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SCIENCE

Geomorphology of the Durmitor Mountains and surrounding plateau Jezerska Površ (Montenegro)

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The geomorphological map of the northeastern Durmitor Mountains and the plateau Jezerska Površ (1:10,000, 47 km^2, Montenegro, Dinaric Alps) was prepared from an intensive fieldwork campaign and remote sensing analysis, and was compiled within a GIS. The basic components of the legend are (i) processes/genesis, (ii) materials, (iii) morphometry/morphography, (iv) hydrography, (v) vegetation and (vi) anthropogenic features. The geomorphological setting of the area consists of Mesozoic limestones which are physically deformed by Quaternary glacial and periglacial activity and chemically affected during interglacials. Glacial deposits on the plateau of three middle-to-late Pleistocene glacial phases are intersected by a well-developed network of palaeo meltwater channels. In the mountains, Holocene glacier retreat left behind a series of well-preserved recessional moraines. The map serves as a valuable tool for Quaternary research in the Durmitor Mountains, and also in other mountains of the Western Balkans.

Keywords: Debeli Namet glacier; Dinaric Alps; Geographic information system; Geomorphological map; Glacial landforms; Karst

1. Introduction

The Durmitor Mountains are situated in northern Montenegro and culminate at 2523 m a.s.l. (Bobotov Kuk). They relate to the Dinaric Alps, which stretch from the Julian Alps in Slovenia to the Prokletije Mountains in northern Albania (Figure 1). As for many other Mediterranean mountain ranges, the Durmitor Mountains are built up of carbonate rocks of Mesozoic age (Djurović, 2009), that were folded and uplifted during the Alpine orogeny (Morley, 2007). The topography is characterised by a Quaternary glacial-interglacial imprint, that drastically modified the pre-glacial topography (Fagan, 2009), and geomorphological processes were altered by human occupation throughout the Holocene (Lewin & Woodward, 2009).

This study focuses on the northeastern part of the Durmitor Mountains and surrounding lower plateau (Figure 1), where evidence is found for three middle-to-late Pleistocene glacial phases which have been correlated to Marine Isotope Stages (MIS): the Skamnellian Stage (MIS 12), the Vlasian Stage (MIS 6) and the Tymphian Stage (MIS 5d-2) (Hughes, Woodward, van

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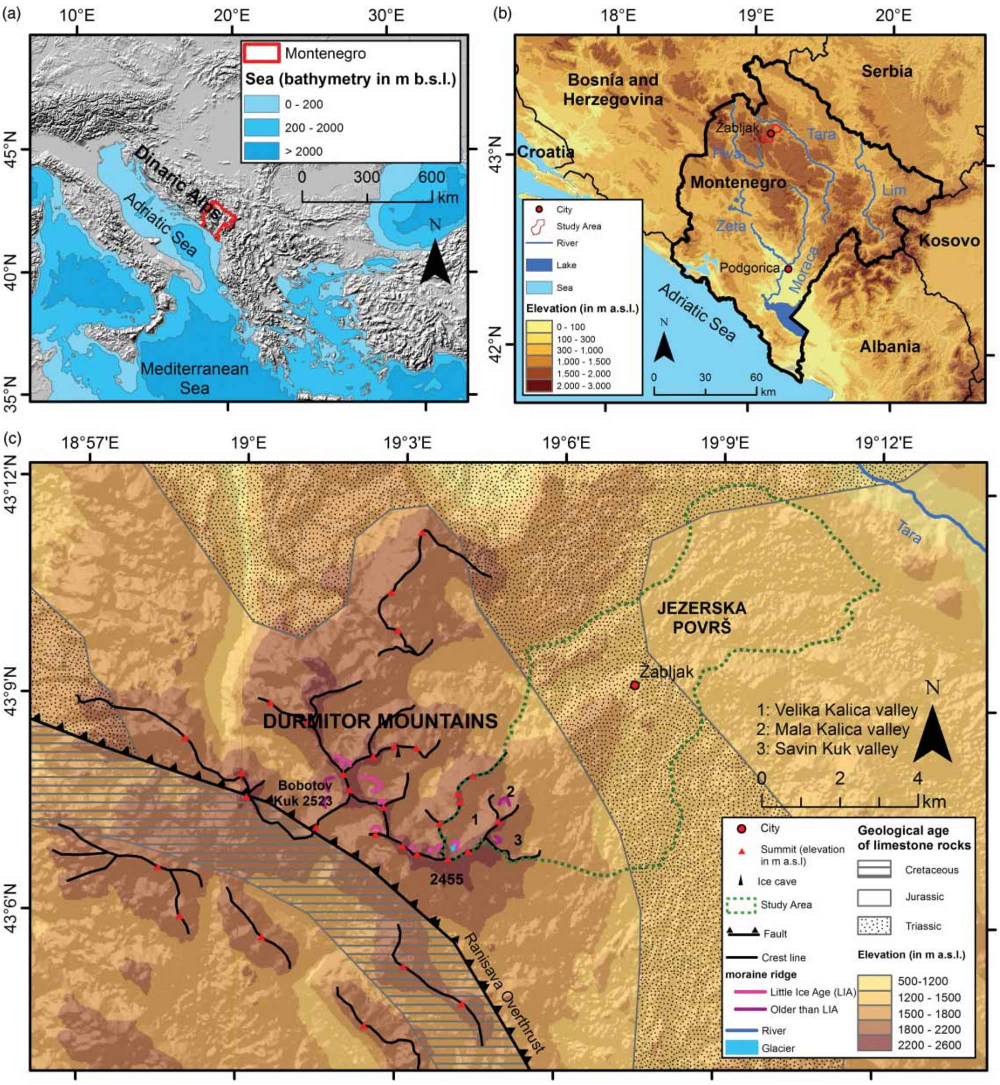

Figure 1. Location of the study area; (a) position of Montenegro in Western Balkan (available from http://naturalearthdata.com/); (b) position of the study area in Montenegro on the SRTM DEM (available from http://srtm.csi.cgiar.org/); (c) Durmitor Mountains and surrounding plateau Jezerska Površ, indicating several upper cirque moraine ridges on the ASTER DEM (available from http://reverb.echo.nasa.gov/reverb/).

Calsteren, & Thomas, 2011). These cold stages are in concordance with the findings in other mountains in Montenegro (Hughes, Woodward, van Calsteren, Thomas, & Adamson, 2010) and in the Balkan peninsula (Hughes, Woodward, & Gibbard, 2006). The degree of severity of the cold stages was most likely determined by differences in temperatures and not by a decrease in moisture supply (Hughes & Braithwaite, 2008). Fall in temperature was of the same magnitude as values calculated by Hughes and Braithwaite (2008) for glacial stages in the Pindus Mountains in Greece. Hereby, the oldest glaciation was the most important in severity and longevity; younger glaciations were smaller in extent. The present-day climate in northern Montenegro is determined by its mountainous character, with snow cover from November to April, moist conditions all year long and warm summers (Kern, Suranyi, Molnar, Nagy, & Balogh, 2006; Kottek, Grieser, Beck, Rudolf, & Rubel, 2006; Nyssen et al., 2012). In Žabljak, at 1450 m a.s.l., the annual total precipitation is 1454 mm and the mean annual temperature is 5.1 °C (Kern et al., 2006). Present-day glacial activity is limited to the avalanche-fed Debeli Namet glacier (0.05 km^2) in the Velika Kalica valley with an Equilibrium Line Altitude (ELA) at 2150 m a.s.l. The glacier is the remnant of a larger glacier that gradually retreated during the Holocene and is currently one of the southernmost glaciers in Europe (Djurović, 2012; Grunewald & Scheithauer, 2010; Hughes, 2007). The dominant trend in Žabljak for the last 50 years, just as in the whole northern Montenegrin area, is one towards higher mean annual temperatures and larger inter-annual fluctuations (Djurović, 2012).

In the Balkans, few studies exist on Quaternary glaciations and the relationship with palaeoclimates (Hughes et al., 2006). In addition, there are few detailed geomorphological maps for this region in which karst and glacial geomorphologies strongly interacted (Meković & Djurovć, 1993). Both processes/landforms have received increasing interest over the last two decades (Djurović, 1996, 2009, 2011, 2012; Hughes, 2007, 2010; Hughes et al., 2011). The geomorphological map presented in this paper aims at creating a geomorphological framework for understanding the landforms and their development throughout the Quaternary in the Durmitor Mountains. It allows a better reconstruction and understanding of the climatic past of the Balkans and its geomorphological impact.

2. Material and methods

The Durmitor area (Figure 1) was initially studied on the macro scale by analysis of remote sensing data. Orthophotographs (1:2500) collected from the Real Estate Agency Montenegro and Japan International Cooperation Agency (2007) were used to visualise ground cover and as a basis layer during the production of the map. Google Earth offered additional advantages. First, vertical exaggeration of the 3D terrain amplifies terrain characteristics which are otherwise often overlooked, such as undulations on the plateau. Second, digitizing options allowed the compilation of transects, which facilitate interpretation of small-scale geomorphological entities. Orthophotographs and Google Earth are complementary in use and give important insights in to the macro geomorphology of the terrain and allow preliminary interpretations of landforms. These media prove to be important, since no stereoscopic aerial photographs could be consulted for the Durmitor area, which are frequently used for accurate remote sensing analyses (e.g. Boike & Yoshikawa, 2003).

A field campaign was organised during August and September 2012. The aim of the field survey was to collect ground data on the micro- and meso-scale landforms, which cannot easily be performed using remote sensing data alone. Features which were described during the field work are limestone pavements, alluvial fans, debris of varying size, glacial erratics (materials), soli-/gelifluction lobes, solifluction ribbles, river terraces, karst features and channel morphology (morphography/morphometry). Most hydrological, anthropogenic and vegetation characteristics were also observed on-site. Moreover, slope gradients of scree slopes and debris cones were measured with a clinometer. In addition, notes were made concerning the activity of those slopes. Finally, the glacial sedimentary environment was characterised through (i) measurements of the volumetric stone content and (ii) analysis of the particle size distribution of fine earth ($<$ 2 mm) (Annys, Frankl, Spalević, Milić, & Nyssen, 2013). Ground-truth was recorded using a Garmin eTrex H handheld Global Positioning System receiver (GPS, $<$ 10 m RMS, over 1300 terrain points). All observations were photographically documented and described in the field.

A profound knowledge of the terrain obtained through remote sensing analysis and fieldwork allowed the preparation of a detailed, terrain-fitting legend which provides a high diversity of geomorphological information (Figure 2). Different properties of landforms are considered separately and organised in a 'box of blocks' legend. Building blocks of the legend are: processes/genesis, materials, morphography/morphometry, hydrography, vegetation and anthropogenic features. Only by combining the different symbols and colours on the map are landforms defined. This concept was first developed by De Graaff, De Jong, Rupke, and Verhofstad (1987) for large-scale mapping of complex mountainous areas and further refined and integrated into a

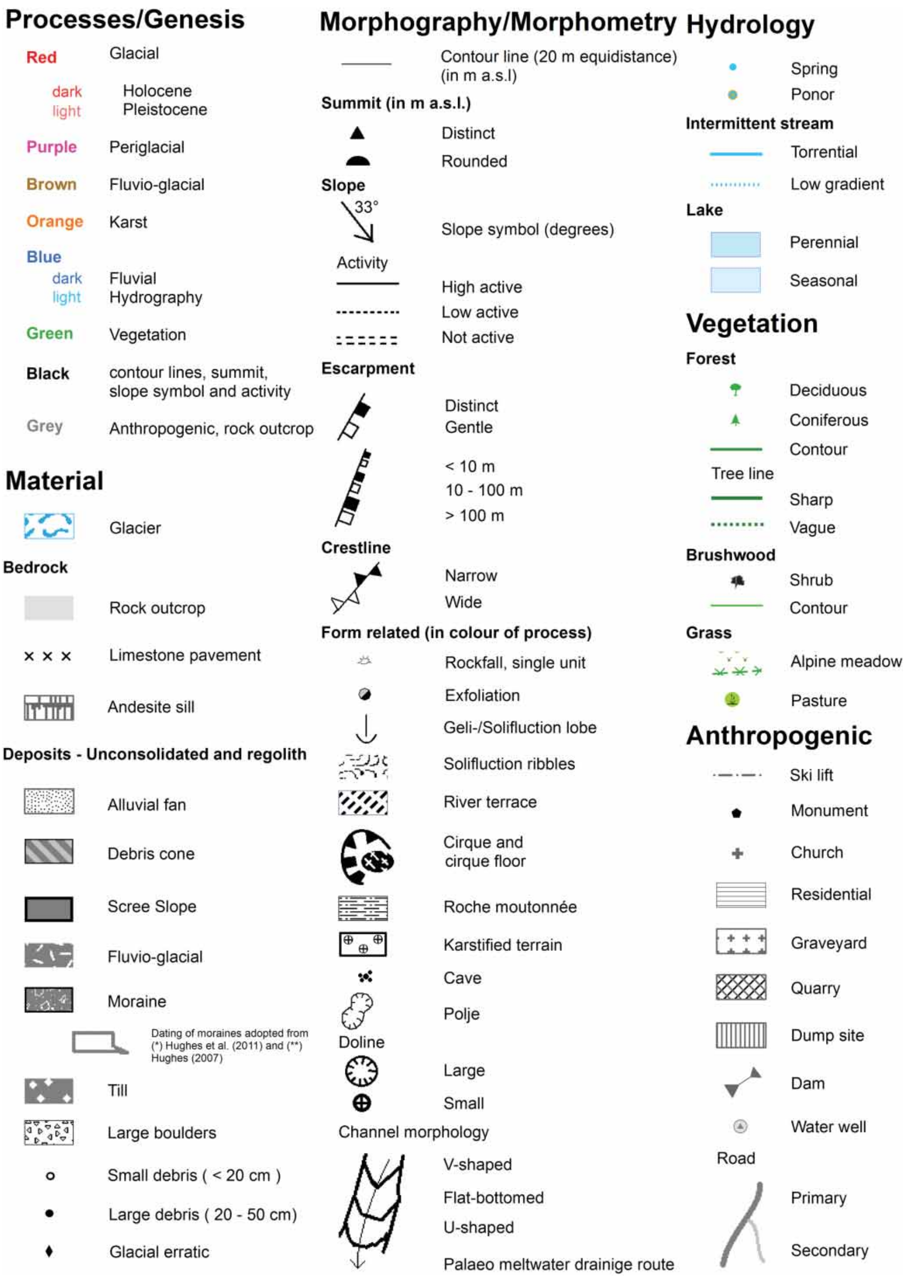

Figure 2. Box of blocks legend adjusted to the study area.

geographical information system (GIS) by Gustavsson, Kolstrup, and Seijmonsbergen (2006). The box of blocks legend has been applied to various environments (e.g., Evans, 2012; Frankl, Nyssen, Calvet, & Heyse, 2010; Loibl & Lehmkuhl, 2013; Poppe et al., 2013). The resulting thematic structure of the legend fits the practical implementation within a GIS, as unique features are represented by unique symbols.

Finally, the geomorphological map was produced within a GIS (Esri ArcMap 10.1) at a standard scale of 1:10 000. The geographic datum used is WGS 1984 and the projection a Transverse Mercator. Contour lines were derived from ASTER GDEM 30 m resolution (National Aeronautics and Space Administration, 2011) in ArcMap through use of the Spatial Analyst Contour tool. However, before contouring, data were first slightly smoothed using the function 'Focal Statistics' in the Spacial Analyst Tools, according to the proposed methodology of Price (2006).

3. Results

The geomorphological map includes both the northeastern part of the Durmitor Mountains and the surrounding lower plateau Jezerska Površ (Figure 1). Both areas have distinct glacial, periglacial and karst landforms. The main valley is Velika Kalica and is host to the small Debeli Namet glacier. The study area is a case study for mountainous areas in the Western Balkans which have undergone a similar environmental history.

3.1. *Glacial erosional and depositional features*

Large U-shaped valleys with smoothed sidewalls were formed in the mountainous area during the middle-to-late Pleistocene glacial stages (Figure 3(a)). Glaciers moved towards the lower plateau, where topographic irregularities were smoothed and *roches moutonnées* of varying size and extent were formed (Figure 3(b)). These glaciers carried large amounts of debris supra-, en- or subglacially before they were melted out on the lower plateau along the glacier margin during a glacier stabilisation or recessional phase. Glacial deposits form several high elongated lateral moraines with gentle slopes, stretching from southwest to northeast. This indicates the former glacier flow orientation from the mountain towards the Tara canyon in the northeast, outside the study area. The Pitomine ridge northwest of Žabljak is a good example of a lateral moraine (Figure 3(c)), composed of materials from several former north-facing glaciers in the Durmitor Mountains. Polygenetic tills cover most of the remaining surface on the plateau and are characterised by the even or slightly undulating surface. Scattered glacial erratics ($> 1\ m^3$) are also a primary distinguishing mark of the former glacial extent, although, only few were observed.

In the mountain valleys, gradual retreating glaciers deposited a series of arcuate, recessional latero-frontal moraines. The intervening valley floor is covered by a chaotic ensemble of large boulders (Figure 3(a)). The youngest moraine ridge is situated at the glacier snout of the avalanche-fed Debeli Namet glacier ($0.05\ km^2$) beneath the backwall cliffs of Sljeme. Transverse crevasses indicate the glacier is still actively moving downwards and is not just a static ice-patch. Thin supraglacial moraines cover about one fifth of the glacier and can increase the summer melting due to a lowered albedo (Nakawo & Rana, 1999), albeit the pale-coloured limestone debris is less effective than dark-coloured debris (Paul, Machguth, & Kääb, 2005) (Figure 4). Former glaciers in the cirques in the southwest and in the east of the Velika Kalica valley, in the Mala Kalica valley and in the Savin Kuk valley are melted. In these cirques, small- to meso-scale roches moutonnées and limestone pavements are now exposed. Exfoliation due to pressure release is observed in the Savin Kuk valley.

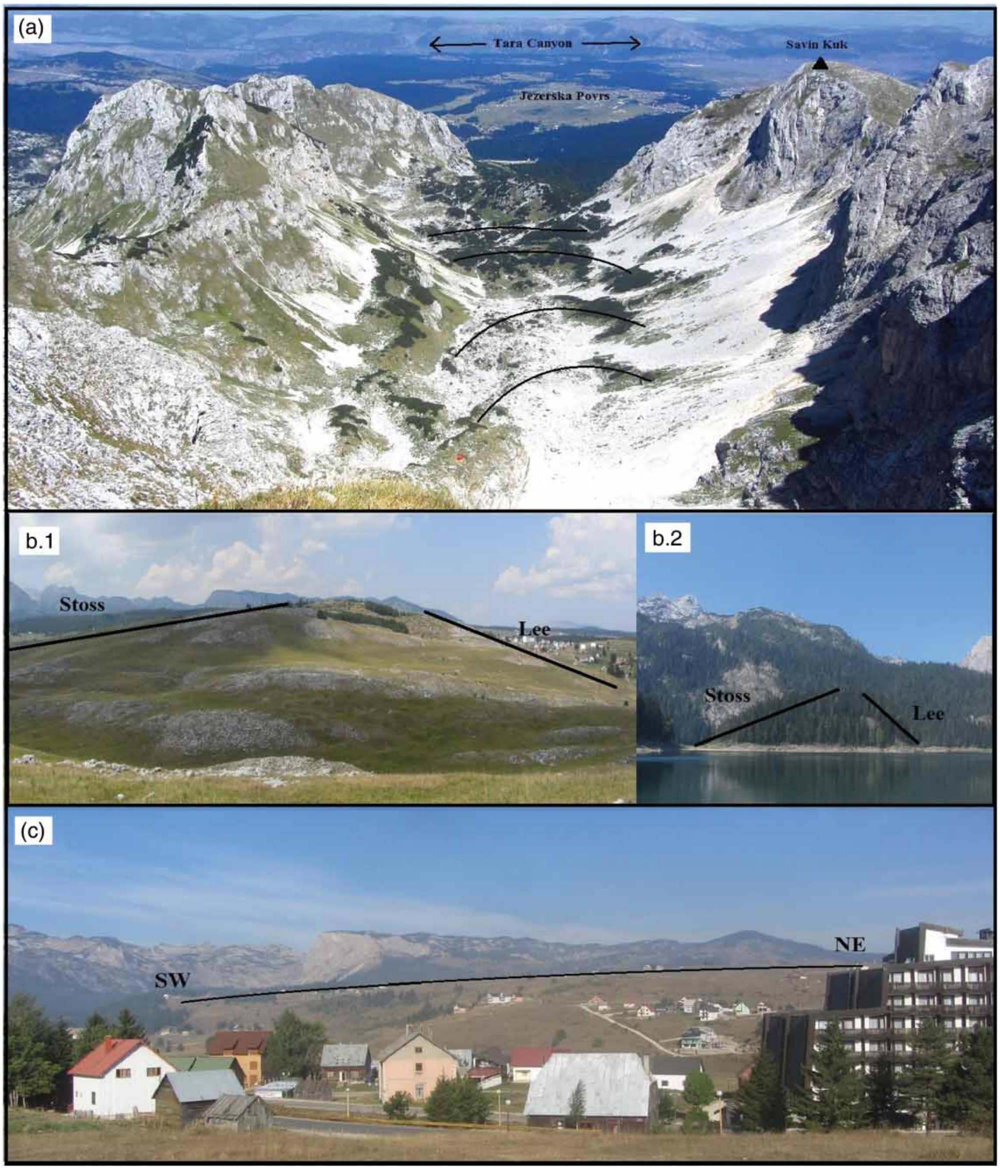

Figure 3. Glacial geomorphological features: (a) view from Vrh Sljemena (2455 m a.s.l.) towards the NE on Velika Kalica U-shaped valley with a series of Holocene moraine ridges, and on the undulating lower plateau Jezerska Površ; (b) *Roches moutonnées* with stoss and lee side: (b.1) in the southeast of Žabljak; (b.2) between the two glacial lakes of Crno Jezero. (c) lateral moraine ridge Pitomine in the northwest of Žabljak with southwest – northeast orientation.

Based on U-series dating (Hughes, 2010; Hughes et al., 2011) and lichenometry (Hughes, 2007, 2010), glacial deposits on the plateau have been attributed to three middle-to-late Pleistocene glacial phases, while the recessional valley moraines are Holocene in age. The moraine ridge in front of the Debeli Namet glacier formed at the end of the Little Ice Age and was most recently modified at the end of the twentieth century (Hughes, 2007). Dates are also indicated on the geomorphological map.

Figure 4. Debeli Namet glacier at the beginning of September 2012, indicating the Little Ice Age moraine ridge and patches of supraglacial moraines.

3.2. *Ice-marginal and periglacial landforms*

During the most severe glacial phases, piedmont glaciers covered large parts of the study area and periglacial conditions prevailed in the ice-marginal areas. Under permafrost conditions, glacial meltwater streams incised the glacial deposits and bedrock on the plateau and formed an extensive network of channels. These channels merged in the northeast of the study area, from where meltwater was drained towards the Tara canyon some kilometres to the east. There is one palaeo meltwater drainage route, however, which is not connected to the network of channels, but drained meltwater northwards (Figure 5(a)). Analysis of Google Earth imagery showed that meltwater was drained towards a closed basin (Figure 5(b)). During fieldwork, profiles of thick packages of deposits were observed in a quarry in the closed basin (Figure 5(c)). Laboratory analysis of fine materials showed that the coarser sandy fractions are dominant. From these observations, the deposits are interpreted as fluvio-glacial in origin, and thus, the basin was once a proglacial lake. Sediment is partly melt-out material, although most was probably transported by glacial meltwater and summer rain. In addition, the lake was at some point captured through headward erosion at its northernmost point (Figure 5(a)), from which the lake drained towards the Tara Canyon in the north. Several palaeo meltwater channels and river terraces occur along its length, which could be attributed to variations in meltwater discharge through time. Climatic conditions ameliorated throughout the Holocene and smaller valley glaciers occurred in the inner-mountains. Consequently, meltwater discharge was geomorphologically of lesser importance and favoured the preservation of old middle Pleistocene deposits. The high permeability of the limestone rocks prevented strong and long-lasting fluvial erosion to occur (Smith, Nance, & Genes, 1997) and so both the moraine ridges and valley morphology are well-preserved (Gale & Hoare, 1997). For the same reason, surface runoff is low and water is scarce in the mountainous part of the study area.

Today, active periglacial processes dominate in the high-mountain region, where steep scree slopes form beneath cliffs. Other observed periglacial forms are geli-/solifluction lobes and solifluction ribbles on steep slopes and frost shattering. Finally, periglacial conditions also occur in karstic hollows, where ice patches survive summer warmth due to local topographic controls (Hughes et al., 2006).

3.3. *Karst*

Physical erosion was the dominant process during glacial stages, while chemical erosion is the dominant process during interglacial periods. Karst forms in the study area are most likely Holocene in age, with older karst forms likely erased by glacial erosion.

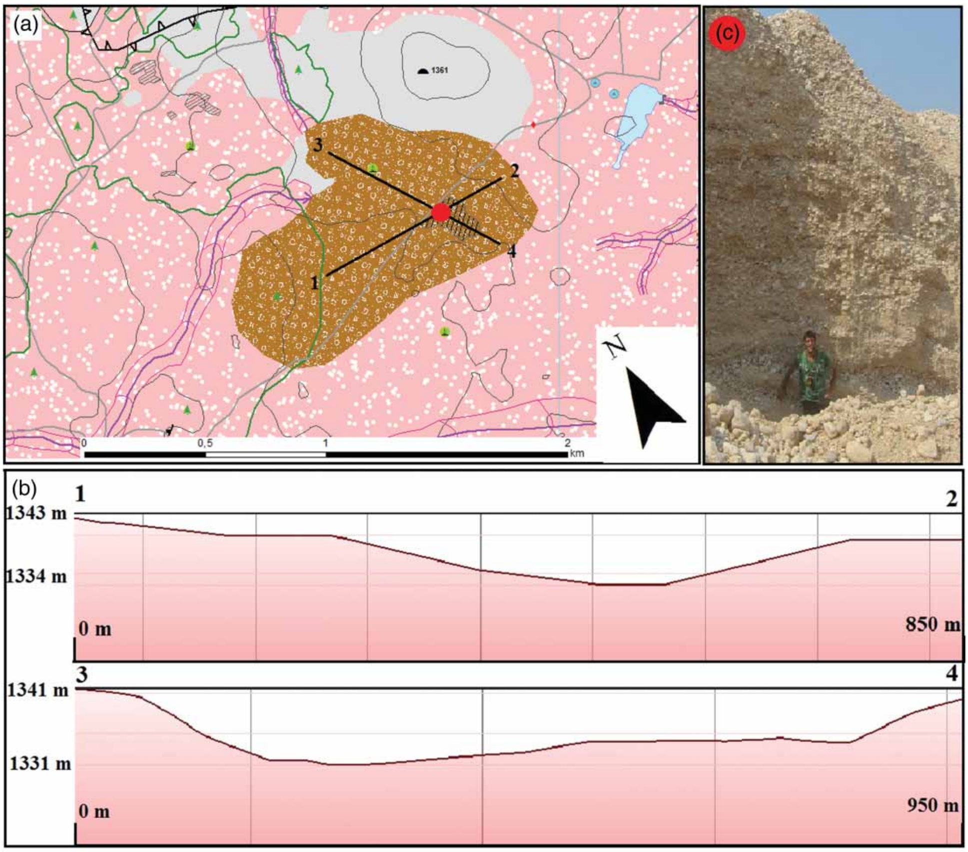

Figure 5. Former proglacial lake on the plateau Jezerska Površ: (a) snapshot from the geomorphological map, indicating its capture through headward erosion in the north; (b) height profiles from Google Earth (1–2, 3–4; see Fig 5.a); (c) quarry profile of fluvio-glacial materials.

On the lower plateau, few karst processes are observed since bedrock is mostly covered by glacial deposits. However, two roof-collapsed dolines are observed and in some places, the surface morphology of the tills is more hummocky than its direct surroundings, which are interpreted as a karstified terrain beneath a shallow depth of glacial materials. In the mountainous part of the study area, more karst forms occur. Many forms are too small to be represented on the geomorphological map and are, instead, subdivided in to different karstified terrain. The observed karst forms are deep grikes (*kluftkarren*), small runnels (*rundkarren*), pans and pits (*kamenitzas*) on individual blocks, meso- and large-scale grooves on vertical walls (*rillenkarst*), caves, small and large dolines and a polje (Figure 6). Terminology is based on Waltham, Simms, Farrant, and Goldie (1997) and Lewin and Woodward (2009).

Furthermore, karst forms tend to accumulate snow masses from which glacier growth could originate (Hughes et al., 2006). Therefore, pre-glacial karst forms could have enhanced initial glacier growth, forming glacio-karstic landforms. Cvijić (1917) even introduced the term ‘karst-glacier’ in the Dinaric Alps as a new type of glacier. The relationship between glacial and karstic landforms is dual. In the mountainous area, former glaciated terrains are strongly modified by chemical erosion, forming karstic-glacial landforms. Closed depressions here drain water from the surrounding slopes, for instance after snowmelt or summer rains, where it

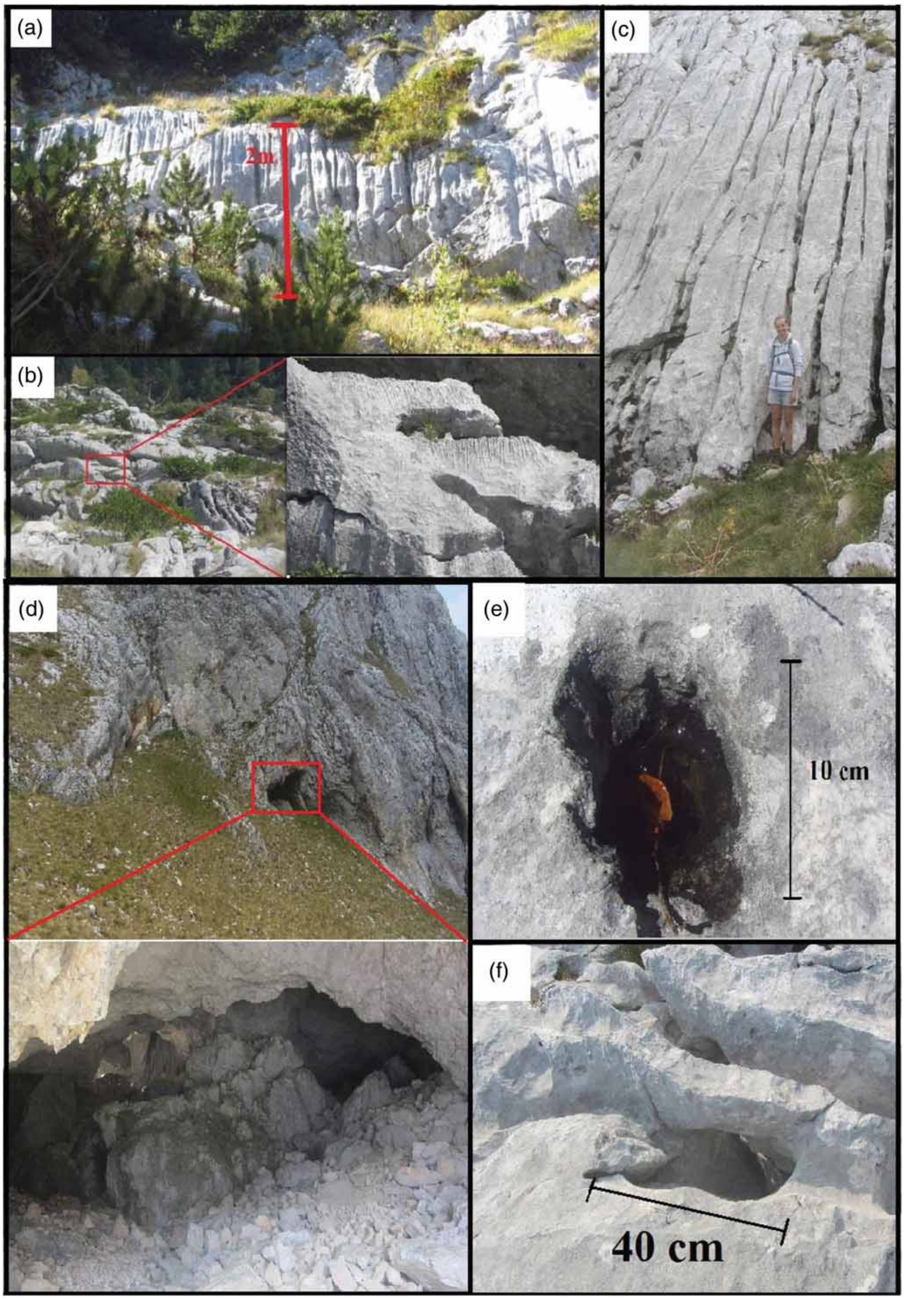

Figure 6. Karst forms observed in the field: (a) grikes at meso-scale (*kluftkarren*); (b) runnels at micro-scale (*rundkarren*) (c) grooves at macro-scale (*rillenkarst*); (d) cave; (e) pan; (f) pit (*kamenitzas*).

percolates deep into to the rocks. Karst forms appear due to the dissolution of the soluble limestone rocks. Cirque floors, for instance, are covered by dolines. The relationship may be dual, but cyclic alternation of cold and warm stages may result in the development of polygenetic and polymorphic forms (Djurović, Petrović, & Simić, 2010; Klimchouk, Bayari, Nazik, & Törk, 2006), which leads to an increasingly complex terrain.

4. Conclusions

The geomorphological map, prepared from detailed field survey and analysis of orthophotographs and Google Earth imagery, shows part of the Durmitor area, of which the topographic character is predominantly shaped by glacial and periglacial processes. During three middle-to-late Pleistocene glacial phases, elongated lateral moraines and tills were deposited on the plateau. Palaeo meltwater flows incised and formed a well-connected network of drainage channels, of which the outlet in the northwest leads towards the Tara canyon. In the Alpine uplands, a series of smaller, well-preserved recessional moraines of Holocene age occur. Here, frost shattering is the dominant contemporary geomorphological process, forming steep scree slopes beneath high cliffs.

The large-scale geomorphological map is the first of its kind in the Durmitor area and aims to help reconstruction of the evolution of the landscape in order to fully understand the current geomorphological setting. The cartographic legend is adjusted to the specific study area, but the classification of elementary symbols and graphics is deliberately available for extension to one's own research objectives. For this reason it is proposed to use the structure and major subdivisions of the legend as a steppingstone for the development of legends applied to large-scale maps of similar geomorphological areas. In conclusion, the presented map and accompanying legend serve as valuable tools for Quaternary research in the Durmitor Mountains, and in addition in the mountains of the Western Balkan, to reconstruct and understand the climatic past and its geomorphological impact upon the landscape.

Software

The glacio-geomorphological map is partly based on analysis of Google Earth imagery and is constructed in Esri ArcMap 10.1.

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Supplementary data

The geomorphological maps of the Durmitor Mountains and surrounding plateau Jezerska Površ (Montenegro) can be found as supplementary data on: http://dx.doi.org/10.1080/17445647.2014.909338

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