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A lidar, GIS and basic spatial statistic application for the study of ravine and palaeo-ravine evolution in the upper Vipava valley, SW Slovenia

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ABSTRACT

The analysis of high resolution airborne lidar topography represents an essential tool for the geomorphological investigation of surface features. Here we present a detailed lidar-based geomorphological analysis of the ravines cut into the slopes of the upper Vipava valley, NW Slovenia. The NE slopes are defined by an Oligocene thrust-front of Mesozoic carbonates overthrusted on Tertiary flysch and covered by numerous fan-shaped Quaternary gravity flows, deposited in palaeo-ravines cut into the flysch base rock. In contrast, the opposite SW slopes are composed solely of flysch. The large dextral-slip Vipava fault extending in the NW–SE direction is present in the central part of the valley. Our research revealed that although the ravines on both slopes of the Vipava valley are lithologically and tectonically controlled, significant statistical differences in their directions exist. Thus, ravines on opposite slopes are not solely related to the Vipava fault system deformation, but instead reflect a more complex tectonic setting. We believe that the ravines are controlled by second-order faults and fault zones that connect the Vipava fault with adjacent faults. On the SW slopes, these include connecting faults between the Vipava and the southwestern Raša fault, with the ravines on the NE slopes formed in fault zones connecting the Vipava and northeastern Predjama faults.

1. Introduction

Located in western Slovenia, the upper part of the Vipava valley represents a geomorphological boundary between the northeastern Nanos mountain range and the southwestern Karst plateau (Fig. 1). The valley is characterised by a generally asymmetric transverse (NE–SW) profile; whereas the NE slopes (an area known as Rebrnice) are defined by a thrust front of Mesozoic carbonates over Tertiary flysch deposits, the SW slopes (Vipavska Brda) are composed solely of flysch (Fig. 1). The distinctive geomorphological feature of the upper Vipava valley is the presence of numerous ravines that are cut into both sides. Both slopes are characterised by active or recent ravines, although the Rebrnice slope also contains numerous 'palaeo' ravines filled with Quaternary gravity flows. The ravines exhibit marked differences in shape as well as in direction, indicating a polyphase evolution with different geological controls on their origin.

The present work represents a detailed geomorphological study of the ravines using detailed mapping, sedimentology, lidar data, and basic spatial statistical methods. The study includes an analysis of not only all recent/active ravines, but also filled 'palaeo' ravines (hereafter referred to as palaeo-ravines). Whereas the shape and direction of active ravines were measured directly via GIS, the features of the palaeo-ravines were established based on a combination of sedimentological, spatial, and statistical data (see Section 4.2).

On the basis of the obtained data, we aim to define and quantify the differences in ravine shape and direction before relating these features to the different processes controlling their formation. The data is then also used to interpret the tectonic geomorphology of the valley and to reconstruct the area's Neogene tectonic kinematics.

2. Geological setting

The investigated area is geotectonically part of a complex SW-verging Eocene to Oligocene fold-and-thrust structure of the External Dinarids (Placer, 1981, 1998). The Vipava valley belongs to three different nappes (from structurally lower to higher): the Komen, Snežnik, and Hrušica (Fig. 1). The Rebrnice (NE) slopes of the valley are defined by a thrust front of Mesozoic carbonates of the Hrušica nappe, overthrusted on Tertiary flysch of the Snežnik nappe. This geotectonic position is reflected in the distinct asymmetric aspect of the valley slopes; whereas the upper part of the slope is marked by steep carbonate cliffs, the middle and lower areas are more gently sloping and are composed of flysch bedrock covered by numerous fan-shaped Quaternary gravity flows (Popit et al., 2006; Jež, 2007; Popit and Košir, 2010). Both the central part of the valley and the Vipavska Brda (SW) slopes belong to the Snežnik and Komen nappes and are composed solely of flysch devoid of any Quaternary gravity flows. A large Neogene dextral strike-slip fault zone (up to

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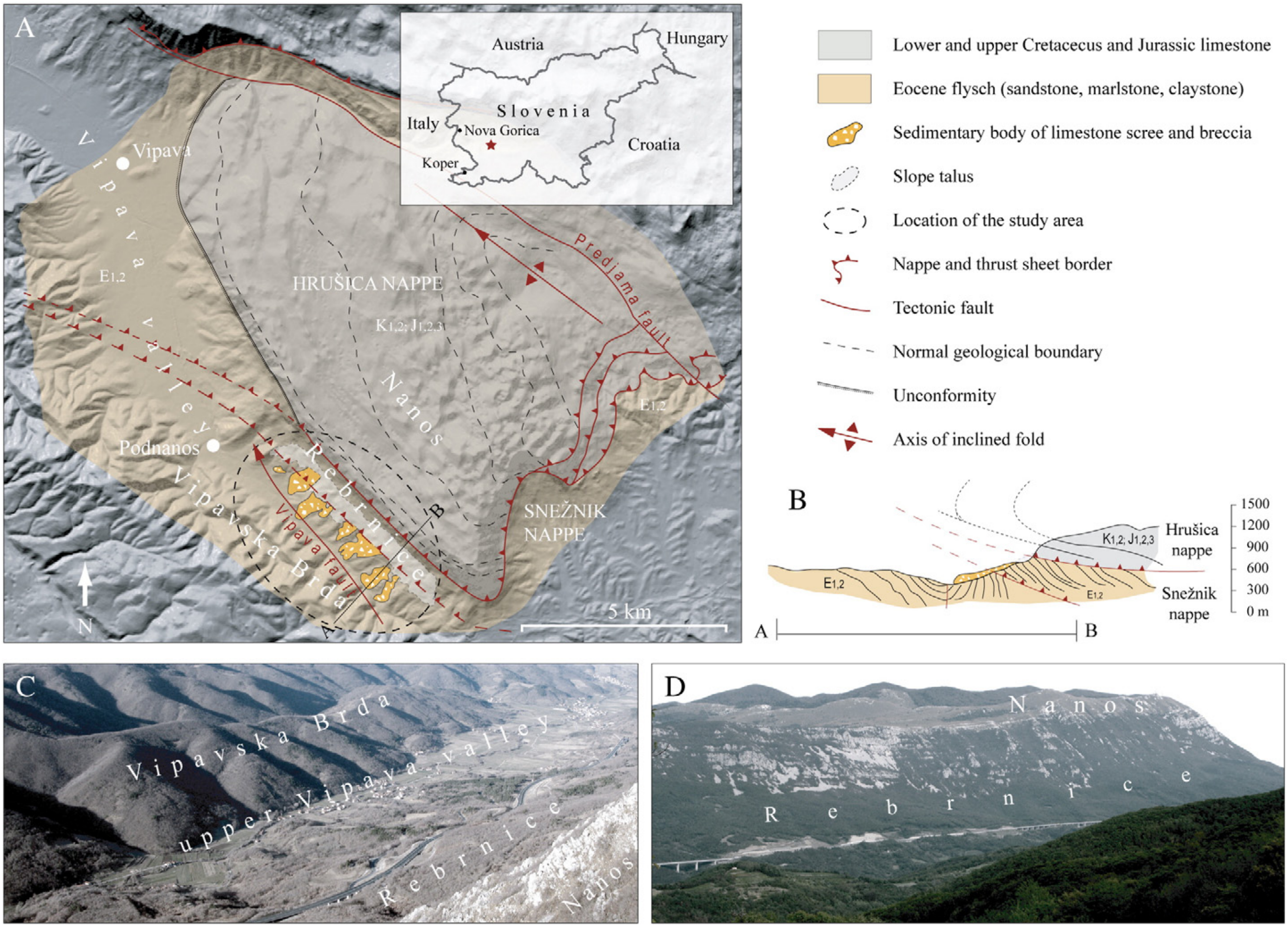

Fig. 1. (A) Geographical location of the study area and a simplified geological map. (B) Cross section through Vipavska Brda across the upper Vipava valley to Nanos, SW Slovenia (compiled from Placer, 1981, 2008). The lower images (C) and (D) show the oblique aerial views approximately parallel to the line of the cross section.

300 m wide) known as the Vipava fault is also present in the central part of the valley (Fig. 1) (Placer, 2008).

3. Methods and materials

The present study was carried out using a combination of detailed geological and geomorphological mapping together with remote sensing data obtained via lidar scanning, the latter covering 44 km^2 of the upper Vipava valley between Razdrto and Ajdovščina. An Optech ALTM GEMINI lidar system was mounted on an aeroplane, with measurements taken during 40 parallel and 4 perpendicular flight lines for the whole area, and another 54 parallel and 4 perpendicular flight lines over the Rebrnice slope area (Table 1). The sampling distance between measurement points on the ground ranged between 0.25 and 1.29 m with an average of 0.66 m. A 1-m resolution DEM was then obtained via a combination of adaptive triangulated irregular network densification (ATIN; Axelsson, 2000; implemented in Terrasolid Terrascan 11) and repetitive interpolation (REIN; Kobler et al., 2007). The REIN algorithm uses a two-step approach to calculate a raster DEM. The first phase involves the employment of a geomorphological filter to eliminate all echo points lying under the terrain, as well as most (but not necessarily all) of those lying above the terrain. The second phase removes the remaining nonterrain points and computes the raster elevation model. In the present study, this procedure was modified by replacing the first phase, i.e., the geomorphological filter, with ATIN filtering because it has a large advantage in the modelling of the noncontinuous surfaces that are characteristic of urban areas (Sithole and Vosselman, 2004). This approach combines the beneficial properties of both algorithms, resulting in effective operation in built-up areas (ATIN) and on sloping forested terrain (REIN). A raster DEM produced using repetitive triangulation is also superior to a directly rasterised DEM for further spatial analyses because REIN employs a greater number of elevation value estimates for each raster pixel. These elevation estimates are calculated from multiple interpolations of neighbouring lidar points combined in a triangulated irregular network (TIN), with an independent set of sample points then selected from the filtered point cloud for each interpolation. Echoes from vegetation that have not been filtered out can also be selected as TIN nodes. Although TIN is a very fast method of calculating elevation estimates, other techniques (e.g., splines, kriging) can be implemented as well. Final elevations are determined by adding the average deviation to the lower limit of elevation distributions that are not influenced by residual echoes from vegetation.

Table 1
Lidar data scanning parameters.

Parameter	Description
Instrument	Optech ALTM GEMINI
Platform	Airplane
Scanning area	12 km by 30 km
Scanning strip width	860 m
Strip overlap	15–25%
Point density	2.5 pts/m^2
Laser scanning error	Between 5 and 8 cm
Spatial resolution of the produced raster relief	1 m