Processing Lidar Data for Geomorphological Mapping of Active Faults: A Case Study of Sveta Nedelja Fault (Žumberak Mt.)

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doi: 10.5281/zenodo.11657468

Abstract: The development of environmental remote sensing technology (ERS) plays a crucial role in modern tectonic geomorphological analyses and consequently in the mapping of active faults. High-resolution terrain imaging provides a deeper insight into landscape evolution and the differentiation of geomorphic forms associated with various geological structures. For this study, utilizing reclassified airborne point cloud dataset, we generated several digital elevation models (DEMs) with a resolution of 0.5 and 1 m, optimised for remote geomorphological analysis, empowering the identification of structural discontinuities that have been active in the most recent geological period, i.e. active fault traces visible in the landscape. GIS processing of the DEMs resulted in multiple raster layers that were used to generate digital drainage networks and various terrain features such as slope, aspect, multidirectional hillshade, openness, etc., leveraging remote sensing data. The processing procedure of combined ERS and GIS technologies previously applied in the Hrastovica area for the mapping of the Petrinja-Pokupsko Fault, the main source of the Petrinja 2020 Earthquake (Mw 6.4), is now applied to the Sveta Nedelja Fault in Žumberak Mountain. The integration includes morphometric analysis of elevation differences, detection of tectonic deformation over time and identification of characteristic geomorphic forms associated with active faults. The results derived from the analysis of raster dataset in combination with geological data are initial step towards detailed mapping of the Sveta Nedelja Fault. Further studies based on these fundamental datasets are essential for a better understanding of tectonic processes and their environmental impacts, particularly for the assessment of natural hazards and risks.

Keywords: tectonic geomorphology; processing lidar; active faults; geohazard.

1 Introduction

The earthquakes that struck Croatia in 2020 raised awareness among the public about the unpredictable hazards and risks presented by active faults. To reduce earthquake damage in the future and enhance disaster risk management, an essential requirement is the development of a database and map of active faults as a fundamental prerequisite for seismic hazard assessment (SHA) (Coburn and Spence 2002). Over the past two decades, laser technology has emerged as the most significant method for spatial data acquisition. In Croatia, over the past few years, the main sources of DEM data have primarily been Copernicus 25 m DEM and ESRI Terrain 5 m DTM. However, ALS (Airborne laser scanning) data opens new possibilities for geomorphological studies. Its development has made it possible to generate lidar-derived high-resolution DEMs even in areas with dense vegetation (Figure 1), previously a limitation of the aero photogrammetric method.

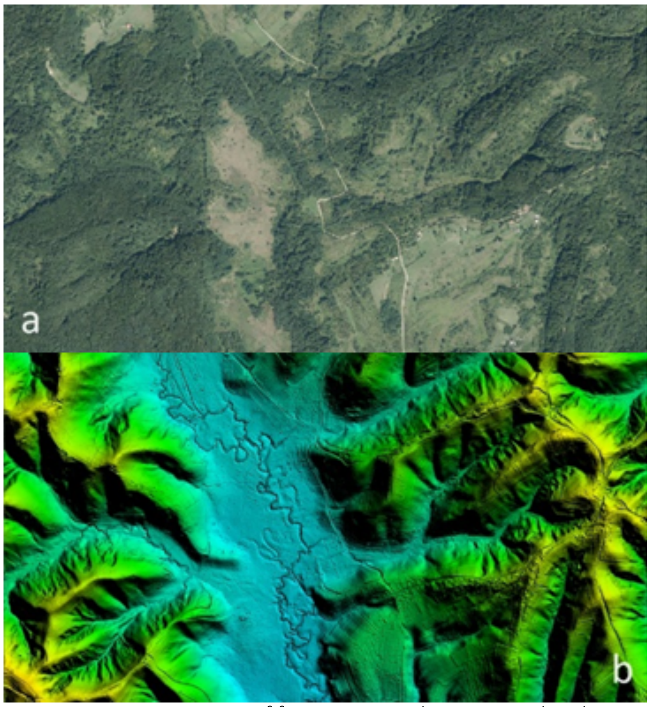

Figure 1. Comparison of forest-covered area in orthophoto imagery (a) and LiDAR-generated DEM (b).

Modern application of tectonic geomorphology considers a high-resolution DEM (≤1 m) as essential input data for any analysis contributing to topographic accuracy and providing new insights into landscape-shaping processes (Burbank and Anderson 2011). The initial utilization of these data to identify active faults occurred following the Petrinja 2020 Earthquake when the Croatian Geological Institute acquired ALS data for Hrastovica Mt. These data were the fundamental data in detecting both short-term activities, evidenced by geomorphological mapping of earthquake-induced changes on the field (Baize et al. 2022), and long-term activity, assessed through detailed geomorphological analyses (Henriquet et al. in prep). This study aims to showcase the efficacy of lidar data processing procedure that is applicable to remote geomorphological mapping of tectonic activity indicators within the Sveta Nedelja Fault area (Žumberak Mt.).

2 Materials and methods

We have obtained point cloud data from the State Geodetic Administration (DGU) for research purposes. This data is provided in LAZ (Lidar area) format files, each covering an area of 1 km^2. Depending on whether the area is open, covered with dense vegetation, or saturated, the point cloud resolution on the ground ranges from 4 to 6 points per m^2. The point cloud is classified into 10 classes and provided in the HTRS96/TM reference coordinate system and the HVRS71 reference height coordinate system (URL 1).

The point cloud with classified data has been filtered for the ground-related class. There are no points in water-covered areas due to the limitations of lidar technology in collecting spatial data on non-reflective surfaces. Bilinear interpolation fill method was utilized within a GIS environment to address areas lacking elevation data points.

2.1 DEM processing

A DEM with a 1 m resolution was created for preliminary geomorphological investigation of a wider research area encompassing Žumberak and Vukomerić Hills. It was utilized for visualizing of various raster datasets employed in the initial qualitative analysis of active faults: i) Sveta Nedelja Fault, located in the southern part of Žumberak, and ii) extension of the Petrinja-Pokupsko Fault System in the Vukomerić area. Afterwards, DEM with a resolution of 0.5 m were derived for more precise analyses, detailed geomorphological mapping, and on-site verification of results. Additionally, to enhance the smoothness and continuity of DEM, bilinear interpolation techniques were implemented.

2.2 Raster visualization

For both datasets, identical cartographic techniques were used for advanced data visualization using the QGIS software package. Layer overlay with transparency enhances the visualization method through blending mode and allows us to produce new visualizations with a 3D impression of terrain without graphic design software. This includes Relief Visualization Toolbox (Kokalj and Hesse 2017) designed specifically for visualizing local scale raster data, derived from ALS missions. Specifically, we generated Slope Degree, Slope Aspect, Contours (1 m equidistance), Hillshade, Multidirectional Hillshade, Positive and Negative Openness and Sky View Factor (SVF) raster as initial dataset for tectonic analyses.

Relief shading, also known as hillshading, is a cartographic technique used in GIS and remote sensing to visually represent terrain by generating a shaded relief from a DEM. Among various techniques, Yoëli's method (Zakšek et al. 2011) has become standard in GIS software due to its straightforward computation and interpretation. It assumes the terrain is a Lambertian surface illuminated by direct light from a fictive light source at an infinite distance. Where areas perpendicular to the light beam are the most illuminated, and those with an incidence angle of 90° or more are in shadow.

A single light beam may not reveal linear structures that lie parallel to it, making some small or elongated landforms less visible or even invisible. This limitation of one-directional hillshading arises from anisotropy (directional dependence). Another possibility is to use isotropy-based visualisation with multidirectional lighting, which can create a 3D impression of relief independent of light direction. In this study, we have used *Red Relief Image Map* (RRIM) (Chiba et al. 2008) which extends the *Openness* parameter (Yokoyama et al. 2002) and slope gradient information. Openness visualization is more suitable for automatic detection of linear structures because it exposes numerous edges, while *SVF-based* visualization is better for distinguishing slopes (Zakšek et al. 2011). To enhance the 3D effect, multiple visualization techniques were used, combining contour lines with slope degree and slope aspect raster to display the steepness and direction of the slopes.

2.3 Drainage network processing

The drainage network for an entire area was modelled by the Hydrology Toolbox (ESRI). The initial data preparation involved filtering and correcting DEM for anomalies and artefacts that could affect natural flow patterns. Data accuracy depends on the resolution, distance between sampling cells, and the type and method of data sampling. Calculation of a flow direction raster (Jenson and Dominique 1988) assumes that flow is determined by the direction of the steepest change from each cell of the previously smoothed elevation raster. Identifying streams and catchments required processing the flow accumulation raster, which shows the amount of water passing through each cell. Following the delineation of watersheds and streams, the accuracy of modelled network was verified through comparison with actual drainage network from Topographic Maps, Basic Maps of Croatia and INSPIRE hydrographic database (URL 2). If changes were necessary, the drainage network was calibrated by adjusting parameters and algorithms to match real data better.

3 Results

Hillshading of high-resolution DEMs (DGU, 1 m and 0.5 m) has significantly enhanced the visualization of landforms (Figure 2) in comparison with previously used hillshades of 25 m (Copernicus) and 5 m (ESRI Terrain), which often mask linear changes in ridges, valleys, and terraces – key geomorphological markers of active tectonics.

The shading effect with varied colouring has improved the identification of landforms by employing multiple light sources from different directions. The limitation of one-directional hillshading has been effectively overcome, thus emphasizing relief features with diverse orientations. This model serves as a basemap for subsequent 2D and 3D visualizations (Figure 3), acting as the initial step for tectonic geomorphology research, such as digital geomorphological mapping and topographic analysis, including *SWATH profile* assessments (Pérez-Peña et al. 2017).

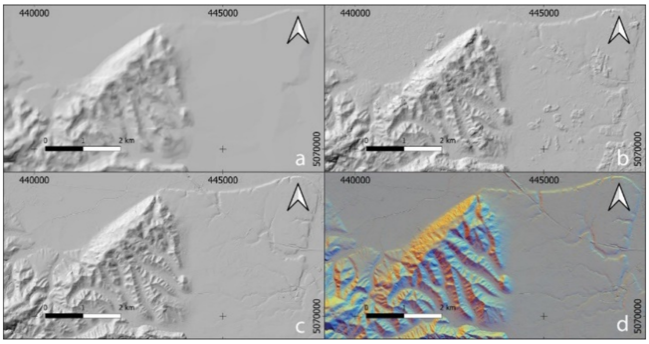

Figure 2. Generated hillshading of Svetonedeljski Breg area from various sources used for interpretation: Copernicus DEM 25m (a), ESRI Terrain DTM 5m (b), DGU DEM 1m (c) and 0.5m (d). The last one is a multidirectional colored hillshade.

The generated drainage network provides precise stream paths that are pivotal for hydrogeological and geomorphological analysis. These are instrumental in identifying changes in drainage patterns, deviations, and stream capturing along the fault zones, which are evident as knick-points in morphometric studies (Figure 3). Additionally, the precise drainage network crossing over an active fault can also be utilized to define horizontal displacements and estimate activity rates.

4 Discussion

Based on the existing data, the processed point cloud data provided by DGU has resulted in a high-resolution elevation model. This model provides a deeper understanding of landscape evolution and the differentiation of geomorphic forms associated with various geological structures, by implementing the methods and principles of tectonic geomorphology (Burbank and Anderson 2011). Optimized for remote geomorphological analysis, the 1 m and 0.5 m DEMs facilitate the identification of structural discontinuities that have been active in the most recent geological period (2.58 million years ago). These high-resolution datasets enable the accurate detection of active fault traces in the landscape. Additionally, tectonic activity manifests in the evolution of the drainage network, whose representation is significantly improved through this methodology. In comparison to the previously utilized INSPIRE database, the newly generated drainage network enhances spatial accuracy and rectifies deficiencies in the depiction of drainage patterns. The main findings obtained by remote survey of the Sveta Nedelja Fault in the Žumberak Mountain need further verification in the field. The integration of GIS database within platforms allows efficient fieldwork, crucial in confirming shallow subsurface tectonic deformations to validate the reliability of digital relief interpretation.

5 Conclusions

Processed rasters have become fundamental datasets essential for a better understanding of tectonic processes and their environmental impacts, particularly for the assessment of natural hazards and risks. Applying combined ERS and GIS technologies to the morphotectonic analysis of the Sveta Nedelja Fault in the Žumberak

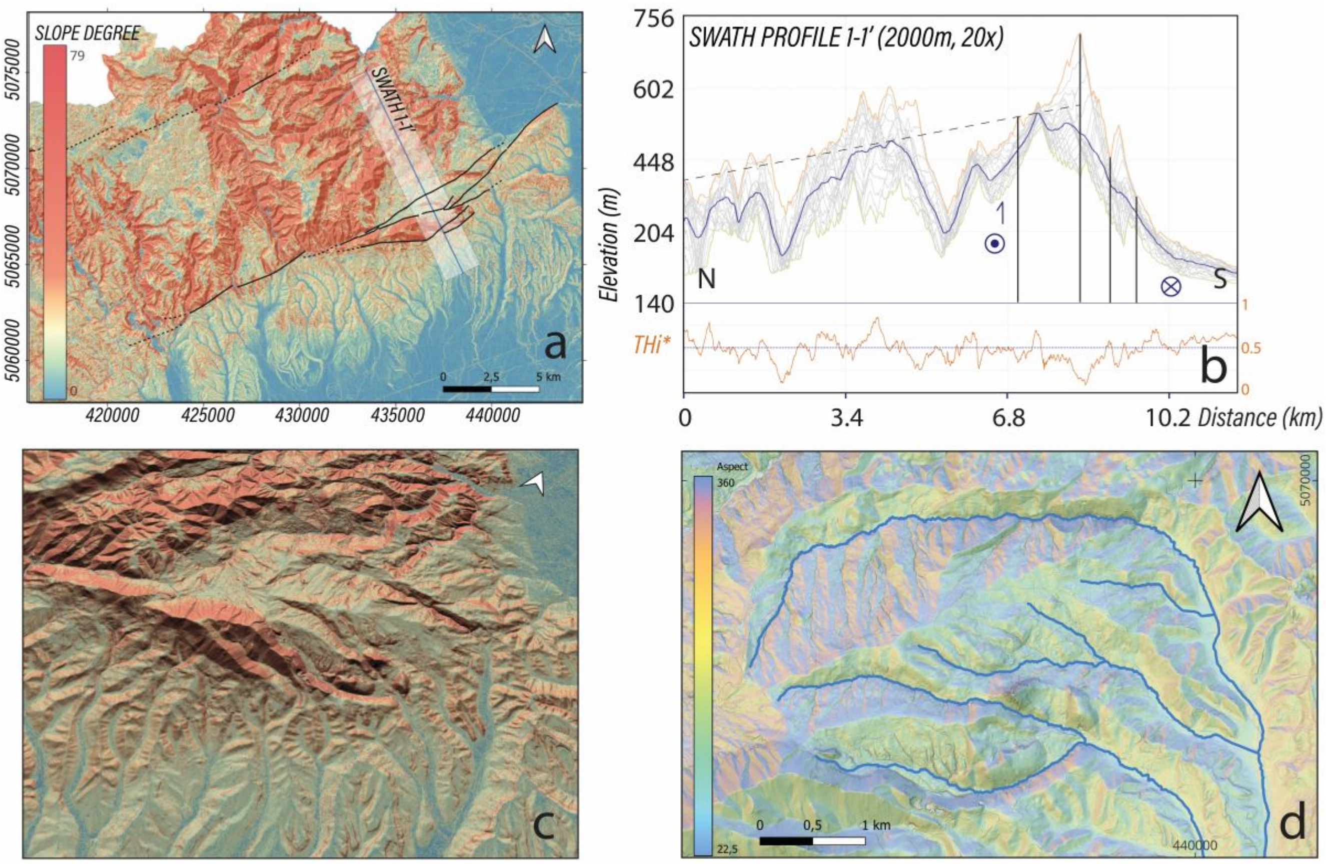

Figure 3. Example of applying visualizations for topographic analysis of Sveta Nedelja Fault: slope degree map (a), SWATH profile (b), 3D view of slope degree map overlaid on DEM (c), and Konšćica stream basin on SVF and Slope Aspect basemap (d).

Mountain has proven successful, representing a new approach in the study of active faults in Croatia. This integration includes morphometric analysis of elevation differences, detection of tectonic deformation over time and identification of characteristic geomorphic forms associated with surface active fault trace. The results derived from the analysis of raster dataset in combination with geological data are initial step towards detailed tectono-geomorphic mapping of the Sveta Nedelja Fault.

Acknowledgments: This research was conducted in the scope of the internal research project "GeoSAVAGE" at the Croatian Geological Survey, funded by the National Recovery and Resilience Plan 2021–2026 of the European Union – NextGenerationEU, and monitored by the Ministry of Science and Education of the Republic of Croatia; Geological mapping programme of HGI-CGS and Mobility project of the Croatian Science Foundation. Special thanks to Croatian Geodetic Administration for providing lidar data, crucial for this research. PJR acknowledges the support of the Slovenian Research and Innovation Agency (ARIS), through the program group Dynamic Earth (P1-0419) and RSF-O ACTIVIST2CRO project.

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