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Origin of planation surfaces in the hinterland of Šumljak sedimentary bodies in Rebrnice (Upper Vipava Valley, SW Slovenia)

Nastanek reliefnih izravnav v zaledju sedimentnih teles Šumljak na Rebrnicah (Zgornja Vipavska dolina, SW Slovenija)

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Ključne besede: reliefna izravnava, strmi robovi, pobočni sediment, melišče, fosilni plaz

Abstract

The Rebrnice area forms the north eastern slopes of the Upper Vipava Valley and is located between Karst plateau to the southwest and the Nanos plateau to the northeast. The Rebrnice slopes are geomorphologically defined by a thrust front of Mesozoic carbonates over Tertiary flysch deposits and are characterised by a variety of polygenetic landslides (being the most prominent geomorphological features). Among them, the three Šumljak sedimentary bodies of fossil landslides (approximately 0.56 km² in area) comprise carbonate gravels and breccia. The most distinctive geomorphological element is the planation surface of the carbonate breccia blocks positioned in the hinterland of the Šumljak sedimentary bodies. Another feature is the presence of local escarpments (steep scarps) defining the border between the planation surface in the hinterland and sedimentary bodies.

Our research suggests that the whole area in the hinterland of the Šumljak sedimentary bodies form part of a deep-seated rotational landslide formed of carbonate breccia. On the basis of the dipping of the breccia beds, in particular parts of the rotational blocks, the rotation can reach up to 60°. Planation surfaces developed above the curved, sliding plane in the central part and/or slightly outer part of the landslide. Steep scarps on the external parts of the planation surface represent the main scarps of the Šumljak sedimentary bodies. We propose that these bodies originated from the remobilization of material accumulated in outer parts of large-scale rotational slides and its transportation further downslope, mostly by rock avalanches.

Izvleček

Območje Rebrnic predstavlja severnovzhodna pobočja Zgornje Vipavske doline, ki se nahajajo med kraško planoto na jugozahodu in Nanosom na severovzhodu. Topografijo območja Rebrnic opredeljuje čelo narivnega robu mezozojskih karbonatov, ki so narinjeni na terciarne kamnine fliša, kontakt pa prekrivajo kvartarni pobočni sedimenti, med katerimi so najpomembnejši fosilni in recentni poligenetski plazovi. Med fosilnimi plazovi izstopajo tudi tri sedimentna telesa Šumljak (velikosti 0,56 km²), sestavljena iz karbonatnega grušča in breče in imajo specifične geomorfološke značilnosti. Najbolj značilen geomorfološki element so planarne (izravnane) površine blokov karbonatnih breč v zaledju sedimentnih teles Šumljak in prisotnost lokalnih morfoloških stopenj v obliki strmih robov, ki opredeljujejo mejo med izravnano površino v zaledju in sedimentnim telesom.

Raziskave kažejo, da je celotno območje v zaledju sedimentnih teles Šumljak lahko del globokih rotacijskih plazov karbonatnih breč. Na podlagi plastnatosti breče na posameznih delih rotacijskih blokov, ugotavljamo, da so bloki rotirali do 60°. Izravnana površina je razvita predvsem v osrednjem delu planarnih površin, na zunanjih delih izravnav pa se pojavljajo strmi robovi, ki predstavljajo glavne odlomne robove sedimentnih teles Šumljak. Menimo, da so telesa, predvsem v zgornjem delu pobočja nastala kot posledica remobilizacije materiala z zunanjih delov velikih rotacijskih palzov, kjer se je material nato v obliki kamninskih plazov transportiral nižje po pobočju.

Introduction

A large accumulation of carbonate gravel, that formed by different transport mechanisms and deposition processes, is positioned under the head of the thrust contact in the Rebrnice area. The spatial distribution of sedimentary bodies within the quaternary slope deposit and the type of deposition processes can be directly influenced by the regional structural, lithological, hydrological and geochemical conditions. Studies of these elements are supplementing our understanding of the gravitational events that were triggered throughout the north and north-eastern parts of Vipava Valley (Kočevar & Ribičič, 2002; Logar et al., 2005; Fifer Bizjak & Zupančič-Valant, 2007; 2009; Placer, 2007; Jež, 2007; Placer et al., 2008; Mikoš et al., 2009; Lenart & Fifer Bizjak, 2010; Petkovšek et al., 2011; Popit & Verbovšek, 2013; Mikoš et al., 2014; Pulko et al., 2014; Košir et al., 2015; Martín Pérez et al., 2016; Popit et al., 2017; Verbovšek et al., 2017a; 2017b). The structure and composition of the sedimentary bodies are extremely complex but this is not visible at ground level, where carbonate gravels prevail. This surface feature is still useful for distinguishing the mass-movement, sedimentary bodies from the primary flysch base rock (Popit et al., 2013, Popit et al., 2016; Popit, 2016).

The present work deals with the form and structure of a planation surface in the hinterland of the three Šumljak sedimentary bodies (SB1, SB2 and SB3) in the Rebrnice slope area. These approximately horizontal, planar surfaces are well-expressed and unusual for this area which is why there is interest in researching their origin.

General geological setting

In tectonic terms, the investigated area is part of a south west verging, Eocene to Oligocene fold-and-thrust structure in the External Dinarids (Placer, 1981; 1998). The Šumljak sedimentary bodies are located in the upper part of the Vipava Valley, which belongs to three different nappes (from structurally lowest to highest): The Komen Thrust Sheet, the Snežnik Thrust Sheet and the Hrušica Nappe (Fig. 2). The Topography of the studied area is defined by the Hrušica Nappe, which comprises Mesozoic (Cretaceous and Jurassic) limestone that has been thrusted over the Paleocene and Eocene flysch deposits of the Snežnik and Komen thrust sheets (Fig. 2); these have also been folded and fractured. The overlying carbonate rocks are intensively fractured along the thrust contacts and within wide zones of NW–SE trending strike-slip faults (the Predjama, Vipava and Raša faults) that cut the thrust contact (Placer, 1981; 1998; 2008; Čar & Gospodarič, 1988; Janež et al., 1997).

The upper part of the slope of the Vipava Valley is marked by steep carbonate cliffs, while the lower parts of the slope are more gently sloping and are composed of flysch bedrock covered by Quaternary slope deposits. The latter represent an array of composite, fan-shaped, sedimentary bodies with diverse composition, internal structures and textures, which indicate a complex depositional history and polyphase genesis (Popit and Košir, 2010; Popit et al., 2013; Popit, 2016, Novak et al., 2017).

Methods

The mapping of the sedimentary bodies and their hinterland is based on geological field mapping and analysis of shaded digital terrain models (DTMs) that were obtained by airborne laser scanning with a resolution of 1 × 1 m. The basic elements used for the visual interpretation of the shaded digital terrain model (Fig. 1) were texture, shape and tint (cf. Podobnikar, 2003; 2005; Oštir, 2006). An additional aid was a map of surface roughness, made using the Height Variability Method (Ruszkiczay-Rüdiger et al., 2009) and this proved to be the most useful of all the methods used for the quantification and visualisation of deposits with different sedimentary composition and genesis (Popit & Verbovšek, 2013; Popit et al., 2016).

The results of the Height Variability Method are presented in Fig. 5B and Fig. 7B, and they represent the difference between the highest and the lowest elevations. The casts of colours were divided roughly into three levels: low, medium and high variability of slopes. Areas marked in light to dark pink correspond to smooth surfaces (e.g. the bottom of the Upper Vipava Valley), the blue-green areas correspond to intermediate values (between smooth and rough surfaces), and the yellow-brown areas correspond to rough surfaces (e.g. Nanos cliff) (Figs. 5 and 7). Colour visualisation was found to be a useful way of illustrating the areas with low and/or high slope variability (Popit & Verbovšek, 2013; Popit et al., 2016). Based on both methods (geological mapping and surface roughness analyses), specific geomorphological and geological features were interpreted.

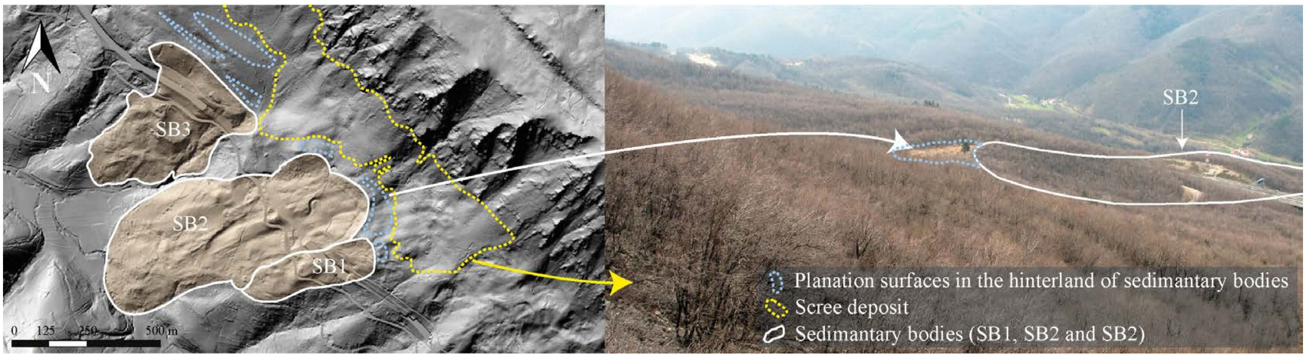

Fig. 1. (A) Shaded digital elevation model of the Šumljak sedimentary bodies (SB1, SB2 and SB3) and locations of planation surfaces in the hinterland and scree deposits. (B) View to Šumljak 2 sedimentary body (SB2) and its planation surface in the hinterland.

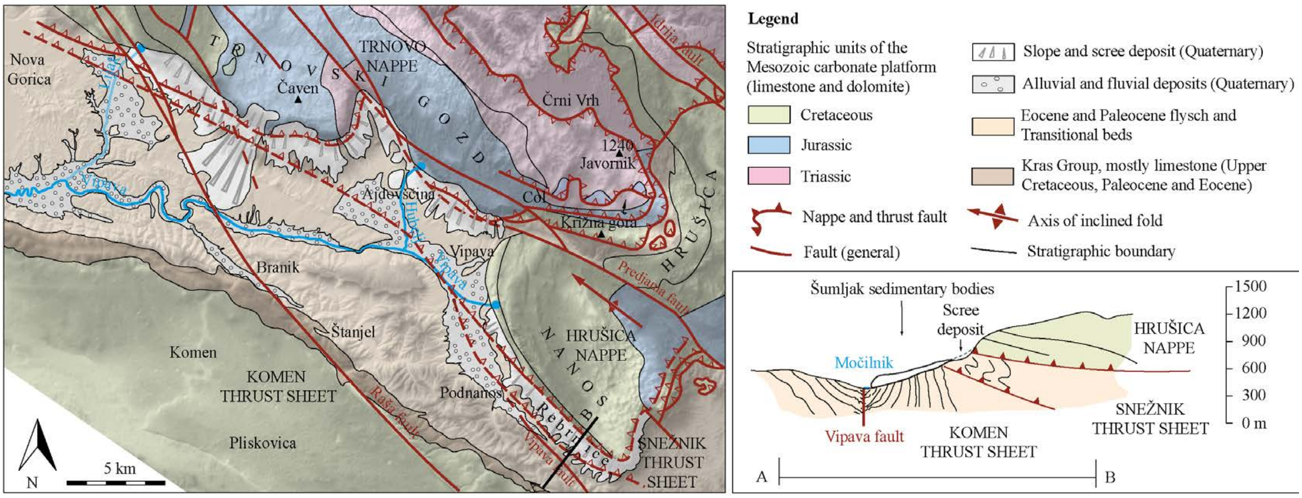

Fig. 2. Simplified geological map and cross-section of the Upper Vipava Valley and the Nanos Plateau. Compiled from Buser, (1973; 1986), Placer (1981; 2008), Janež et al. (1997) and others.

Šumljak sedimentary bodies and geology of their hinterland

Over the entire Rebrnice area, there are 11 isolated sedimentary bodies (of very complex genesis and composition), covering areas of between 0.09 km^2 and 0.50 km^2. The total surface area of the bodies in the Rebrnice area is approximately 2.8 km^2 (Popit, 2016; Jemec Auflič et al., 2017). In total, the surface of the Šumljak sedimentary bodies is approximately 0.58 km^2 and this represents 21 % of the surface area of all sedimentary bodies in the Rebrnice area.

The surface area of SB1 is 0.095 km^2. The difference between the height of the lowest and the highest edge of the sedimentary body is more than 160 m (Fig. 3). The surface area of SB2 is 0.332 km^2. The height difference between the lowest edge of the sedimentary body in Dolenje Žvanuti village, near Lozice, and the upper edge of the body is more than 230 m (Fig. 3). The surface area of SB3 is 0.156 km^2 and the difference between the lowest and the highest edge of the sedimentary body is 165 m.

Just above the scarps of the direct hinterland of the Šumljak sedimentary bodies, the morphology flattens out to planation surfaces. The baserock of these surfaces is composed of carbonate breccia (Figs. 6A and B), which occurs in bedding or in lenses (usually up to 1 m thick). It originated from the partial lithification of scree material. The dip direction and dip angle of the beds are different, depending on their position on the slope (see below). Near the carbonate cliff in the upper part of the slope, the dip angles of breccia beds are parallel or nearly parallel to the directions of the slope. In the middle part of the slope, the dip angles of the beds are sub-horizontal and in the lower parts of the slope the carbonate breccia beds dip towards the slope (Fig. 6). In the upper part of the slope (on the north-eastern side), the planation surface is bounded by recent scree aprons which follow the line of the carbonate Nanos cliff.

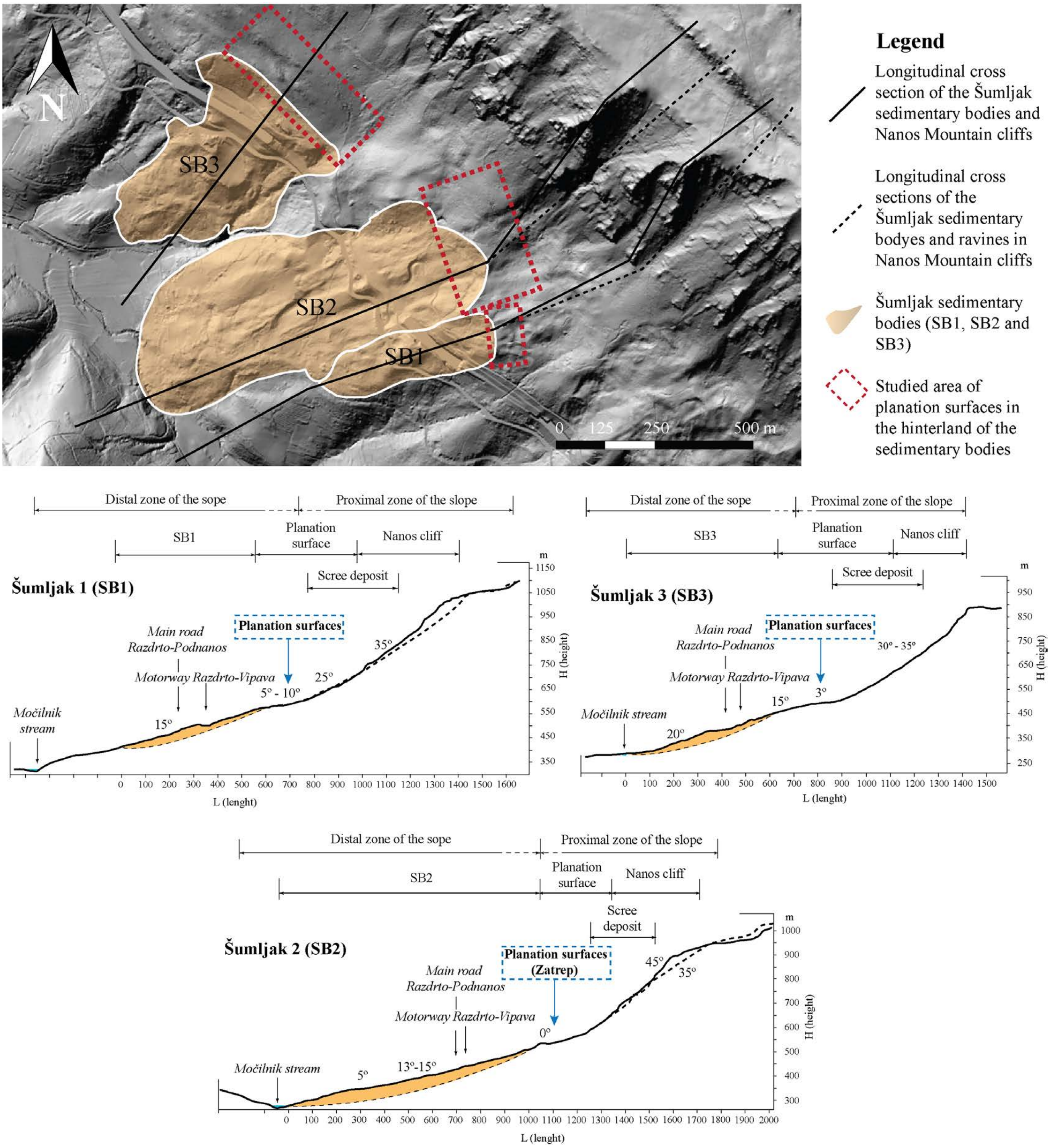

Fig. 3. The longitudinal profiles across Šumljak sedimentary bodies (SB1, SB2 and SB3) and location of the study area.

Geomorphometric analysis in the hinterland of Šumljak sedimentary bodies

By visual analysis of the DTMs and height variability map (Figs. 4, 5A and 5B) it can be identified that the Šumljak sedimentary bodies and their immediate surroundings represent areas with different surface roughness. It was found that carbonate gravels (which, in most cases, cover the individual sedimentary body surfaces) have a height variability and consequently represents an area with a high degree of surface roughness. By contrast, the hinterland of the Šumljak sedimentary bodies shows a low degree of height variability and the surface in this part is smooth. The transition from sedimentary bodies to hinterland is marked by steep scarps. Along the slope in the hinterland of the Šumljak sedimentary bodies, we distinguished three different areas with diverse morphology; from the bottom of the slope to the top, these are: *steep scarps*, *planation surfaces* and *scree deposits*.

Steep scarps

In the upper edge of the sedimentary bodies, on the boundary with the planation surfaces, we recognized steep, convex and strait scarps formed of carbonate breccia. The values of the surface roughness of the steep, convex scarps on the top of SB2 are very high. The convexity of the scarps also occurs in the upper part of SB1, whereas in the hinterland of SB3 they only appear as a few straight lines (Fig. 4). The strait lines of the SB3 hinterland is also recognized on the height variability map (Figs. 4 and 5), where approximately parallel, narrow bands extend over the upper part of SB3 and resemble a stepped feature in the hinterland of the sedimentary body.

Planation surface

In the hinterland of the Šumljak sedimentary bodies, above the Nanos cliff and below the steep scarps, there are large areas of carbonate breccia with extremely low roughness, named planation surfaces (Fig. 4). The largest uniform planation surface, named "Zatrep", is in the hinterland of SB2 and extends for approximately 0.03 km^2. SB1 is the smallest of the sedimentary bodies (Fig. 2) and, therefore, the planation surface in the hinterland of this body is also the smallest in area. The hinterland of SB3 is more complex. The shaded digital terrain model and the height variability map indicate the location of levelled edges (at the boundary between height and low surface roughness) (Fig. 5). Belts of high surface roughness can be easily recognized in the straight scarps mentioned above. Individual smooth surfaces between the scarps, represent three separated planation surfaces in the hinterland of SB3, forming a stepped structure.

The largest planation surface in the hinterland of SB3 is also the highest and extends to approximately 0.005 km^2 while the planation surfaces in the lower part of the slope are smaller, elongate and parallel to the steep scarps. In some parts in the hinterland of SB3, it was possible to recognize the dip direction and dip angle of the carbonate breccia strata. Measurable outcrops were mainly located close to, or just above, the steep scarps (Figs. 6A and 6B). The dip direction of the carbonate breccia strata, outcropping at the highest altitude closest to the Nanos cliff, is 230/30 (Fig. 6C, steep scarp 1). The next outcrop of carbonate breccia, detected lower down the slope on the secondary steep scarp, has a dip direction 210/20 (Fig. 6C, steep scarp 2), while the lowest lying breccia is dipping to the northeast (azimuth = 50°) with a relatively large dip angle of 25° (Fig. 6C, steep scarp 3).

Scree deposits

Scree deposits are located below the carbonate cliffs present in the uppermost part of the slope. Depending on the specific lithological and structural predisposition of the Nanos cliff, the deposits are deposited in talus cone shapes or scree

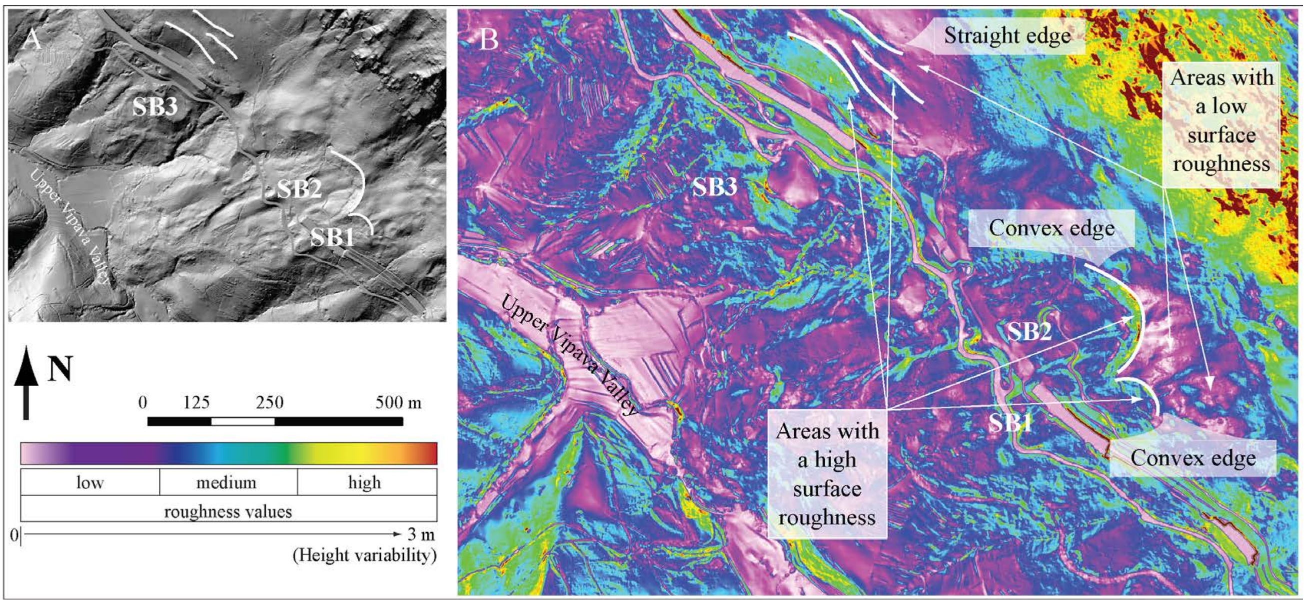

Fig. 4. (A) Shaded, digital terrain models (DTMs) with a resolution of 1 × 1 m, obtained by airborne laser scanning in the areas of SB1, SB2 and SB3 indicating the location of the convex and straight scarps. (B) A height variability map with the convex and straight scarps marked on SB1, SB2 and SB3. The upper arrows indicate an individual area with a very low surface roughness attributed to planation surfaces and the lower arrows indicate areas with high surface roughness, which are bound to individual convex scarps.

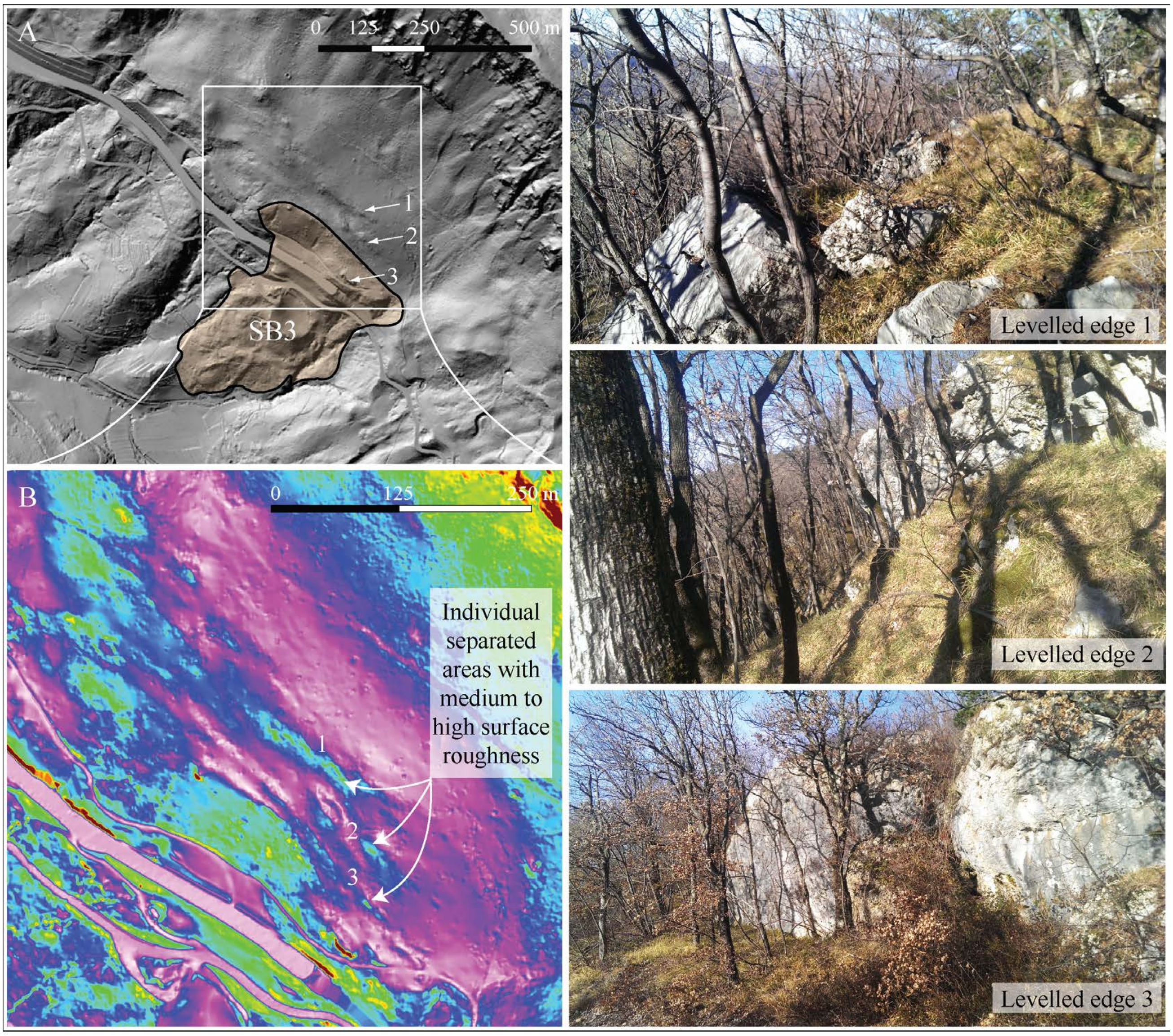

Fig. 5. (A) Shaded digital terrain model of the broad area of SB3 and indicated location of levelled edges (boundary between height and low surface roughness). (B) On the height variability map, belts with a high height variability are well recognized showing the steep scarps, forming a stepped structure in the hinterland of the Šumljak 3 sedimentary bodies. The scarps and individual rupture surfaces that were recorded in the field are shown on the right.

sheets (Popit et al., 2014a). On the basis of their spatial distribution, we were able to separate two levels of scree deposit, separated by the primary outcrop of Mesozoic limestone. The upper level scree deposits are smaller and accumulate on individual primary outcrops at their lower edges, while the scree deposits in the lower level are larger and distinctly cone-shaped (Fig. 7). The slope angles of the scree deposits appear to be between 33° and 45°.

Discussion

In the hinterland of the steep scarps of the SB1 and SB2 planation surfaces, carbonate breccia is observed, continuing almost to the foothills of the Nanos cliff (Fig. 8). We interpret the formation of these planation surfaces as being the result of a deep-seated rotational slide, where the carbonate breccia block and poorly lithified scree deposits rotated along the sliding surface that originated on the contact with the underlying weathered flysch base rocks and/or muddy mass-flow deposits.

Downslope, the planation surfaces pass through the steep scarps into the Šumljak sedimentary bodies. The Šumljak sedimentary body SB2 is characterised by a recognisable convex edge that is incised in carbonate breccia. We interpreted it as being the main scarp of the rock avalanche in SB2 (Fig. 4), that was triggered in the accumulated material at the outer margin of a large-scale, deep-seated rotational slide. Today, remobilized material forms the cover of SB2 in the upper part of the sedimentary feature.

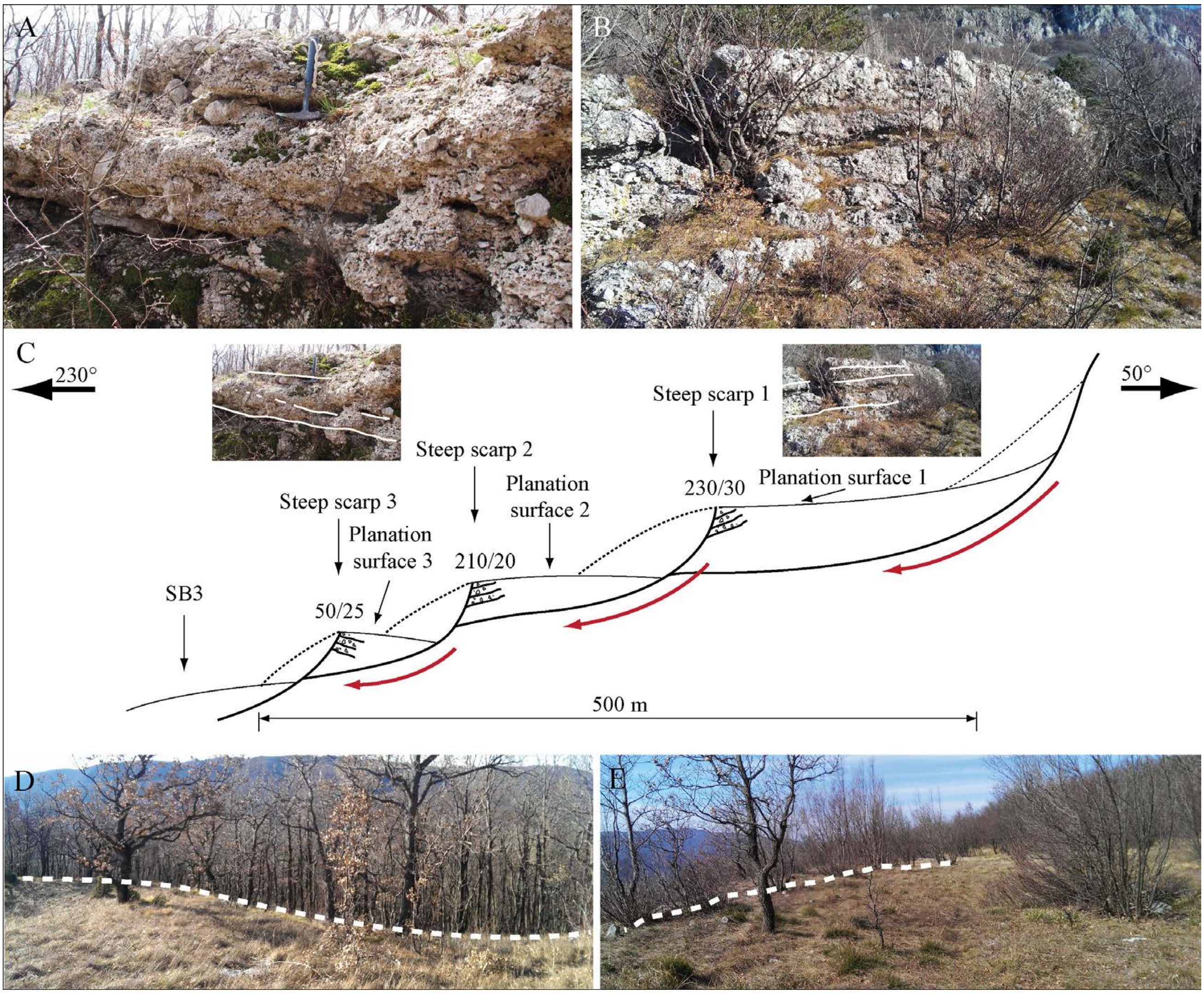

Fig. 6. Examples of planation surfaces and steep scarps which are connected to SB3. (A and B) Bedding of slope breccia in the upper parts of the steep scarps 1 and 3. (C) The slope breccia at scarp 1 (in the highest altitude and the nearest to Nanos cliff) has a bedding orientation of 230/30; at scarp 2, the orientation of beddings is 210/20 and the orientation of bedding of the breccia of the lowest-lying scarp (scarp 3) is 50/25. (D) The dashed line indicates the upper steep scarp 1 and (E) steep scarp 3.

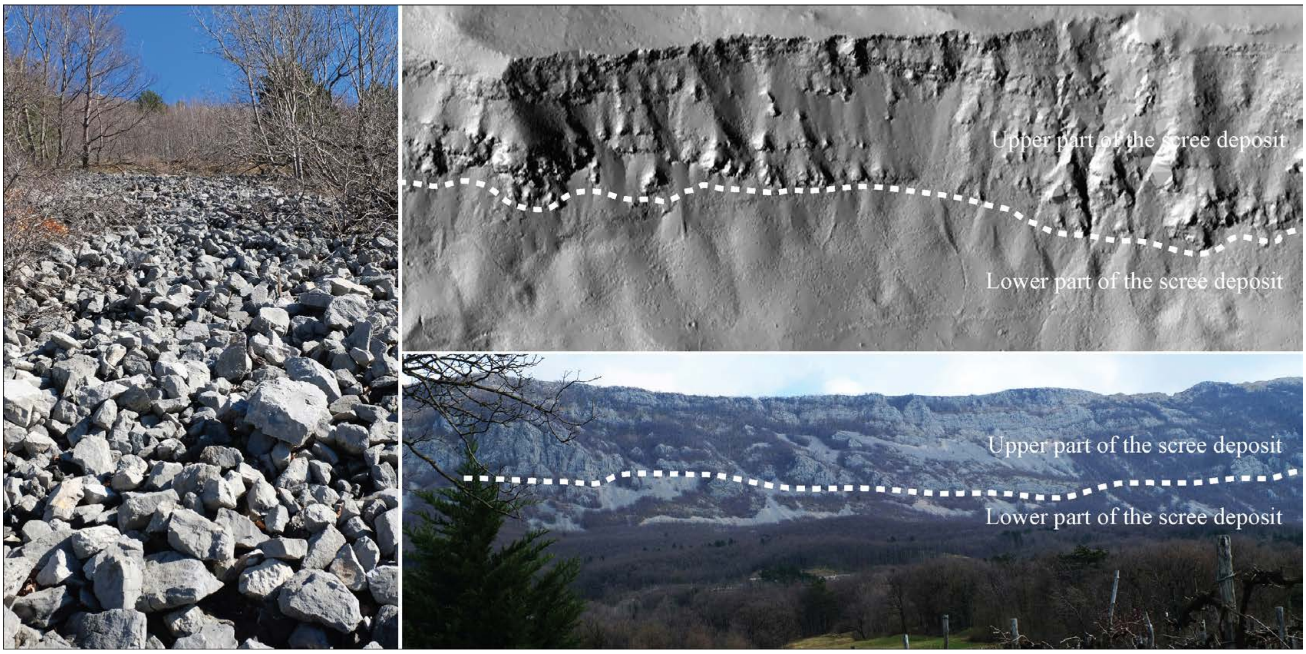

Fig. 7. Two positions of the scree deposits (talus cone and scree sheets) in the Rebrnice area. The photograph of the scree deposit (left figure) was taken in the upper part of the Nanos cliff.

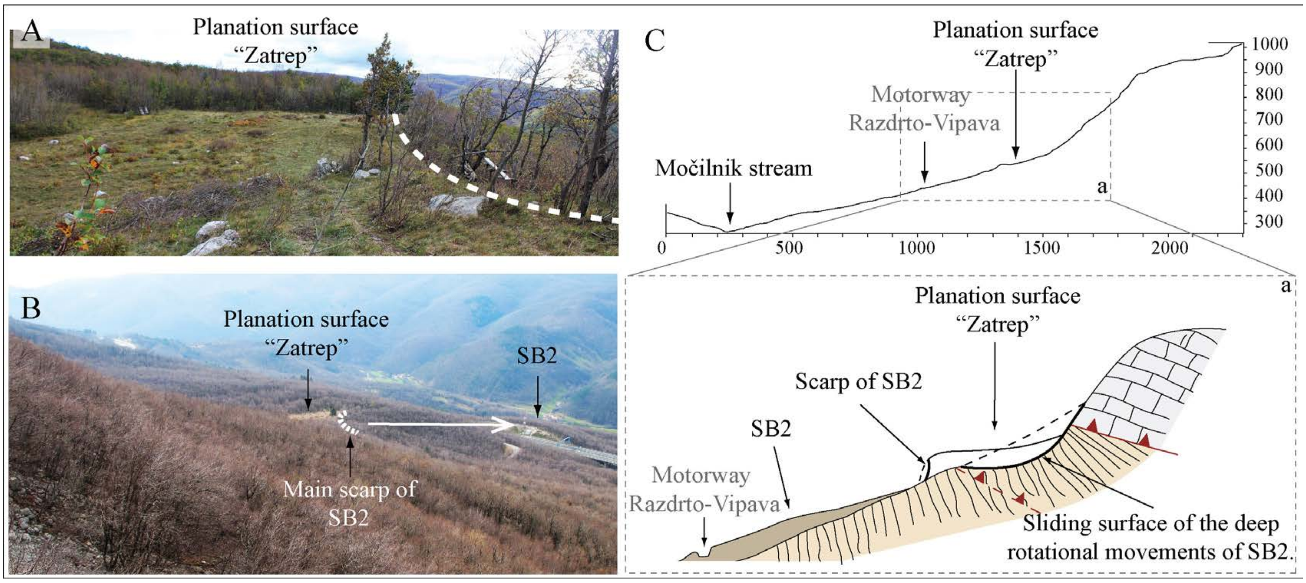

Fig. 8. (A) The example of the "Zatrep" planation surface and main scarp behind SB2. The dashed lines indicate the upper scarp. (B) The white arrow shows the direction of transport of material and is at right angles to the scarp. (C) Schematic longitudinal profiles through SB2 and (D) Flat surface resulting from the rotating block of carbonate breccia. A new steep scarp was formed in the toe of the rotational block, due to deep rotational movements along the sliding surface of the block in SB2.

The same observations are reported from deep-seated landslides, where a steep scarp often forms at the outer part of the sliding mass (Amudsen et al., 2010). The main direction of extension of the convex edge at SB2 is approximately perpendicular to the direction of transport (i.e. the direction of the lateral edges of the sediment body) but with a smaller deviation in the case of SB2 (8.2°) and a slightly larger one in the case of SB1 (20.5°). This is one of the typical properties of steep scarps (Van Den Eeckhaut et al., 2012a; 2012b) and can be identified in the Rebrnice area.

In the case of SB3, the overall architecture and depositional evolution is more complex. It was possible to identify at least three scarps that are approximately parallel to each other and laterally 'wedge out' (Figs. 5 and 6). By our interpretation, this step-like sequence is formed by the same large-scale mechanism that operated in the case of SB1 and SB2, i.e. a deep-seated rotational landslide, which developed into a rock avalanche in the lower slopes. Additionally, above the steep scarp, two parallel scarps occur which signify multiple, rotational landsliding that successively developed at the outer part of the large-scale, rotational landslide. The architecture of these landslides corresponds well to so-called 'diminishing' landslides, where the volume of the moving mass gradually decreases (cf. Cruden & Varnes, 1996). The planation surfaces between the individual scarps can be attributed to the different rotation of individual carbonate breccia blocks. Individual breccia blocks slipped down the slope and, at the same time, rotated towards the slope. Stairstepped patterns of displaced backward-rotated blocks, also called reverse slopes (Van Den Eeckhaut, 2011).

A deep-seated rotational slide is further indicated by the variation of dips within the breccia beds. The dip direction and dip angle of the breccia beds, which forms the base-rock of the planation surface, depends on their spatial position. Upward, near the Nanos carbonate cliff, the slope and the dip angles of breccia beds are parallel or nearly parallel to the directions of the slope. In the middle section, the dip angles of the bedding are subhorizontal and, in the lower parts of the planation area just above the lowest scarp, the carbonate breccia beds dip towards the slope (Fig. 6). If the dip angle in the lower part of the rotary block (50/25°) is reversed back to its primary orientation of between 210/35° and 230/35° (i.e. the inclination of the recent scree and breccia layers in the highest part of the slope) then the total rotation is approximately 60° (25° + 35°).

Conclusion

The planation surface in the hinterland of the Šumljak sedimentary bodies is a morphological expression of a deep-seated rotational landslide that developed along a line of transect from the Nanos carbonate cliffs to the less-steep, lower Rebrnice slopes and it is marked by flysch base rocks. The rotational slides are composed mostly of a well-stratified, carbonate breccia, originating from the partial lithification of scree deposits. Dipping of the breccia beds in particular segments of the rotational blocks in SB3, indicates that the overall rotation can reach up to 60°. The planation surfaces occur in the lower parts of the landslides, where the dipping of the breccia beds is rotated from being 35° parallel to the slope to becoming subhorizontal (or even up to 25°) towards the slope. The lower margin of the planation surface is defined by steep scarps that are the result of the subsequent debris and/or rock avalanches. The material that accumulated in the lower parts of the rotational landslide, was remobilised and transported further downslope, where it also covered older mass-movement deposits, created by a variety of previous transport mechanisms and depositional processes. All of the mass-movement deposits below the steep scarps now comprise the internally complex Šumljak sedimentary bodies.

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