival (1964–1965) and contemporary (2009) aerial photographs and data from aerial laser scanning (LiDAR) taken in 2012 with density of 6 points per 1 m^2.

The determined position of timberline (Czajka et al. 2015a, b; Kaczka et al. 2015a, b) indicates its lowered position in places where, similarly as in e.g. the Tatras, avalanches run down counteracting the succession of spruce forest up to the altitude delimited by the treeline. The physiognomy of the forest edge on both sides of the lowered timberline is characterized by the occurrence of secular, high spruce trees representing a peculiar "wall of trees" without a transition zone typical for a timberline and a treeline (Fig. 3).

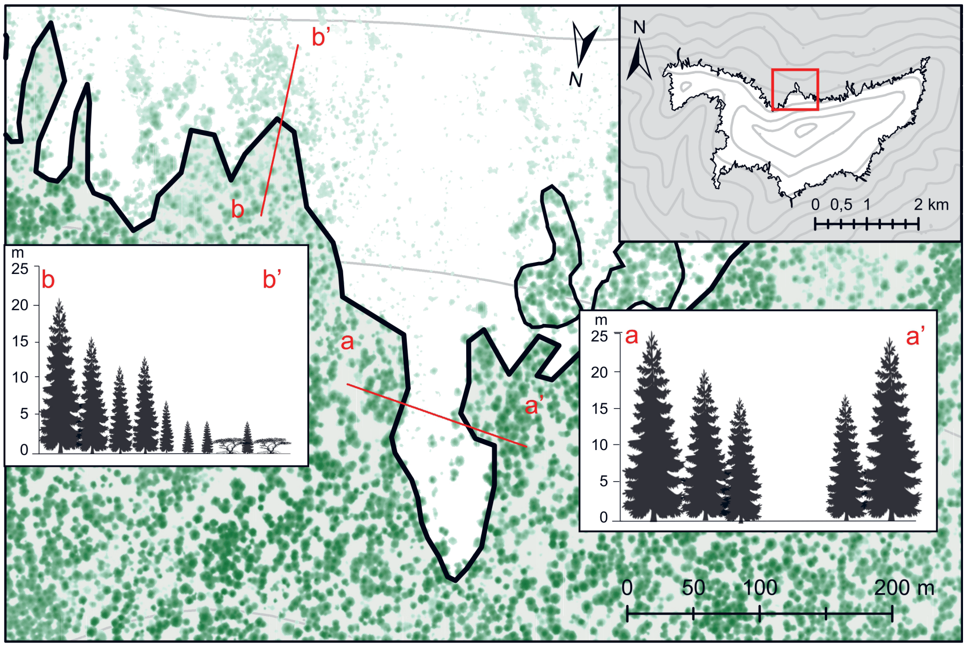


Fig. 3. An example of the timberline impacted by avalanches with a characteristic type of spruce forest and dwarf mountain pine bushes physiognomy at the limit of avalanche track

In the area of lowered timberline, large trees overthrown by avalanches commonly occur and in the places where they used to grow, the saplings of spruce and rowan start to grow usually between thick bushes of dwarf mountain pine. The mentioned character of forest boundary is typical for avalanche tracks (Kaczka et al. 2015b). The course of timberline makes it possible to apply high-resolution detection of long avalanche tracks, but it is not possible to detect short tracks in subalpine belt (Spyt et al. 2016). The limit of all avalanche tracks is shown by location of avalanche snow deposits observed by the authors even in late spring, whereas in surrounding areas the snow has already melted. The application of all these methods created a complex approach which was introduced to evaluate the length of individual avalanche tracks which enabled the authors to determine what percent of avalanches reaches the morphogenetic zone of temperate forest system.

The location of timberline and all the determined locations of snow avalanche deposits were placed on geomorphological map of Babia Góra Mt. at a scale 1:5000 (included in Łajczak 1998) and on Digital Terrain Model, Slope Map, Shaded Relief Model accomplished basing on LiDAR data. This was a base to determine the location of geomorphological sections of timberline of lowered disposition.

Since 1997, numerous measurements of snow depth have been carried out using avalanche sounder along forest roads, tourist trails and other places on Babia Góra Mt. (Łajczak 2004, 2016). The results of these measurements made it possible to determine the areas of reduced snow cover, places of increased snow cover, and also places where snow cornices develop below which potential conditions for snow mass detachment may occur (Fig. 4A,B). In places of the thickest snow cover its depth was determined using levelling method in relation to characteristic objects (marked rocks and trees) which was repeated after snow cover melted. The analysis of snow depth was linked to directions of predominated winds, especially in winter season, at different elevations on Babia Góra Mt. and the neighbouring Pilsko Mt. (e.g. Obrębska-Starklowa 1963;

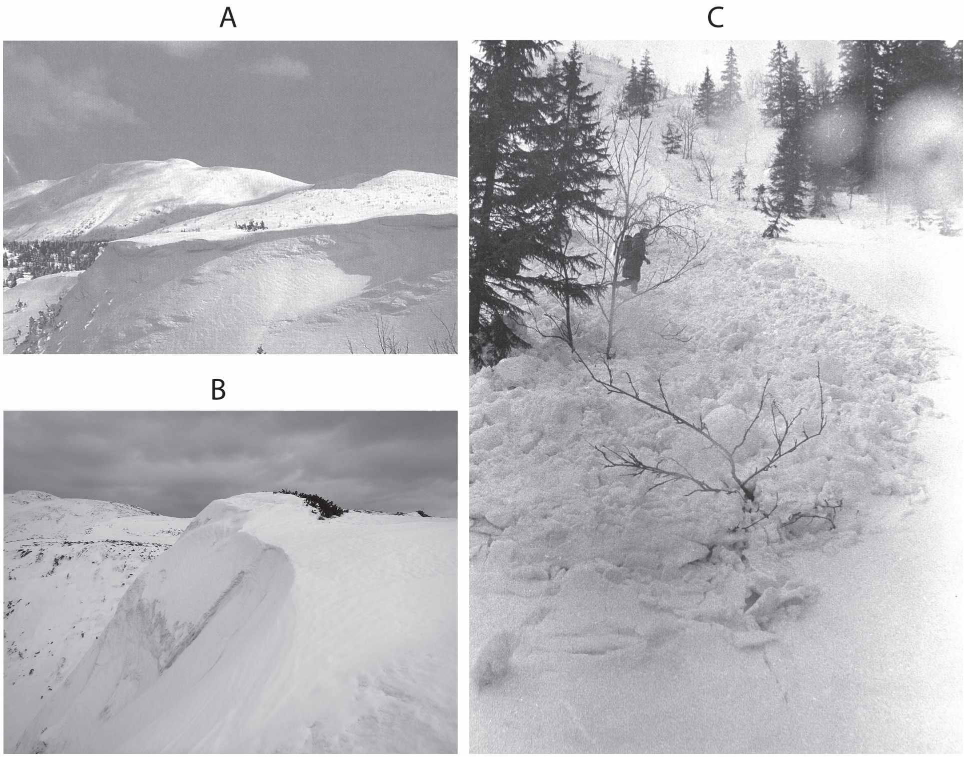


Fig. 4. Snow cornices at the northern edge of the ridge plateau of Babia Góra Mt.: A – Brona Pass (1409 m a.s.l.), B – Kamienna Dolinka headwall (1600 m a.s.l.). C – avalanche on the northern slope below the Brona Pass

N i e d ź w i e d ź et al. 1985; Ł a j c z a k 1996). During the field work a few "fresh" avalanches, usually of small dimensions, were observed (Fig. 4C). Large amounts of avalanche snow were observed in late spring above the sites with lowered timberline disposition and also in some places in the subalpine vertical zone.

Based on photointerpretation of aerial photographs and field observations, the locations on the slopes of Babia Góra Mt. were determined where avalanche tracks start and finish. Their disposition was compared with geomorphological map of Babia Góra Mt. and with high-resolution digital elevation models. This was the base to determine which slope profile (straight, concave, step-like, convex) and also the character of slopes (convergent, divergent) occur in the area occupied by individual avalanche tracks and additionally their sections (starting zone, track zone, runout zone). The next stage of investigation was to find out what types of landforms occur along these sections of individual avalanche tracks. This made it possible to classify them into a confined or unconfined avalanche tracks. The character of sections of the starting zone of each avalanche track was defined as from a point or a line fracture. Based on cartometric analysis the parameters of individual avalanche tracks were determined (excluding their individual sections), i.e. elevation [m a.s.l.], vertical drop Δh [m], mean and maximum inclination α [°], length on slope L [m], sinuosity index [%]. The last parameter was determined as a ratio of real length of an avalanche track to a length of a stretch joining the start and the end points of the track.

RESULTS

NATURAL DETERMINANTS INFLUENCING AVALANCHES ON BABIA GÓRA MT.

A typical feature of snow cover on the Babia Góra Mt. is increasing contrast during winter between the snow depth on the northern and southern slopes, mainly because of snow being wind-blown towards the north and east. Fig. 5A shows windroses on the foot of Babia Góra Mt. and on the summit area of the neighbouring Pilsko Mt. in January and in the whole year, and on the northern slope of Babia Góra Mt. in the whole year including intervals of wind speed (O b r ę b s k a-S t a r k l o w a 1963; N i e d ź w i e d ź et al. 1985; Ł a j c z a k 1996). In each topographic situation in the area studied, winds from S, SW and W directions predominated, especially in winter season. Strong winds (10–15 $m \cdot s^{-1}$) blow only from S and SW directions (O b r ę b s k a-S t a r k l o w a 1963). Because wind speeds are the highest on Babia Góra Mt. and Pilsko Mt. in winter, strong winds from the S, SW and W are considered to be most responsible for snow dislocation from the southern slope to the northern slope of Babia Góra Mt. (Fig. 5B). Wind-blowing of snow from vast areas of higher elevated and gently sloping part of the southern slope of the massif is facilitated by the fact only dwarf mountain pine bushes and high-mountain grasses cover this area (see Fig. 1, Fig. 2). The blown snow is accumulated on the northern slope down to the timberline

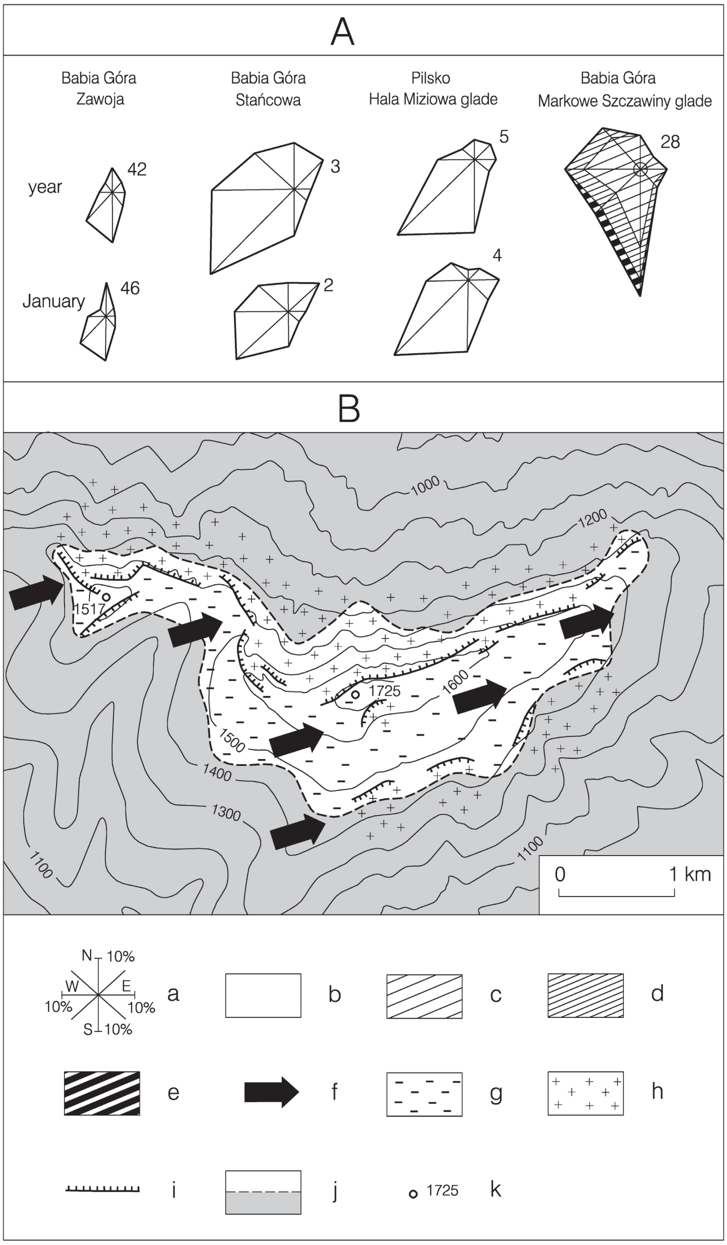


Fig. 5. Climatic and geomorphological conditioning of snow depth in the upper part of Babia Góra Mt. in March. A – windroses for the whole year and for January: northern (Zawoja) and southern (Stańcowa) foot of the massif, northern slope of the massif (Markowe Szczawiny glade), northern slope of the adjacent Pilsko Mt. (Hala Miziowa glade). Values at windroses show percentage of number of days with calm air in a year and in January. B – differentiation of snow depth. a – wind directions. Wind speed only on the northern slope: b – ≤1 m/s, c – 2–5 m/s, d – 6–9 m/s, e – ≥10 m/s. f – predominant direction of snow blowing, g – areas with reduced snow depth, h – areas with increased snow depth, i – snow cornices, j – treeline, k – massif elevations

adjacent areas, especially at the edge of the ridge plateau, where long snow cornices develop (see Figs 4A, 4B, 5B). Snow accumulation is also very extensive in deep landslide troughs and headwalls and also in couloirs in the subalpine belt. Snow brows along the northern edge of the ridge plateau develop during each winter along the whole length of the ridge above the timberline. On the southern slope of Babia Góra Mt., accumulation of wind-blown snow takes place only along the edges of headwater areas and the deepest landslide headwall in the subalpine vertical zone (see Fig. 5B).

Predominating direction of snow blowing, lower winter precipitation and higher evaporation of snow cover on the southern slope cause that snow cover thickness before spring thawing is larger on the northern slope. According to E. Hudziak (1987) just in this phase of snow cover occurrence (March, April) avalanches are most common on Babia Góra Mt. During the last two decades, in March, the thickness of snow cover on the northern slope increased from 0.5 m at the altitude of 700 m a.s.l. to 3.0 m at the altitude of 1300–1400 m a.s.l. Above this level it was differentiated reaching 10 m in deep headwalls. Along the ridge plateau the snow depth did not reach 0.5 m and locally it was not continuous. On the southern slope of the massif the snow cover thickness was about twice as thin as the cover on the northern slope and only in headwalls it locally reached 10 m (Łajczak 2004, 2016). The snow depth in cornices at the northern edge of the ridge plateau and above headwater areas on the southern slope was estimated to at least 5 m (see Fig. 4A,B).

The shape of slopes in the part of Babia Góra Mt. built of Magurskie sandstone reflects long-term development of the relief and is conditioned by the substratum structure (Łajczak 2014). Therefore, along the northern slope of the massif, starting from the edge of the ridge plateau, first, zones of straight profile predominate, lower, at the base of the precipitous part of the cuesta, concave profiles predominate, and below the timberline, step-like profiles commonly occur. Only in the areas modelled by a deep-seated landslides, even the highest located parts of the slope show step-like profile. Lower located headwater areas of steep slopes and convex or straight profiles are separated from timberline in this part of the massif by wide forest zone of altitudinal distance of over 300 m. In the western part of the northern slope of the massif, the headwater areas with slopes of straight profile exceed the timberline. The upper part of the southern gently inclined slope of Babia Góra Mt. shows a straight profile and only in the areas with deep-seated landslides the profile is step-like. Lower, in the altitude zone with vast headwater areas, the slope profile is convex (see Fig. 1). Headwater areas in this part of Babia Góra Mt. usually occur above the timberline.

Steep convergent slopes, the most favourable for development of long avalanches, embrace headwater areas on both sides of the massif partly located in subalpine zone and also two vast concave forms showing features of glacial transformation located in this zone on the northern slope. Another avalanche-favouring feature is the shape of the northern wall of the massif on the eastern side of the culmination where numerous rocky couloirs occur on a long slope of straight profile and inclination over 40°. On the other hand, divergent slopes in the subalpine belt not favouring avalanche formation include boundary zones of headwater areas, and sub-boundary areas of convex glacially re-modelled forms on the abrupt northern slope.

LOCATION OF AVALANCHE TRACKS VERSUS TIMBERLINE

57 mapped avalanche tracks have been recorded on Babia Góra Mt. (44 on the northern slope and 13 on the southern slope) (Fig. 6A). The starting zone of each avalanche track is delimited by a line with snow cornices on the slope and its runout zone is delimited by a depression in timberline which is located below areas with avalanche snow deposition. 10 short avalanche tracks, up to 160 m long, occurring within the subalpine zone do not reach the timberline and their limit is assessed by a location of avalanche snow deposition. On the northern slope, the lines of snow cornices occur just below the edge of the ridge plateau, whereas on the southern slope they are located 50–250 m below this edge. Avalanches develop each winter but in the succeeding years the deposition of avalanche snow is observed in various places above the depression in the timberline. Every dozen or so years the avalanches reach the timberline but hardly ever exceed this line; if so they are a hazard for popular tourist track called "górny płaj" (Łajczak et al. 2015). The most exceptional avalanche limit for the last three decades was the one which occurred in March 1987 in Cylowy Potok valley (Fig. 6A, western part of the northern slope); snow deposits at the altitude 1070 m a.s.l. were located 36 m below the most lowered in that place timberline of Babia Góra Mt. (Czajka et al. 2015b) and melted in the end of July (Hudziak 1987).

The timberline on the northern slope of Babia Góra Mt. in the places of avalanche occurrence is lowered by 230 m and on the southern slope by 130 m in relation to the average altitude of the timberline on both slopes. 45 avalanche tracks (79% of their total number) go across the treeline (see Fig. 6A). "Deep" penetration of avalanche tracks in the forest zone of Babia Góra Mt. in two areas of the northern slope and five areas of the southern slope should be mentioned. The places of deposition of avalanche snow in these areas are located from 120 to 240 m below the treeline.

LOCATION OF AVALANCHE TRACKS VERSUS SHAPE OF SLOPES

On the northern slope of Babia Góra Mt. avalanche tracks are located within 3 mesoforms (see Fig. 1D, Fig. 6A): the abrupt part of the cuesta along its whole length, gently sloping base of this abrupt, and the highest located headwater areas. On the southern slope most of avalanche tracks occur within one mesoform, i.e. the headwater areas with steep slopes. On the northern slope 10 areas with avalanche tracks can be distinguished, while on the southern slope 6 areas (Tab. 1, see Fig. 6A). The areas with avalanche tracks on the northern slope are: I – headwater area and upper part of valley of Cylowy Potok stream, II – upper part of headwater area of Klinowy Potok stream, III – slope below Izdebczyska slip, IV – rocky walls of Kamienna Dolinka headwall, V – couloirs on slopes

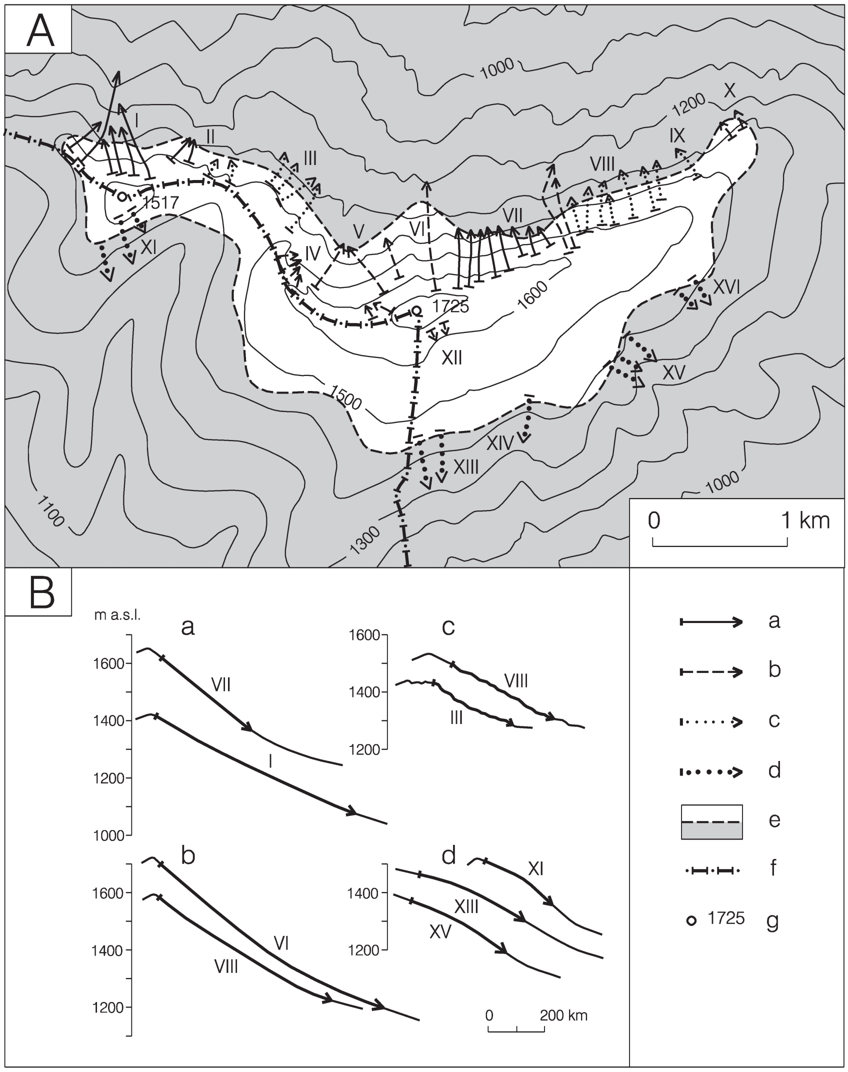


Fig. 6. Avalanche tracks on Babia Góra Mt. A – distribution of tracks and shape of slopes, B – examples of profiles of avalanche tracks. Slope profiles: a – straight, b – concave, c – step-like, d – convex, e – treeline, f – Polish-Slovakian border, g – massif elevations. For numbering of areas with avalanche tracks (I–XVI) see the text

Table 1

Characteristic of slopes with avalanche tracks

No of area with avalanche tracks	Expo-sition of slope	No of avalanche track	Profile of slope	No of area with avalanche tracks	Expo-sition of slope	No of avalanche track	Profile of slope
I	N	1	straight	VII	N	30	straight
I	N	2	straight	VII	N	31	straight
I	N	3	straight	VII	N	32	straight
I	N	4	straight	VIII	N	33	concave
I	N	5	straight	VIII	N	34	concave
I	N	6	straight	VIII	N	35	step-like
II	N	7	straight	VIII	N	36	step-like
II	N	8	straight	VIII	N	37	step-like
II	N	9	step-like	VIII	N	38	step-like
II	N	10	step-like	VIII	N	39	step-like
III	N	11	step-like	VIII	N	40	step-like
III	N	12	step-like	VIII	N	41	step-like
III	N	13	step-like	IX	N	42	step-like
III	N	14	step-like	X	N	43	concave
IV	N	15	concave	X	N	44	concave
IV	N	16	concave	XI	S	45	convex
IV	N	17	concave	XI	S	46	convex
IV	N	18	concave	XI	S	47	convex
V	N	19	concave	XII	S	48	concave
V	N	20	concave	XII	S	49	concave
V	N	21	concave	XIII	S	50	convex
V	N	22	concave	XIII	S	51	convex
V	N	23	concave	XIV	S	52	convex
VI	N	24	concave	XV	S	53	convex
VII	N	25	straight	XV	S	54	convex
VII	N	26	straight	XV	S	55	convex
VII	N	27	straight	XVI	S	56	convex
VII	N	28	straight	XVI	S	57	convex
VII	N	29	straight				

For numbering of areas with avalanche tracks (I–XVI) see the text.

of deep corrie, VI – wide corrosion gully (Szeroki Żleb), VII – couloirs on the most precipitous slope, VIII – couloirs on slope below Zimna Dolinka and Kępa ridge troughs, IX – couloir on slope below Zła Dolinka headwall, X – rocky wall of Sokolica. The areas with avalanche tracks on the southern slope are: XI – western part of headwater area of Bystrá stream, XII – headwall near summit of the massif, XIII – headwater area of Szumiący Potok stream, XIV – headwater area of Krzywy Potok stream, XV – headwater area of Potok Skalnica stream, XVI – headwater area of Potok spod Jam stream.

The avalanche tracks on the northern slope include its zone of straight and/or concave profile and also part of the slope of step-like profile embracing vast areas with deep-seated landslides. This area contains 16 avalanche tracks on slopes of straight profile, 14 avalanche tracks on slopes of concave profile and 14 tracks on step-like slopes. On the southern slope, apart from its highest located headwall, 11 avalanche tracks are located in the zone of convex profile (Fig. 6A,B, see Tab. 1).

Convergent slopes with long avalanche tracks occur within the areas I, V, VI, and XIII–XVI, whereas divergent slopes without avalanche tracks occur within the fringes of forms I, II, III, V, VI, and XI–XVI. A vast part of the southern slope of windward exposition is worth to be mentioning as it does not contain any avalanche track because the snow is wind-blown from this area (see Fig. 5B) and additionally because of its divergent character.

LOCATION OF AVALANCHE TRACKS WITHIN LANDFORMS

Starting zones of avalanche tracks on parts of the northern slope of straight profile include the areas of inclination 30–40° located below the edge of the ridge plateau, covered by patches of boulders partly grown by grass and/or dwarf mountain pine bushes (areas I and V–VII, see Fig. 6A). In the areas with deep-seated landslides these sections of avalanche tracks include slips inclined up to 40° covered by grass and dwarf mountain pine bushes (areas II, III, VIII, IX). Starting zones of avalanche tracks on rocky walls of concave profile include the areas of inclination up to 70° sparsely grown by grass and by bushes of dwarf mountain pine bushes (areas IV and X). Track zone sections of straight or concave profiles on the northern slope of the massif include up to 80% of the length of all avalanche tracks and occur in couloirs and corrosion gullies, where they are locally inclined up to 45° and also on precipitous headwalls, on the areas re-modelled by former glaciers, and on the slopes of the deep headwater areas (areas I, and V–VII). Track zone sections of step-like profile on slopes modelled by deep-seated landslides lead along less inclined slips, and along colluvium distensions grown by grass and locally dwarf mountain pine bushes (areas II, III, and VIII, IX). Runout zone sections of avalanche tracks, where deposition of avalanche snow covers from several to dozen or so percent of total length of the tracks, occur mostly on torrential cones (inclination 10–20°, areas V–VII, and on landslide flatnesses, areas II–IV, and VIII–X). Only in the area I these sections of tracks include steep slopes within the deep headwater area.

In the highly located landslide headwall on the southern slope of the massif, all the three sections of two short avalanche tracks are located within a steep slope covered by rocky blocks (area XII). Sections of starting zones of tracks present on slopes in lower located headwater areas are placed on landslide slips grown by grass and locally dwarf mountain pine bushes (areas XI and XIII–XVI). Track zone sections and runout zone sections are located within corrosion gullies on slopes of headwater areas.

All the avalanche tracks start in places where snow cornices occur and show the character of starting zone from a line. The track of displacing snow masses is the narrowest in couloirs and corrosion gullies, and the widest on landslide slopes of step-like profile. This is why only avalanche tracks from the areas I, V–VII, and partly VIII and XIII–XVI are classified to confined tracks and all the others belong to unconfined avalanche tracks.

VERTICAL LOCATION OF AVALANCHE TRACKS

The starting zone of individual avalanche tracks is included on the northern slope of Babia Góra Mt. in altitude range 1320–1690 m a.s.l. and on the southern slope in the range 1400–1660 m a.s.l. (Tab. 2). In each 100 m altitude section of the massif, the number of starting zones of avalanche tracks dominates on the northern slope (Fig. 7A). On this slope, the largest number of avalanche tracks

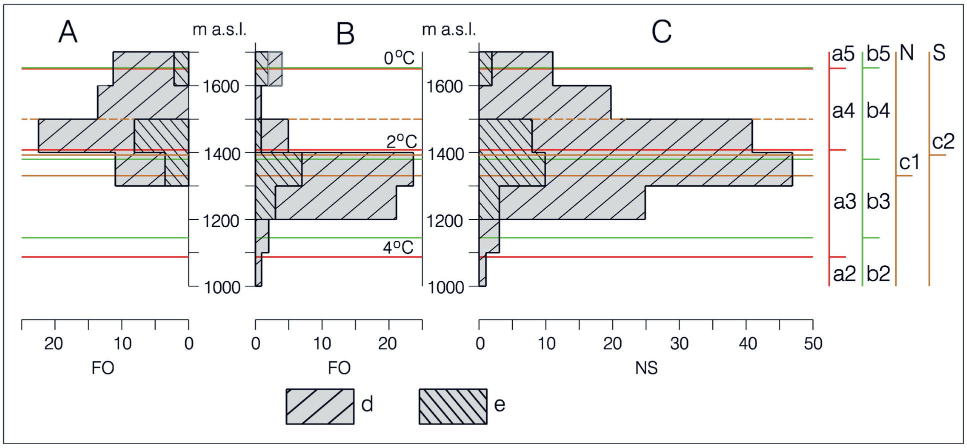


Fig. 7. Vertical location of avalanche tracks on Babia Góra Mt. Frequency of the occurrence (FO) of starting (A) and runout (B) zones of avalanche tracks in 100 m altitude intervals of the massif. C – number of sections (NS) of avalanche tracks in 100 m altitudinal intervals of the massif. For explanations a1–a5 and b1–b5 see the text. c1, c2 – mean altitude of a timberline on the northern (N) and southern (S) slopes, d – N slope, e – S slope

Table 2

Parameters of avalanche tracks on Babia Góra Mt., part. I

No of avalanche track	[m a.s.l.]	Δh [m]	No of avalanche track	[m a.s.l.]	Δh [m]	No of avalanche track	[m a.s.l.]	Δh [m]
1	1420–1260	160	20	1600–1360	240	39	1490–1290	200
2	1420–1070	350	21	1580–1380	200	40	1480–1300	180
3	1440–1290	150	22	1660–1610	50	41	1450–1270	180
4	1450–1230	220	23	1690–1610	80	42	1420–1270	150
5	1460–1230	230	24	1670–1200	470	43	1330–1240	90
6	1470–1190	280	25	1650–1350	300	44	1320–1220	100
7	1400–1280	120	26	1650–1360	290	45	1460–1320	140
8	1390–1280	110	27	1630–1350	280	46	1500–1350	150
9	1400–1350	50	28	1640–1340	300	47	1500–1420	80
10	1400–1330	70	29	1610–1350	260	48	1660–1620	40
11	1400–1280	120	30	1560–1380	180	49	1660–1620	40
12	1390–1270	120	31	1560–1400	160	50	1450–1320	130
13	1410–1280	130	32	1530–1420	110	51	1430–1330	100
14	1450–1280	170	33	1570–1230	340	52	1450–1330	120
15	1560–1490	70	34	1550–1270	280	53	1400–1270	130
16	1570–1495	75	35	1510–1360	150	54	1400–1280	120
17	1580–1500	80	36	1510–1320	190	55	1400–1300	100
18	1620–1550	70	37	1490–1300	190	56	1430–1370	60
19	1570–1350	220	38	1490–1370	120	57	1420–1350	70

Avalanche tracks are numbered as in Table 1.

(27 i.e. almost 50% of their total number in the massif) starts at the altitude 1401–1600 m a.s.l. These parts of all avalanche tracks occur in climatic vertical zones a3-a5 and they are concentrated in zone a4 with dwarf mountain pine b4.

Places of avalanche track elevation embrace larger altitude range of Babia Góra Mt.: 1070–1610 m a.s.l. on the northern slope and 1270–1620 on the southern slope (see Tab. 2). The number of stretches of avalanche tracks in the succeeding 100 m altitude sections is also larger on the northern side of the massif, however in the highest hypsometric section it is the same on both slopes. On the northern slope, 77% of all avalanche runout zones terminates in the altitude section 1201–1400 m a.s.l. Also on the southern slopes, most of avalanche tracks finishes in this altitude section. Runout zones of avalanche tracks occur in all the climatic vertical zones of Babia Góra Mt., except of the highest located ones (Fig. 7B).

In individual 100 m altitude sections of Babia Góra Mt., both on the northern and southern slopes of the massif, total number of sections of avalanche tracks is in the range from 1 to 47 with an increasing trend up the altitude 1301–1400 m a.s.l., and a decrease above this altitude (Fig. 7C). At the altitude 1301–1400 m a.s.l. there are 37 sections of avalanche tracks on the northern slope of the massif and 10 sections on the southern slope. It should be underlined that the total number of analysed sections of avalanche tracks is 3 times higher than the number of these tracks.

PARAMETERS OF AVALANCHE TRACKS

A vertical drop of avalanche track Δh [m] together with a slope shape and the altitude of a starting point, determine length and inclination of an avalanche track. Vertical drop of individual tracks on the northern slope of Babia Góra Mt. are in the range 50–470 m and on the southern slope in the range 40–150 m (see Tab. 2). Avalanche tracks of the vertical drop larger than 300 m occur only in the areas I, VI and VIII, and those of the vertical drop 201–300 m occur in the areas I, V, and VII–IX. As compared to the whole massif, avalanche tracks of vertical drop in the range 101–200 m represent 44% of the whole tracks, whereas avalanche tracks of vertical drop in the range 40–300 m as much as 95% of their total number (Fig. 8). On the northern slope only 7% of avalanche tracks shows vertical drop larger than 300 m, 34% larger than 200 m and 77% larger than 100 m. On the southern slope the number of avalanche tracks of vertical drop larger or smaller than 100 m is similar.

The length of individual avalanche tracks L [m], measured along the slope is in the range 70–970 m and is much larger on the northern slope than on the

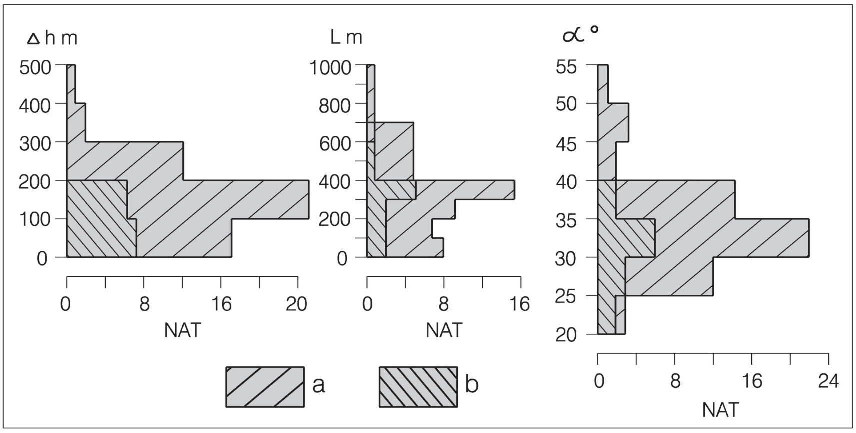


Fig. 8. Number of avalanche tracks (NAT) in the determined intervals of their vertical drop Δh, length L and mean inclination α on the northern (a) and southern (b) slopes of Babia Góra Mt.

southern one, where it does not exceed 520 m (Tab. 3). The most frequent are avalanche tracks of the length 301–400 m, which predominate both on the northern and southern slopes of the massif (see Fig. 8). Avalanche tracks of the length up to 200 m represent 26% of their total number, the tracks of the length up to 400 m represent 68%, and those up to 600 m represent 86% of their total number. Avalanche tracks longer than 600 m occur only in areas I and V–VIII. The longest avalanche tracks (over 800 m) occur only on the northern slope and represent 4% of their total number in the massif.

Mean inclination of avalanche tracks α [°], ranges from 24° to 55°, and is the largest on the northern slope (on the southern slope it does not exceed 38°) (see Tab. 3). Almost 40% of avalanche tracks is inclined in the range 31–35°, and as much as 84% in the range 26–40° (see Fig. 8). Tracks of optimal inclination for snow avalanche occurrence from 41° to 55° represent only 11% of the total num-

Table 3

Parameters of avalanche tracks on Babia Góra Mt., part II

No of avalanche track	L [m]	α [°]	[%]	No of avalanche track	L [m]	α [°]	[%]	No of avalanche track	L [m]	α [°]	[%]
1	310	32/36	110	20	570	28/39	100	39	400	34/38	110
2	830	30/35	115	21	390	35/42	100	40	380	27/33	100
3	310	31/40	100	22	100	33/43	100	41	320	37/39	100
4	430	32/39	100	23	160	38/43	100	42	580	32/42	110
5	460	33/37	105	24	970	39/45	100	43	160	38/70	100
6	700	28/34	100	25	670	39/45	100	44	160	42/70	100
7	240	33/40	105	26	630	40/45	100	45	300	31/35	100
8	210	33/40	105	27	640	38/44	105	46	370	34/37	100
9	100	32/42	100	28	690	41/46	100	47	180	30/36	100
10	140	31/41	115	29	580	38/43	100	48	70	38/44	100
11	300	28/45	105	30	360	32/38	100	49	70	38/45	100
12	270	26/43	105	31	290	34/39	100	50	500	34/39	100
13	370	26/40	100	32	190	40/42	100	51	520	35/41	100
14	460	25/39	105	33	740	28/39	120	52	320	34/41	105
15	90	50/70	100	34	550	36/42	105	53	330	32/39	100
16	90	50/70	100	35	280	35/39	100	54	320	29/38	100
17	100	55/70	105	36	360	36/40	100	55	320	26/37	100
18	100	50/70	120	37	380	33/37	100	56	220	24/36	100
19	430	36/43	105	38	240	30/37	100	57	200	25/35	100

Avalanche tracks are numbered as in Table 1 and Table 2.

ber of objects and occur on the most abrupt parts of northern slope (areas IV, VII, X). Only three avalanche tracks show average inclination 24–25° including two on the southern slope. Local maximum inclination of avalanche tracks in their starting zones or track zones on straight or concave slopes is from 2° to 32° larger than mean inclination (see Tab. 3). In tracks located along rocky walls, the inclination reaches even 70° (areas IV and X). Maximum inclination of avalanche tracks on slopes of step-like profile occurs along their total length whereas in case of convex tracks the maximum inclination occurs usually in track zone and runout zone. A wide range of mean (25–55°) and maximum (33–70°) inclination of avalanche tracks on the northern slope is connected with more diversified morphology of this slope. In case of the southern slope the mean (24–38°) and maximum (35–45°) inclination is smaller.

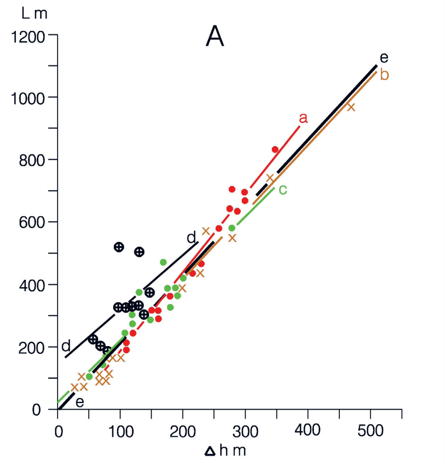
38 avalanche tracks (67% of their total number) show a straight course (sinuosity index = 100%), 12 tracks show slightly winding course (sinuosity index = 101–105%), and 7 remaining tracks show even more winding course (sinuosity index = 106–120%) (see Tab. 3). The avalanche tracks with straight course (sinuosity index = 100%) occur mainly on straight or convex slopes, whereas the most winding tracks (sinuosity index = 111–120%) usually occur on concave and step-like slopes.

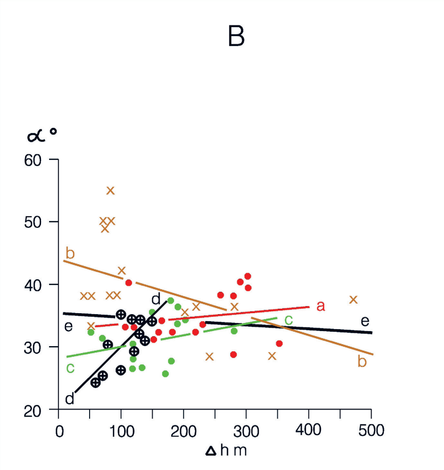
CORRELATION OF PARAMETERS OF AVALANCHE TRACKS

The length of avalanche track L [m] and its vertical drop Δh [m] are parameters, the relationship of which seems to be self-evident: the longer the track, the larger denivelation. Avalanche tracks on Babia Góra Mt. show such relations ($r = 0.93$; $p = 0.00$) (Fig. 9A). This relation is true in case of tracks of straight profile ($r = 0.99$; $p = 0.00$), concave profile ($r = 0.99$; $p = 0.00$) and step-like profile ($r = 0.73$; $p = 0.00$). It's interesting, however, that the length of avalanche track on slope of convex profile is not related with its vertical drop ($r = 0.53$; $p > 0.05$). This should be explained by the location of a starting point and a terminal point of individual avalanche tracks in different distances from the convex curve of the slope which results in the fact that tracks of similar lengths may have different vertical drop according to the extent of track sections into lower located and steeper parts of slopes. Moreover, if vertical drop of avalanche track is smaller than 200 m, tracks on straight slopes are the shortest and the tracks located on convex slopes are the longest. In case of larger vertical drop, avalanche tracks on step-like and concave slopes are the shortest and those located on straight slopes are the longest.

Comparison on mean inclination of avalanche tracks α [°] with their vertical drops Δh [m] shows that there is no any functional dependence α–Δh in any of groups (Fig. 9B). The only exception are avalanche tracks located on convex slopes ($r = 0.72$; $p = 0.01$): the larger vertical drop of tracks, the larger their inclination.

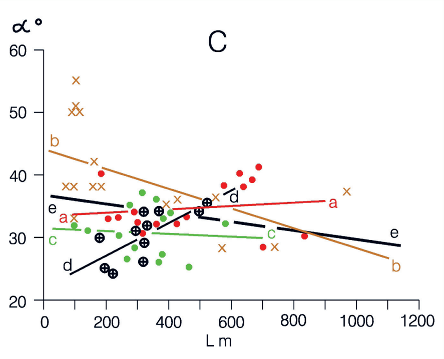
The largest divergence among the four investigated groups occurs while comparing relationship between mean slope inclination α [°] and length of avalanche track L [m] (Fig. 9C). In the whole massif no relationship between these parameters were determined ($r = -0.22$; $p > 0.05$) both in the group of avalanche tracks on slopes of straight profile ($r = 0.14$; $p > 0.05$) and step-like profile





a	L=-99,30+2,61Δh	r=0,99	p=0,00
b	L=-39,59+2,20Δh	r=0,99	p=0,00
c	L=28,01+1,95Δh	r=0,92	p=0,00
d	L=108,87+1,99Δh	r=0,54	p>0,05
e	L=9,43+2,14Δh	r=0,94	p=0,00

a	α=32,56+0,09Δh	r= 0,18	p>0,05
b	α=44,26-0,03Δh	r=-0,50	p>0,05
c	α=28,15+0,02Δh	r= 0,26	p>0,05
d	α=19,90+0,10Δh	r= 0,72	p=0,00
e	α=35,20-0,01Δh	r=-0,08	p>0,05



a	α=33,36+0,003 L	r= 0,14	p>0,05
b	α=44,33-0,02 L	r=-0,57	p=0,02
c	α=31,67-0,003 L	r=-0,08	p>0,05
d	α=21,90+0,03 L	r= 0,72	p=0,01
e	α=36,68-0,007 L	r=-0,22	p>0,05

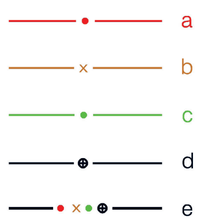


Fig. 9. Correlation of parameters of avalanche tracks: A – length L and vertical drop Δh, B – mean inclination α and vertical drop Δh, C – mean inclination α and length L. Tracks on slopes of the following profiles: a – straight, b – concave, c – step-like, d – convex, e – all slope profiles (a–d)

(r = –0.08; p > 0.05). On the other hand, avalanche tracks on slopes of convex profile show strong relationship: the larger the mean slope inclination, the longer the avalanche track (r = 0.72; p = 0.01). In case of tracks located on concave slopes this dependence is inversely proportional and weaker: the larger the mean slope inclination, the shorter the avalanche track (r = –0.57; p = 0.02).

The analyses of relationship between the intensity of avalanche track sinuosity, their length, mean slope inclination and vertical drop revealed lack of any dependence.

DISCUSSION AND CONCLUSIONS

The analyses of the newest information sources and field work results revealed that the number of avalanche tracks in Babia Góra Mt. and their dimensions are larger than it was so far assumed (Midowicz 1930; Hudziak 1987; Łajczak 2004; Czajka et al. 2015b; Łajczak et al. 2015). The main concentration of avalanche tracks on the northern abrupt slope was confirmed as well as their local occurrence on the gentle southern slope, which earlier had rather not been noticed. In terms of number of avalanche tracks and their dimensions, Babia Góra Mt. is on the same position as the Polish Karkonosze Mountains and second after the Tatras (Kłapa 1959; Kłapowa 1969; Kwiatkowski 1985; Gądek et al. 2016; Rączkowska et al. 2016).

Morphometric analysis of avalanche tracks conducted according to recommendations from the literature (Schweizer et al. 2003; McClung, Schaerer 2006; Eckerstorfer, Christiansen 2011, 2012; Voiculescu et al. 2016) revealed that on Babia Góra Mt. of differentiated slope morphology, the avalanche tracks are not only concave or convex but also show straight or step-like profile. The longest avalanche tracks occur on convergent slopes regardless of their shape, whereas no avalanche tracks were found on divergent slopes. On the abrupt northern slope, the number of avalanche tracks of straight, concave or step-like profile is similar (16, 14, 14 respectively) whereas on the southern slope there are 11 avalanche tracks of convex profile and only two tracks of concave profile. All the avalanche tracks start in places of snow cornices on the convex morphological curves of slopes therefore these sections of avalanche tracks were classified as a starting zone of line. Sections of track zones were classified as confined forms of avalanche tracks which in majority show straight course. 44% of the number of avalanche tracks shows vertical drop 101–200 m and 42% reaches the length 201–400 m (only two tracks on the northern slope are longer than 800 m). 40% of avalanche tracks shows mean inclination in the range 31–35° and 84% in the range 26–40°. The most frequent inclinations of the investigated avalanche tracks are generally similar to T. Sekiguchi et al. (2005).

The results of investigations shown in this paper will let to supplement a gap in literature concerning the slope profiles most favourable to avalanche development. On Babia Góra Mt. the longest avalanche tracks occur on the abrupt northern slope, in places where its profile is straight or concave (see Fig. 6A, Tab. 1, Tab. 3). 50% of the longest avalanche tracks on the slopes of straight profile is 460–830 m long while 25% of the longest tracks reaches the length 670–830 m. In case of avalanche tracks on the slopes of concave profile, these values are 160–970 m and 550–970 m, respectively. On the southern slope due to smaller vertical drop of avalanche tracks, these values are in the range 320–520 m and 370–520 m, respectively. Also on parts of the northern slope of step-like profile modelled by deep-seated landslides, a half of the longest avalanche tracks shows the length in the range 320–580 m and 25% of the longest tracks is from 380 to 580 m long.

Altitudinal location of avalanche tracks and their individual sections on Babia Góra Mt. depend not only on vegetation cover but also on slope relief which is considerably differentiated in this massif. Similar remarks can be found in the literature (Birkeland, Mock 2001; McClung, Schaerer 2006; Voiculescu et al. 2016). Almost all the avalanche tracks on Babia Góra Mt. are located in dwarf mountain pine zone however in their starting zone and track zone sections dwarf mountain pine bushes are thin and dominated by alpine meadows partly covering patches of boulders or rocky walls. Possibilities of avalanche occurrence are only slightly limited by vegetation cover and conditioned, apart from weather conditions, on slope morphology. 75% of avalanche tracks exceeds the treeline causing local lowering of the timberline even by 200 m (see Fig. 6A). The number of avalanche tracks on Babia Góra Mt. entering the forest zone is relatively large as compared to other massifs (Bebi et al. 2009; Czajka et al. 2012; Kaczka et al. 2015b). Location of runout zone sections of these avalanche tracks above places with lowered course of the timberline represents a result of cumulative influence of spruce forest, dwarf mountain pine bushes and slope relief (places of smaller inclination on torrential cones, on landslide flattenings and in the bottom of headwater areas).

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