# Geomorphometry helps to distinguish between mountain fronts of various origin (Sowie Mts., SW Poland)

Kacper Jancewicz, Milena Różycka, Mariusz Szymanowski, Piotr Migoń[§]
Institute of Geography and Regional Development, University of Wrocław
pl. Uniwersytecki 1, 50-137 Wrocław, Poland
[§] piotr.migon@uwr.edu.pl

*Abstract*—**Mountain fronts may have more than one origin and not all of them are necessarily fault-controlled. Their occurrence may also reflect the presence of significant lithological boundary and result from differential erosion. In this study we apply various geomorphometric and geostatistical measures to two mountain fronts in SW Poland in order to check whether they can help to discriminate between fault- versus rock-controlled fronts. The results show that these two mountain fronts differ in terms of the distribution of altitudes, morphometric characteristics of drainage basins and gradient changes along stream profiles, although the discrimination is not as clear-cut as might be expected. However, given homogeneous lithology of the elevated terrain, the hypothesis assuming variable origin of range-bounding fronts receives support.**

## I. Introduction

Many mountain ranges worldwide rise abruptly from the surrounding less elevated terrains, often along approximately straight lines. These topographically distinct marginal zones are called mountain fronts and it is usually implicitly assumed that they owe their origin to uplift of the mountains relative to the foreland and their position indicates the course of an active fault [1,2]. To facilitate comparative analysis of mountain fronts and to assess their state of activity various morphometric measures have been proposed [1] and these are almost routinely used nowadays. However, mountain fronts may have more than one origin. The mountain – piedmont junction may correspond to a lithological boundary and if this is the case, long-term differential erosion produces a topographic escarpment which separates highland terrain in more resistant rock from lowland terrain in weaker formations. Such lithological boundaries may follow ancient fault lines, so that the presence of a fault is not necessarily the evidence of active tectonics.

In this presentation we apply various morphometric and geostatistical measures to two mountain fronts which mark the topographic boundaries of the Sowie Mts. block in SW Poland (Fig. 1). The NE-facing front is of tectonic origin and fault activity has continued into the Quaternary [3], whereas the SW-facing front follows the lithological boundary along an old fault zone inherited from Late Palaeozoic times. Thus, they appear to be of different origin and this may be reflected in different geomorphometric signatures. Consequently, the primary aim of this exercise is to test this hypothesis and to identify opportunities and limits of geomorphometric approach to distinguish between fronts of different origin. Advantageous for this study is the fact that the Sowie Mts. block is built predominantly of gneiss and hence, both marginal zones show similar geology. Thus, the influence of rock factor on geomorphometric properties of the footwall is considerably reduced.

## II. Methods

Mountain fronts were characterized using the following approaches and measures, presented in more detail in the subsequent parts of the paper:

(1) mountain front sinuosity and spacing ratio;

(2) distribution of altitudes in 2 km wide buffer zones extending from the base of a mountain front into the elevated block. This part of the study is based on geostatistical approach and semivariogram analysis to address the structure of variability of altitude;

(3) drainage basin characterization by means of selected morphometric parameters pertinent to shape and relief, commonly applied in morphotectonic studies. The second step involved cluster analysis. In total, 59 drainage basins were subject to analysis, including 32 along the NE front and 27 along the SW one;

(4) analysis of stream longitudinal profiles by means of stream length–gradient index (SL index) [4].

*Kacper Jancewicz, Piotr Migon, Wioleta Kotwicka and Milena Rozycka (2020). Geomorphometry helps to distinguish between mountain fronts of various origin (Sowie Mts., SW Poland): in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_40.*

A LiDAR-based DEM of original 1x1 m resolution was the primary source of data used in this study.

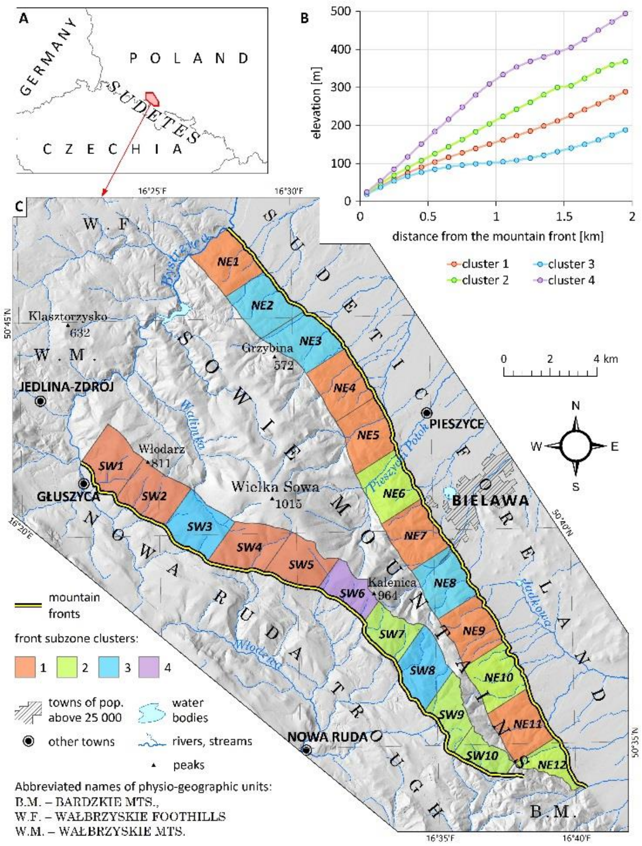


**Figure 1.** Study area (A), mean semivariograms of altitude (B), subdivision of frontal zones following cluster analysis of semivariograms (C).

## III. Geomorphometric Characteristics

### *A. Parameters of mountain fronts*

The parameter of sinuosity does not show any evident difference between two opposite mountain fronts. For the NE front, the value obtained is 1.05, whereas slightly higher value of 1.1 was calculated for the SW front. Although in detail the NE front is better approximated by the straight line, no deep indentations and expansions of flat-floored valleys into the mountain mass occur along the SW front either. The mean distance between exit points of individual drainage basins is nearly identical for both mountain fronts, being 0.88 for the NE front and 0.94 for the SW one. By contrast, spacing ratio shows more variability, being nearly twice higher for the NE front (2.81 versus 1.68).

Geostatistical approach to mountain front characterization was based on semivariogram analysis. Semivariance, given as below, is a measure of similarity/dissimilarity of observations (that is DEM grid) as a function of a separating distance [5].

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(i) - z(i+h)]^2$$

where:

$\gamma(h) - semivariance\ for\ observations\ separated\ by\ distance\ h$
$N(h)$
$-\ number\ of\ pairs\ of\ observations\ separated\ by\ distance\ h$
$z(i) - altitude\ in\ i\ location$
$z(i+h) - altitude\ in\ i+h\ location$

More than 20 empirical semivariograms, for 2.5 km wide sectors of the front-parallel buffer zone, were prepared for comparative analysis (NE1–12, SW1–10; Fig. 1). Given that the variability in altitude depends not only on distance between observations but also on direction in which the analysis is performed (anisotropy), directional semivariograms, instead of omni-directional ones, were created. To do so, a single direction perpendicular to the mountain front base, in which the highest variability of data is observed, was determined on the basis of semivariogram maps. For each semivariogram constant input parameters, such as lag size (100 m), number of lags (max 20), angular tolerance (45°), bandwidth distance (2 lags) were adopted.

To identify subzones similar in terms of variability in altitude as a function of distance between observations, k-means method for non-hierarchical clustering was implemented. In this approach each subzone was treated as an observation described by a sequence of semivariances calculated for each lag in this subzone. The similarity of observations was quantified using Euclidean metric. Semivariance was re-calculated to relative elevations, to facilitate interpretations. Four clusters were distinguished, including one represented only by one sector (Fig. 1). According to this approach, the entire Sowie Mts. block may be subdivided into two parts. In the north-western part both mountain fronts show similar morphometric characteristics, with particular sectors belonging to clusters 1 and 3, whereas the south-eastern one is more diversified and notably, cluster 1 is not at all represented along the southern section of the SW frontal zone.

### *B. Drainage basins*

Morphometric characteristics of river basins, frequently used in morphotectonic studies, were ascribed to 59 entities (Fig. 2) in order to examine the differences between the units located on the opposite sites of the Sowie Mts. block. In the first step, the coefficient of variation (CV) for each measure was calculated to identify and eliminate the variables that do not discriminate the observations efficiently (CV < 10%). The degree of correlation between the parameters was assessed by Spearman's correlation coefficient, the application of which was determined by both statistical distribution of the variables examined by Shapiro-Wilk normality test and the presence of the outliers. From each pair of variables characterized by statistically significant rho value the parameter with the higher average degree of correlation with other measures was eliminated. This approach enabled us to reduce the total number of parameters taken into consideration from six to four (circularity ratio – CIRC, drainage basin compactness – COMP, hypsometric integral – HI, mean slope – MEAN_SLO).

To detect the statistical differences in the parameters values between the river basins corresponding to different mountain fronts both, t-test and its non-parametric equivalent (Mann-Whitney-Wilcoxon test) were applied (Table 1). When the homogeneity of variance between two independent groups of observations were violated in the light of Levene's test (p-value < 0.05), the Welch correction were introduced in the former. Statistically significant differences between independent groups were observed for CIRC and HI parameters. In both cases they appear related to different geomorphic histories of both range-bounding fronts. Tectonic activity along the NE front triggers headward erosion, so that streams cut back into the main ridge, shifting the divide westward. In this way, they become more elongated, as reflected in lower values of CIRC. This decreases the size of west-facing catchments and reduces erosional power of streams, resulting in higher values of HI.

**Table 1**. Statistically significant differences in the parameter values between river basins located on the opposite sites of the Sowie Mts. block.

| Parameter | Shapiro-Wilk normality test for independent river basin groups (p-values) | | Tests of significance of differences (p-values) |
|---|---|---|---|
| | 1 – 32 | 33 – 59 | |
| CIRC | 0.9255 | 0.1008 | t-test 0.0004 |
| COMP | 0.3610 | 0.1256 | t-test 0.1381 |
| HI | 0.9300 | 0.0317 | Mann-Whitney-Wilcoxon 0.0137 |
| MEAN_SLO | 0.1091 | 0.1388 | t-test 0.3740 |

Test results significant at 0.05 level are in red.
Numbers of river basins according to Fig. 2.

Non-hierarchical multivariate k-means clustering was performed in order to distinguish groups of river basins similar to each other from morphometric perspective (Fig. 2). To determine the optimal number of clusters pseudo *F* statistics [6] was calculated. The differences between three independent groups of observations in terms of morphometric characteristics were then testing statistically with the application of ANOVA and its non-parametric alternative (Kruskal-Wallis test). As all tests results were significant at 0.05 level, multiple pair-wise comparisons between groups were performed in order to identify clusters different one from another. Statistically significant differences were not confirmed only in two out of 12 cases in the light of applied post-hoc tests (Dunn's with Benjamini-Yekutieli correction after Kruskal-Wallis and Tukey HSD after ANOVA with no Welch correction), which underlined morphometric similarities between clusters 2 and 3 and clusters 1 and 3 in terms of circularity ratio and drainage basin compactness, respectively.

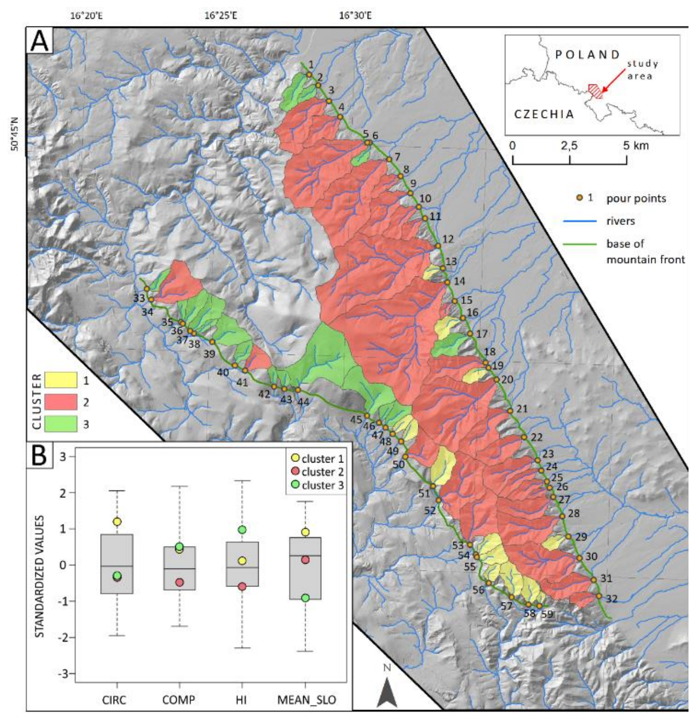


**Figure 2.** Results of drainage basin analysis: A – spatial pattern, B – statistical distribution of parameters, with dots corresponding to the average values. Note the predominance of cluster 2 along the fault-controlled NE mountain front and much less consistent pattern along the SW front.

### C. *Longitudinal stream profiles*

Stream profiles in the Sowie Mts. used to be analyzed in the neotectonic context in the past [3,7], but based on low-quality elevation data and for the NE front only. Here, SL-index was calculated for 40 m long river sections, with the use of a "downstream moving segment". Index values were ascribed to points (segment mid-points) placed regularly every 10 m along the stream. The SL index was calculated for 40 perennial streams more than 2 km long, crossing the mountain fronts (24 and 16 streams for NE and SW front, respectively). Preliminary results were manually filtered in order to remove points of anthropogenically-induced extreme SL values. Further analysis concerned the change of SL values with the distance from the mountain front. It was based on mean minimum, mean maximum and mean SL values within zones of 100 m interval, generated with use of Euclidean distance from the mountain front line.

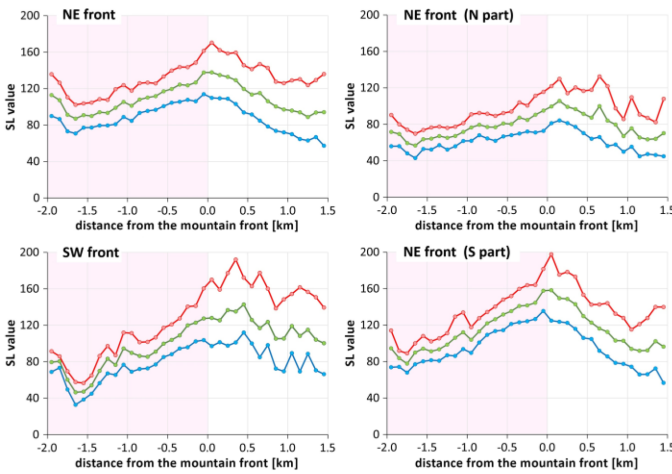


**Figure 3**. Aggregate downstream change of SL values along the main streams crossing mountain fronts of the Sowie Mts. Block. Explanation of colours: red – mean maximum, green – mean, blue – mean minimum. Data for the NE front were additionally split into the N (drainage basins 1–11, see Fig. 2) and S part (drainage basins 16–32), to highlight the differences within the front.

The results showed certain differences between the opposite fronts. Along the NE-facing front the highest mean SL values are noted at the mountain–piedmont junction and they are more evident in the southern sector, corresponding with higher relief of the entire frontal zone. By contrast, no analogous pattern exists along the SW-facing front and both mean and maximum values continuously rise going downstream, beyond the mountain front.

## IV. Conclusions

Morphometric parameters, both simple and more complex, are often used in morphotectonic analysis [2,8,9]. The novelty of our approach is twofold. First, we applied geomorphometric approach to two opposite fronts of a mountain range, apparently of different origin – one clearly tectonic, another one more complex and significantly controlled by differential erosion. The purpose of this exercise was to explore whether geomorphometric measures will reveal evident differences between the two fronts. Although the differences are not as clear-cut as expected, they nevertheless appear in all three crucial components of this analysis: (a) spatial structure of variability of altitude within the frontal zones; (b) drainage basin characteristics shown by means of cluster analysis; (c) spatial distribution of SL index values across both fronts. Second, we tested geostatistical approach to the whole relief of frontal zones, not very often applied in such context and were able to show differences both within and between mountain fronts. This seems to be a promising avenue of research and will be subject to further inquiry.

This presentation is a contribution to Research Project no. 2015/19/B/ST10/02821, supported by the National Science Centre.

## References

[1] Bull, W.B., McFadden, L.D., 1977. "Tectonic geomorphology north and south of the Garlock Fault, California". In: Doehring, D.O. (Ed.), Geomorphology in Arid Regions. Proceedings of the 8th Annual Geomorphology Symposium, State University of New York at Binghamton, pp. 115–138.

[2] Bull, W., 2007. "Tectonic Geomorphology of Mountains: A New Approach to Paleoseismology". Blackwell Publishing, Oxford.

[3] Krzyszkowski, D., Migoń, P., Sroka, W., 1995. "Neotectonic Quaternary history of the Sudetic Marginal Fault, SW Poland". Folia Quaternaria 66, 73–98.

[4] Hack, J., 1973. "Stream-profile analysis and stream-gradient index". U.S. Geological Survey Journal of Research 1, 421-429.

[5] Cressie, N.A.C., 1991. "Statistics for spatial data". New York, Wiley.

[6] Caliński, T., J. Harabasz, 1974. "A dendrite method for cluster analysis". Communications in Statistics 3, 1-27.

[7] Krzyszkowski, D., Olejnik, W., 1998. "The role of neotectonics in the Quaternary evolution of the landscape of the Sowie Mts, Sudetes, southwestern Poland". Geologia Sudetica 31, 221–239.

[8] Ferraris, F., Firpo, M., Pazzaglia, F.J., 2012. "DEM analyses and morphotectonic interpretation: The Plio-Quaternary evolution of the eastern Ligurian Alps, Italy". Geomorphology 149–150, 27–40.

[9] Pérez-Peña, J.V., Azor, A., Azañón, J. M., Keller E. A., 2010. "Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): Insights from geomorphic indexes and drainage pattern analysis". Geomorphology 119, 74–87.