GEOMORPHOMETRY 2020 PERUGIA, ITALY JUNE 22 - 26 2020

Physically-based segmentation of the Alps and the Western Carpathians: comparison and interpretation

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Abstract— **Results of a delineation of morphometrical-morphostructural individuals for the regions of Alps and Western Carpathians, using physically-based geomorphometric variables as input data and object-based image analysis, are presented. After the segmentations Index of Steady State (ISS) for entire object levels and their parts was computed. ISS was then used for evaluation and mutual comparison of both study areas in terms of their geodynamic development, using the frequency distribution of the ISS among others. Similarities and differences of the development of these relatively alike mountains ranges are interpreted.**

I. Introduction

The land-surface segmentation should not be a tool only for physiographic classification, but also for geoscientific analyses. The physically-based morphostructural segmentation targets to delimitate geomorphic objects determined mainly by endogenous processes and differences in the geological structure (particularly horsts, grabens, variously uplifted and dissected blocks, etc.). Physical quantities as geomorphic energy and work are therefore used not only in the process of segmentation, but also for interpretation of the results. The presented research picks up on the published work of [1, 2, 3], focused mainly on the segmentation aspect, and [4], where three physically-based geomorphometric variables were introduced – Endogenous geomorphic work (EnW), Exogenous geomorphic work (ExW) and Relief brake force (R_{BF}), leading to delimitation of morphotectonically well-interpretable segments.

The physically-based variant of morphostructural segmentation using object-based image analysis (OBIA) and physically-based geomorphometric variables [4] was first tested in the territory of the Western Carpathians (Slovakia) [2], where the complex object-oriented approach was developed. The goal of this study was not only the challenge of automatic replication of traditional manually-made geomorphological regions, but also formulation and test of hypotheses of morphotectonic development of the study areas. To test versatility and robustness of the method, territory of the Alps is now elaborated, too. The OBIA approach was selected as it proved successful in our task [3]. The location of both study areas is displayed in Fig. 1, along with the figures of traditional geomorphological regions (Fig. 1 I and J).

Similarities and differences in the geological structure and geodynamic development of the two mountain ranges are reflected by **I**ndex of **S**teady **S**tate (ISS), introduced in [4]. ISS compares the ratio of the EnW and ExW preserved in recent land surface; the R_{BF} expresses various rock resistances: together they can characterize the stage of segment´s morphotectonic development.

II. Data and Methods

A. Computation of input data and their pre-processing

Computation of physically-based geomorphometric variables required two sorts of input data. Vector-based geological maps of the study areas [5, 6] were used for spatial representation of rock density (σ). They were compiled based on available regional geophysical research, forming, along with gravity acceleration (g), the physical components of the variables.

SRTM V4 dataset [7] with 90-meter spatial resolution was used as input DEM for the calculation of geomorphometric components of the variables. First, maximum, mean and range of elevation was computed in ArcGIS (ESRI). Size of the circular moving window based on the mean topographic grain [8] was set to 1800 m for the Western Carpathians and to 1900 m for the Alps. Next, morphologically-based stream networks, generalised using the same window sizes, was computed in GRASS GIS [9].

Then, three physically-based geomorphometric variables [4] were computed:

Peter Bandura, Jozef Minar, and Miroslav Bielik (2020) Physically-based segmentation of the Alps and the Western Carpathians: comparison and interpretation

in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_72.

$$\text{EnW} = \text{max. elev.} \times \sigma \times g/2 \quad (1)$$

$$\text{ExW} = (\text{max. elev. - mean elevation}) \times \sigma \times g/2 \quad (2)$$

$$R_{BF} = \text{range of elev.} \times g / 2 \times \text{mean dist. to streams} \quad (3)$$

Prior to the segmentation, these layers were normalized by square root function to nearly normal frequency distribution and to the same range to make them equal.

B. Physically-based segmentation

Complex hierarchical top-down object-oriented approach, consisting of several segmentations and nested classifications described in [2], was used for the segmentation of the Western Carpathians. The last object Level 3 with 209 objects covering the very Western Carpathians was taken as the result. This concept was first applied on the territory of the Alps as well. However, such approach was evaluated as not necessary, since the terrain is less contrasting than in the Western Carpathians.

Therefore, simple multiresolution segmentation (MRS) based on the Estimation of scale parameter 2 tool (ESP 2) [10] in the eCognition® Developer software [11] proved to be sufficient. Using this tool, three object levels at super-regional (Level 3 - L3), regional (Level 2 - L2) and detailed scale (Level 1 - L1) were obtained. The settings were left to default, only the values of shape and compactness were increased to 0.5 and 0.7, to ensure production of more compact, tectonic block-like objects.

C. ISS index computation and evaluation

Concept of the topographic steady state reported e.g. in [12] supposes an equilibrium state between the erosion rate and endogenous uplift. It is reflected in relatively stable topography and characterized by specific altitudes, available relief and slopes. All these characteristics are represented in the input data of our physically-based segmentation. EnW (maximum altitude), ExW (Glock's available relief) and R_{BF} (average slope) can be combined to express the ISS [4], modified:

$$ISS = \frac{EnW}{ExW} \cdot \left(\frac{R_{BF}}{ExW} \cdot \frac{ExW_{mean}}{R_{BF_{mean}}} \right) \quad (4)$$

where ExW_{mean} and R_{BFmean} are mean values of ExW and R_{BF} for the whole analysed territory.

The first member of (4) expresses, for a litho-structural homogeneous territory in topographic steady state, a basic morphometric characteristic dependent on intensity of uplift and denudation. The second member of (4) eliminates an influence of different litho-structural conditions (reflected in the ratio R_{BF}/ExW) on the value of the index. If a tectonically, litho-structurally and climate genetically homogeneous territory is segmented and analysed, normal, triangle or quadratic distribution of ISS values of the segments is expected. Another statistical distribution points to important spatial differences of the analysed territory. Because the second part of (4) is dependent on the study area delimitation, the evaluation of ISS was done for both study areas as following:

1. entire area,
2. Alps without foreland; core area of W. Carpathians,
3. Alpine foreland; transitional area of W. Carpathians,
4. combination of 2 and 3, respectively.

III. Regional settings

Both the Alps and the Western Carpathians are part of Alpine-Himalayan orogenic belt. Until the Miocene, both mountains had similar orogenesis, developing as a collisional mountain belt between the African and Eurasian tectonic plate. Early in the Miocene, the microplate ALCAPA was extruded from the East Alpine domain and formed a core of the current Western Carpathians. Whereas the Alps remained as a typical collision mountain, the Western Carpathians had a complex neotectonic development. Subduction at the orogenetic front characterized by extensional regime formed a set of individual small mountains and intramontane basins. During the following oblique collision with the European platform, the neo-Alpine accretionary wedge of the Outer Western Carpathians was formed. The back-arc extension led to intensive rifting and formation of the Pannonian basin between the Alps and Carpathians [13]. While the boundary of the Pannonian basin and the Alps is rather clear, the boundary against the Western Carpathians is perceived as a fuzzy transition. Still ongoing collision in the Alps forms a compact mountain belt that was probably in a steady state before the Quaternary glaciation [14]. Only the Eastern Alps have preserved a significant remnants of planation surfaces, e.g. [15], contraindicating this steady state. The Western Carpathians acquired character of a complicated dome-like morphostructure with preserved significant remnants of planation surfaces in a prevailing part of the mountain during the post-collisional (Pliocene and Quaternary) stage [16].

IV. Results and discussion

A. Comparison of the ISS index in the Alps and the Western Carpathians – effect of the geodynamic development

Segmentation results for the Alps (ESP2 tool Level 2 with 659 objects) and Western Carpathians (Level 3 of object-oriented approach [2] with 209 objects) is displayed in Fig. 1. Although much larger, the Alps appear more homogeneous than the Western Carpathians (based on both the maps and histograms). This points to the different geodynamic development in these regions (ongoing collision vs. complex geodynamic history).

Highest ISS values in the Western Carpathians are found in lower mountains with later uplift (so-called delayed elevations [16]), and thus with delayed erosion and extensive remnants of planation surfaces [4]. On the contrary, in the Alps they are found in the central parts with highest elevations, which were mostly glaciated in the Pleistocene. It could be due to the protection from intense denudation by a conservation effect of the ice cap. Some high ISS values are present also in the lowland objects with very flat fluvial landforms ($R_{BF} < 0.25$, hatched objects in Fig. 1). If $R_{BF} \rightarrow 0$, the result of (4) starts to be unstable and very sensitive to DEM errors (relatively high in the case of SRTM in lowlands). Therefore, resultant ISS values for such objects should be taken with a grain of salt.

Overall higher values of the ISS in the Western Carpathians indicate higher contribution of EnW (in comparison with ExW) into formation of the terrain. It can be explained by the fact that after the collisional phase of development ended, the region was planated and subsequently uplifted, and therefore the scale of exogeneous processes had not reached the scale of endogenous ones. The region is generally far from the steady state. It is also confirmed by histograms in Fig. 1. The distribution closest to the normal (triangle) have the Alps itself, much smaller core area of the Western Carpathians has clear log-normal distribution of ISS.

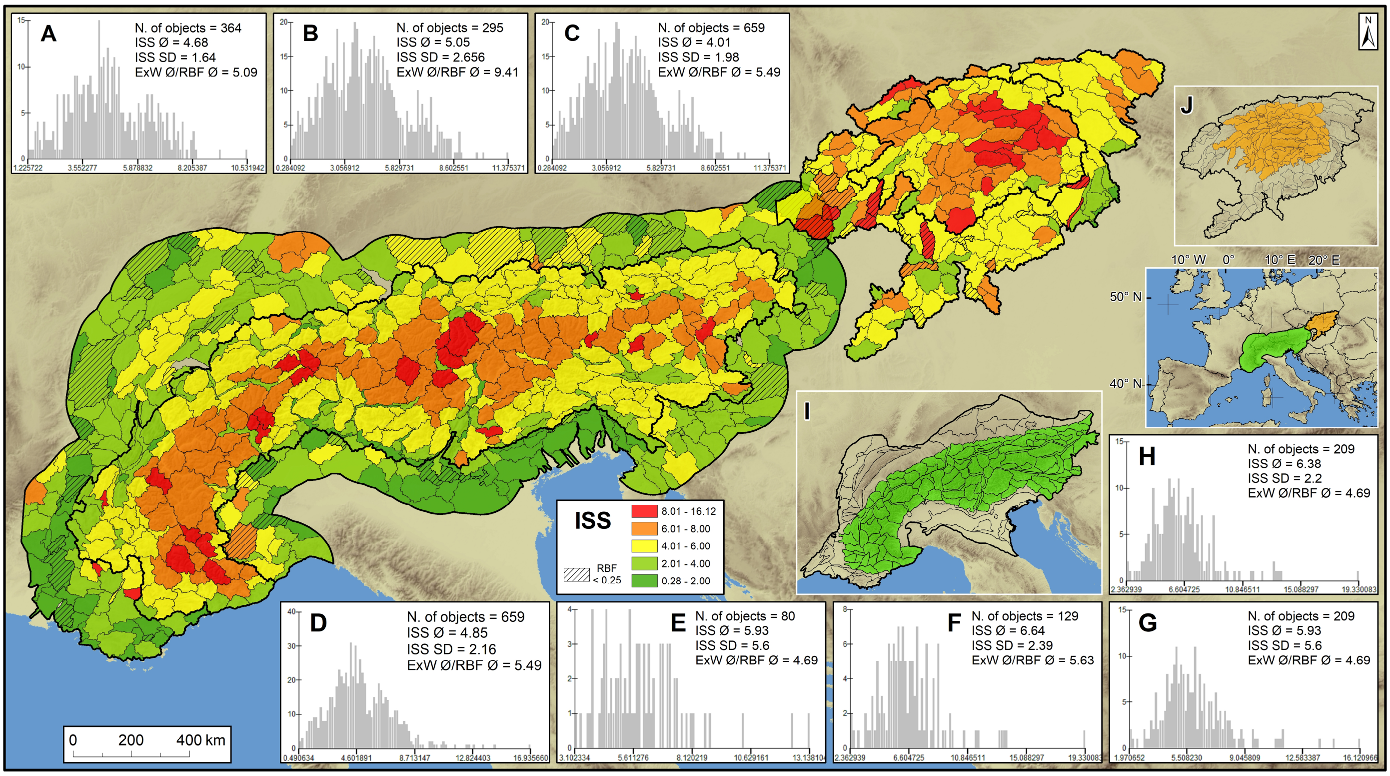

Figure 1. Results of the segmentations for the Alps and the Western Carpathians. Displayed ISS was computed for the entire object levels. Hatched objects have extremely low R_{BF}: the value of the ISS here can be unrealistic. Histograms of the ISS represent distribution for: Alps (A), Alpine foreland (B), Alps with foreland (C), combination of Alps and foreland (D); and for Western Carpathians: core area (E), transitional area (F), entire area (G), combination of core and transitional area (H). Traditional geomorphological regions of the Alps (I) made by [17] (Alps itself highlighted with green) and of the Western Carpathians (J) compiled by [16] (core area highlighted with orange).

B. Comparison of the ISS index for different hierarchical levels of segmentations

Fig. 2 captures the results of the segmentations of the Alps region using the automated ESP2 tool. Depiction of the ISS here is related to the detail of segmentation, since its values are changing naturally not only with the computation extent, but also with the size of the reference objects. Visually, there is no significant spatial difference between Level 1 and Level 2, but distribution of values tells otherwise. A tendency to the more normal (triangular) distribution is evident at Level 2, which points to a capture of non-tectonic features at Level 1. However, main morphostructural blocks of the region are probably best captured by Level 3. Comparison of mean altitudes and ISS shows inversion situations. ISS comparably higher than altitude (arrow 1 and 4 in Fig. 2 C, D) can point to a later neotectonic uplift of the territory. On the contrary, ISS lower than altitude (arrow 2 and 3 in Fig. 2 C, D) could be related to longer denudation of the area.

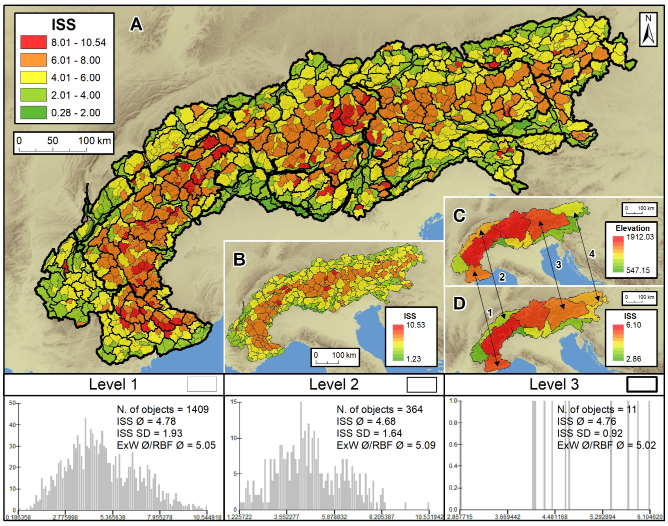

Figure 2. Results of the hierarchical segmentation of the Alps (Level 1, 2, and 3), along with the histograms of ISS index and its statistics. Visualization of ISS in the main map (A) is based on the most detailed Level 1, Level 2 (B) has the same classification brake values. Mean elevation (m a.s.l.) of objects (C) is compared with values of ISS of object Level 3 (D). Arrows point to an inversion of ISS and altitude values (more explanation in the text).

V. CONCLUSIONS

According to the results, our concept of physically-based segmentation can be used not only in the area of the Western Carpathians, where it was developed, but also in other areas. ISS index was used for evaluation of the development of study areas individually as well as for their mutual comparison and provide non-trivial morphotectonic interpretations.

Future work will focus on testing of the behaviour of ISS index when the study area is subdivided into even smaller parts (preferably using other variations of the segmentation); testing of the distribution of ISS values against the distribution patterns using statistical approaches; carrying out more detailed interpretation using deeper local geological and geodynamic knowledge.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-15-0054.

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