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Quantification of relationships between geomorphic and lithological parameters representing rock resistivity (erodibility) in N-Hungary using statistical surface analysis (Summary)

Introduction, aims

The quantification of petrophysical features instead of descriptive characterisation and furthermore, the identification of relationships between geomorphic and geological factors has always been of key importance not only in engineering, but in geomorphology as well. This work aims to investigate the relationship between geomorphic and geological endowments based on a large scale database using geoinformatics with the aid of statistical methods such as correlation, regression analysis and cluster analysis, and to quantify the rock resistance to denudation by combining and comparing traditional experiments, and investigations applied mainly in civil engineering (unconfined compressive strength, attrition resistance, frost resistance). Qualifying rocks based on their resistivity to denudation can be a useful method applied in geomorphological mapping. Thus the first part of this work is to promote the adaptation of methods used in engineering in geomorphology. The adaptibility and reliability of these methods measuring rock strength (resistance) was also investigated.

The second part of the dissertation deals with structural morphology from the aspect of methodology. The relationship between geology and morphology (not simply the connection but appearance as well), which has always been an important research topic in the geomorphology has stimulated an increasing interest during the last decade. These studies help to specify the relationship between geological and morphological structures and features.

Researchers developed several models to quantify and model slope formation and denudation. Statistic surface analysis had 3 objectives in the 1960s': to identify morphometric parameters relevant for surface analysis; to identify statistical parameters to characterise the dataset, making researches comparable to each other; to find out an equation that symbolises the evolution of the surface. Though the latter soon proved to be impossible, it helped the evolution of 3D modelling and resulted the appearance of branches of surface models emphasizing the predominant role of different features. The early denudation models were based on measuring relief. Ahnert proved that models can be based on slope gradient as well, since surface formation is dependent on slope angle as well. SCHEIDEGGER (1961, 1990) proved that the use of different morphometric parameters results different type of valley/slope formation. AHNERT (1966) proved that the slope gradient is dependent not only on relief or other derivates of height, like slope, but also depends on rock strength. KIRKBY (1971) stated that slopes tend to reach a specific form based on rock strength depending on the

length of surface evolution, but independent from the original slope gradient. Neglecting the role of other external factors (climate, exposition time) we decided to investigate this slope form based on the differences of rock strength.

Apart from measuring denudational resistance based on slopes and geology, the methodology of identifying surface remnants and the evaluation of relationship between valley directions and lithoclase/fault directions were also in the centre of interest in the second part of dissertation.

The aims of this work were the following:
- to investigate which statistical parameters can be regarded as sensitive indicators for statistical surface analyses;
- to investigate which lithological parameters can be regarded as sensitive indicators for statistical surface analyses;
- to learn whether there is deterministic relationship between the examined morphological and the lithological factors and to describe the manner of the relationship; to trace the cause-effect relations, to prove the independency or interdependency of certain morphometric and lithologic parameters, to decrease the number of parameters involved in general investigations, to examine the possibilities of substituting petrophysical data with morphometric data
- to determine the optimum circumstances (e.g. grouping of data, resolution) of the statistical surface analyses;
- to offer possibilities for the use of results in engineering studies especially in architecture;
- to implement methods and parameters (measuring rock strength) of engineering for geomorphic application;
- to improve the methodology of geomorphic mapping by adapting methods and parameters used in engineering;
- to develop new methods of evaluation;
- to compare the relevance of results at regional and local scale;
- to compare the relevance of different denudation equations;
- to estimate the role of time in the modification of relationship between parameters;
- the delimitation of areas sensible for denudation in order to improve the methods of geomorphic mapping;
- to evaluate the sensibility of geoinformatics, to test the the difference of manual/traditional and modern methods and the applicability of softwares in geomorphology developed for different purposes

Methods

The chosen geomorphic parameters were slope steepness (%), height above base level (m), distance from base level (m), costpush, exposition, runoff, while the geological parameters were UCS (unconfined compressive strength, modified by

the abundance of planes of weakness, i.e. faults) attrition resistivity (%), freezing resistance (%) and porosity (%). The latter 4 parameters represent the resistance to denudation (erosion) of the different rock types. These parameters were the independent variables of the statistical analysis carried out by SPSS for Windows 15. The values representing rock resistivity (erodibility) were compared to the results of denudational classification of LÁNG, controlling the reliability of results.

The investigated area extends to 1500 square kms, consisting of highly consolidated palaeozoic-mesozoic limestones, siliciclastic materials and volcanites, semiconsolidated palaeogeneous sandy rocks and loose neogene schliren, sandstones and tuffs. The geological composition of the area is versatile, thus the 67 formations were grouped into 10 petrophysical categories. Morphologically the territory is composed of an elevated mountainous core area (Bükk Mts. N-Hungary), and several hilly regions in the foreland (pedimented piedmont regions, denudational and accumulational glacis).

The area has been continuously uplifted since the upper Miocene and has been denuded throughout the uppermost Tertiary and Quaternary periods, for more than 5 million years. Considering the stage of the surface development, this area as a range represents a transition between the intensely uplifting orogenic belts and the strongly denuded ancient massifs. According to fossil pediment remnants sub-tropical climate determined the denudation process during the Upper Miocene. Since the Late Miocene, these surfaces were overprinted by the valley and slope development determined by the climatic changes of the Late Tertiary and Quaternary period. During the cold phases of the Quaternary, the study area was under periglacial climatic conditions and the dominant surface development was the strong dissection of the palaeo-surfaces, frequently with mass movements. The research area is considered to be uniform considering surface development i.e. exposition time.

The database was based on map with a scale of 1:50000 and contour lines of 10 m digitized in Geomedia Professional 5.0. The vector-type data were transformed into raster-type using IDRISI 32 resulting a quite fine 25x25 m/pixel resolution and a dataset consisting of more than 2 million pixels (cases). Three topographic models were created with different resolutions as 25x25, 50x50 and 100x100 m per pixel. The number of pixels in the investigation area is 2373000, 593000, 148 000 respectively.

After creating a DEM, the derived map of slope steepness, and the map of distances from the base level in Idrisi, the values of these variables were added to each pixels.

The values of geological factors were also incorporated to the database. To each petrophysical category the value of the UCS - based on 350 data available from the literature and further 30 samples measured at the Debrecen University - was added. When measuring UCS a constantly growing pressure is exerted on a cylinder-shape sample until it breaks. UCS is an important factor of

investigating slope evolution and mass movements. Since the purpose of this work is to compare morphology (using slope category) and the long term erosion resistance of geological formations, a petrophysical parameter that adequately describes the resistance against denudation and is applicable for both hard rocks and unconsolidated sediments, was required. Shear strength seems to be an adequate parameter due to its important role in all physical models of transportation processes (fluvial erosion, various mass movements) occurring in the extended and geologically heterogeneous area. Shear strength can be determined directly by laboratory tests, but can be calculated from unconfirmed rock strength (shear strength is usually 6–20% of the unconfined rock strength). The latter is the most frequently used petrophysical parameter in practice (building industry, mining, civil engineering) and it is also used in geomorphological investigations. Additionally, since unconfined compressive strength (UCS) properly characterises most of the Hungarian rock formations this petrophysical parameter was used. The petrophysical data were collected from the National Geological and Geophysical Data Store. Thanks to the intensive mining activity in the study area a sufficient amount of petrophysical data was available from core samples and samples examined for technological purposes. 350 values were collected and grouped into formations. For the statistical analysis we used only the UCS value of dried specimens. Compressive tests were performed according to the Hungarian Standard, that are partly based on the recommendations of the ISRM (1978), so are similar to international practice.

Finally to test the reliability and applicability of UCS we compared it with other methods used in engineering and found it reliable (RMS, RQD, SMR).

The values of attrition resistivity and freezing resistance were measured in the Debrecen University as well. 50 samples (5 for each rock groups) were tested in a Los Angeles cylinder to measure attrition resistivity. The experiment lasted for 30 minutes (900 rotations), representing 1.5 km distance. The weight loss of wet samples due to attrition was measured after each 7.5 minutes, enabling us to draw the tendencies of attrition resistivity of the different rock types. Considering the remainder weight as a variable we tried to identify the connection between attrition resistivity and UCS, and other lithological factors, as well as the nature of relationship between frost resistivity and morphometric parameters.

To measure frost resistivity we used a frost chamber where the daily temperature was fluctuating between -20 ^{o}C and +20 ^{o}C. 30 wet samples (3 for each petrophysical group) were used in the experiment in order to reach quick weight loss. Low temperature was necessary since the water in the capillary tubes freezes only at -10 ^{o}C. The frequency of frost and thaw also influences the rate of weight loss, such as porosity, fractures and foliage (sheeted structure) of the samples does. The experiment lasted for 15 days, then the weight of the samples was measured again. Considering the remainder weight as a variable we

tried to identify the connection between frost resistivity and UCS, and other lithological factors, as well as the nature of relationship between frost resistivity and morphometric parameters. Together with frost resistivity the porosity of different rock types was also measured.

Results

Having created the database a correlation matrix of the variables was calculated including all the 2 million cases. Since i.e. in the case of slope steepness and distance from base level gentle slopes may occur near the river and far away as well due to the abundance of surface remnants (decreasing the correlation) the correlation matrix was also calculated for the average of the data grouped by rock types. The latter resulted better correlations.

After this both the dendrogram of variables (features) and cases (rock types) were created using hierarchic cluster analysis by SPSS for Windows. The data were standardised before clusterisation using the following equation: $y=\lg(x+1)$. The results show the strength of the connection between the different variables used in the research. Of course omitting factors or incorporating new variables or predicting denudation (time as a new variable) may change the relationships.

To control the strength of correlation and its nature (realistic or mathematic connection) partial correlation measurements were also incorporated into the investigation.

Identifying relationship between variables used in engineering or in geomorphology can be important since they reveal the connection between the geologic factors representing some kind of resistibility or erodibility. In the case of the relationship between the morphometric and geologic parameters we must be aware of the fact that sometimes quite tight correlations are the results of the specific features of the area. Although it is often stated that solid rocks form forms of greater heights while loose sediments constitute forms of smaller vertical extension, the strong correlation between the height and the UCS is not necessary.

To prove the connection between a certain slope form (abundance of a certain slope gradient) and rock type, we determined the relationship between the relative frequency of the slope category (SC) values and the UCS. The regression analyses proved significant correlation in the case of low and high slope gradients and a less significant correlation in the transition values. The adequate regression procedure is power regression for slope values lower than 18% while it is logarithmic regression for slope values higher than 22%. The distribution of slope category values between 16–22% showed nearly constant values for any petrophysical group, which can be interpreted as a gradual change of regression from the power to logarithmic. The transitional zone appeared at 16–18% with 0.38 R^2 value while in the interval 18–20% the R^2 is 0.1 for both power and logarithmic regression procedures.

According to the results we tried to classify slope category units which are in close correlation with the UCS. For this re-classification we used the characteristics of the regression procedures and the distribution of the R^2 values. Since the constellation of the two parameters seems to be symmetric, the following units, here called petrophysics related slope category intervals, can be defined.

With the help of the equations the expected UCS of any petrophysical category can be determined regarding the known slope category values and at the same time any expected slope category condition can be calculated from known petrophysical data.

According to our experience the quotient of the relative frequency of the intervals 4–10% and over 44% is determined by the UCS of a petrophysical category. The regression analysis shows good correlation ($R^2=0.87$); this quotient can thus be regarded as a morphological index for a given petrophysical category referring to the UCS.

To test the UCS calculated from slope category values the curves and equations of the intervals 4–10% and over 44% of the diagram were used and the mean of the results was compared with the value calculated from measured data of the petrophysical categories. In the case of data between 6 and 86 MPa the calculated results approach the actual UCS data. Below 6 and above 86 MPa the equations cannot be regarded as adequate.

The determination of relative denuadational resistance:

As the connection between the UCS and the distribution of slope category intervals of a petrophysical category is proved, the petrophysical categories can be characterised by a statistical slope profile. It can be regarded as a kind of cumulative curve of the slope gradients, where the X values are the cumulative values of the relative frequencies of the slope category units (rfSCU) from gentler to steeper. The also cumulative Y values are calculated as the tangent of the upper limit of a slope category unit (counted in degrees) multiplied by the relative frequency of the same slope category unit. Accepting that the shape of the slope has one inflexion point as well as a concave and a convex portions, and that the slope is symmetric to the inflexion point, we can mirror centrally the statistical slope profile constructing a hypothetic slope form. The calculated relative denudation resistance values (%, measured in axis Y) for the petrophysical categories are given in the dissertation.

The above mentioned method represents slopes reaching different height - due to different rock type - with common base level.

The curves were also drawn supposing surface remnants (common ridge level). In this case the top of the curves starts from the same Y value resulting shapes referring to different valley-width for each petrophysical cathegory. The first model equals with Scheidegger's 2nd nonlinear model representing cutting-in erosion, the latter is similar to the 3rd nonlinear modell, symbolizing the role of lateral dissection. This kind of curve is important, since maps usually

underestimate the length of steep slopes - showing only a vertical projection of the slopes not the real length. This curve represents the real length.

Substituting UCS with attrition resistivity, the above mentioned connection between slope frequency and hardness (erodibility) can also be proved. Attrition resistivity can be calculated from slope frequency and slope frequency can be calculated from experiments on attrition resistivity. In the case of frost resistivity the mentioned method does not work, the correlation proved to be weak.

Counting with the absolute values instead of percentages, different results can be calculated in different water catchments composed of the same rock (because of different slope frequencies). Therefore this method can be a key element to define the relative maturity index of catchment areas composed of the same rock. The results of the area under investigation were applied on smaller sections in order to examine their relevance.

Chapter 5 compares different (single and multivariable) denudational models: i.e. linear, nonlinear; based on relief, based on slope angle (Ahnert, Scheidegger); determined by rock type (Láng). The changes in surface levels, the thickness of denudated material, the changes in slope gradients are shown in cartograms, while the changes in correlation between the variables were also measured, as well as between the rock types. Finally we delineated territories sensitive for denudation by dividing slope gradient by rock strength for each pixel, creating a cartogram of potential erodibility.

In order to confirm our research for surface remnants on local scale at the Hódos catchment area we extended our investigations on the whole territory. Since the hipsometric curve of the whole dataset did not prove the existence of several surface remnants, we compared several methods for the identification of surface remnants using Idrisi. The essence of methods were to exclude some pixels that cannot belong to surface remnants. The applied methods were: buffering – isometric lines measured from valleys –, areas of minimum slope steepness, both existing in manual-graphic evaluation combined and other methods like cost push, ridge-lines based on the runoff of an inverted DEM, the set of minimum runoff-values, automatic classification and maximum surfaces. The question of surface remnants is a question of interpretation (the dataset of gentlest slopes on the ridges, and the dataset of area with same distance from the base level is different) therefore the results are not the same using different methods.

The aims of investigations related to the relationship between valley directions and fault direction were the followings:
-   to investigate whether there is connection between fault directions measured at outcrops and valley directions
-   to measure the the differences in valley distribution based on pieces or weighted by length
-   to investigate whether there is difference between the direction of short (young valleys) and long valleys

- to test, how the age and hardness of the base rock modifies the character and/or strength of correlations above
- to investigate how softwares developed for other purposes can be used for gaining valley direction data
- to test the differences of 3 different methods developed for this purpose
- how the results confirm the previous knowledge on the tectonic development of the region and what new results can be derived in terms of the tectonic evolution of a mountainous region

Conclusions

Based on 350 data obtained from literature and with the aid of 30 new measurements we defined the UCS values of petrophisical categories in the Bükk region. We proved that significant correlation exists between the UCS and other geological parameters used in engineering (RMR, internal friction angle, cohesion), so the UCS is a representative feature. The connection between UCS and other geologic factors (attrition resistivity, frost resistance) was also proved to be significant.

Correlation between morphometric (distance from base level, slope steepness, height above base level) and geological parameters was proved. We determined the strength and characteristics of the relationship. In this respect it is worth mentioning that attention must be paid when investigating the connection between height and rock hardness. Although several English and American authors proved the existence of connection between these two features, our opinion is that this relationship is strongly determined by the „favourable" geological conditions in the case of the Bükk Mountains (and generally as well). Due to the lack of data it is not clear whether the selective denudation or the different rate of elevation is responsible for the connection between rock strength and height.

Using the correlation coefficients of distance from base level and slope gradient we managed to identify the curvature type (convexity, concavity) of slopes on different petrophysical categories referring to differences in evolution.

We managed to give the values of attrition resistance based on experiments on 50 samples, and defined frost resistivity as well in the Bükk region using 20 samples. Porosity was also measured using 20 samples. The strong connection between these parameters and between morphometric features and denudation rate were also verified.

We made an attempt to extend the possibilities of geomorphic mapping using variables like UCS, relative erosional resistance, attrition resistance etc.

Correlation between the UCS and the relative frequency of the slope gradients has been proved. Shape of the regression functions developed between the UCS values and the relative frequency of the slope gradients were different according to slope steepness.

Based on the characteristics of the previously mentioned relationships and the calculated R^2 values new slope category intervals related to petrophysics have been identified between 4–10%, 10–16%, 16–22%, 22–44% and over 44%.

The UCS of the base rock can be calculated as the mean value of the two calculated UCS based on the UCS vs. slope frequency functions given for the frequency of the slope category units 4–10% and 44% <. The relationship seems to be valid between UCS values of 6 and 86 MPa.

Constructing the statistic slope profiles of the petrophysical categories their relative denudational resistance (given in percentages) can be calculated. The statistical slope profiles were calculated supposing common base level and supposing common top level (surface remnants) as well, representing deepening valley formation and lateral erosion (**Fig. 3-4**).

Based on the absolute denudational resistance values the relative maturity index of catchment areas composed of the same rock type can be measured.

Substituting UCS with attrition resistivity, the connection between the slope frequency and the geologic factor can be proved giving a formula as above between the UCS and slope gradient distribution. Attrition resistivity of the base rock can be calculated as the mean value of the two calculated UCS based on the UCS vs. slope frequency functions given for the frequency of the slope category units 4–10% and 44% <.

We proved that the relative relief is not applicable in most of the geomorphologic investigations using statistical surface analysis, since it incorporates more than one geomorphic features: valley density (horizontal dissection of the area), and height (vertical dissection) which implicitly includes slope steepness and slope length as well.

The cluster analysis (hierarchic cluster – dendrogram) revealed the closeness between different variables and the relationship between different rocks. The discriminant-analysis brough success: 80% of the data were regrouped successfully into 3 main lithological group using only the morphometric parameters. Partial correlation also proved to be successful to incestigate causality (**Table 1-3, Fig 1-2**).

The application of the above mentioned methods is also relevant in smaller catchment areas, as it is verified in the dissertation using sample areas.

On local scale it has been proved that incorporating derasional valleys into investigations studying the connection between relative relief and valley density decreases the strength of the connection: the denser derasional valleys occur, the smaller the relief is. The occurence of derasional valleys do not promote the dissection of the area but the opposite: they eliminate the differences.

The gaps and contradictions between denudation models were investigated. We investigated the role of rock quality in modifying the denudation. The map of potential erodibility was created for the investigation area (**Fig 5**). The temporal changes of the connection between the parameters were also examined.

Regional investigations were also carried out to measure the connection between morpometric and lithologic parameters on different landscapes using correlation matrices, regression analysis, dendrograms (**Table 4-5, Fig. 6-7**).

Some surface remnants were identified on local (2 terraces, 2 glacis) and regional scale (2 glacis) as well using methods applied in geoinformatics. The method of gentlest slopes and the set of minimum runoff values showed the best results, and are independent of the settings of any sample area.

The correlation between valley directions and fault directions has been proved. The azimuth of valley directions as well as the azimuth of fault lines increases clockwise around the Bükk core area in the Bükk foreland meaning that the core area rotates counterclockwise while upthrusting to its foreland. In the western semi-consolidated paleogene regions the dominant valley directions show 90-110 degree azimuth, while the eastern Paleozoic-Mesozoic regions show a bimodal distribution such as the eastern neogene less consolidated (overlying strata) regions. The 140 degree azimuth represents the original direction measured in the Paleozoic underlying strata, while the 90-110 degree represents the younger direction after the rotation.

We proved that the short - therefore younger – valleys show different directions than longer and older ones. The former show the direction of the general inclination.

The different levels of river magnitude according to Horton also showed differences regarding the valley directions, and the distribution of valleys of 3rd order represents the directions of fault lines.

The examination of the different resolutions proved that 25x25 m/pixel resolution is applicable, 50x50 m/pixel is suitable, but 100x100 m/pixel resolution is irrelevant in statistical surface analysis under circumstances mentioned in the introduction (scale=1:50 000).

Although the software was not developed to identify surface remnants, Idrisi proved to be relevant in solving probles like this. The method of gentlest slopes gave the best results in defining surface remnants. Some of the older manual methods were also applied and new methods were also tried.

We measured the valley directions weighted by length, which is a new method in the Hungarian morphology.

The statistical slope profile ensures a clearer and simple way of presenting slope steepness: unlike in the case of histograms this method allows to present more than one curve in the same diagram, while giving information on denudation processes. We proved that the usage of mean values and standard deviation is equivalent in these investigations

New methods were also developed to compare the distribution of valley and fault directions: investigation on the correlation gives result if those parts of the dataset which do not belong to the mode(s) are omitted.

Estimating UCS based on slope gradients:
$$(y_1 + y_2)/2, \text{ where}$$
$$y_1 = 32500x_{(4\text{-}10\%)}{}^{-2.6} ; \quad y_2 = 7.2e^{0.42x(44\% <)}$$
(y: UCS, MPa; x: frequency of 4-10% or 44%< slope interval in %)

Estimating relative denudational resistance based on statistical slope profile:

$$r_{er\_pc} = \sum_{i=1}^{5} (fr_i \times tg\,\alpha_i)$$

$$r_{reg} = \sum_{i=1}^{5} (fr_i \times ctg\,\alpha_i)$$

fr$_i$ relative frequency of slope interval in %
α$_i$ upper boundary of each intervals given in degrees
r_{er_pc} is dimensionless and comparable

eztimation of attrition resistance using statistical slope profile (wet 0.9 km, given in %-ban)

$$(y_{1+}y_2)/2$$
$$y_1 = -3{,}6x_{(4\text{-}10\%)} + 130$$
$$y_2 = 8{,}25Ln(x_{(44\%<)}) + 75$$
y= attrition resistance in Los Angeles cylinder (%); x: frequency of slopes given in %

Table 1. Pearson correlation matrix of morphometric and lithological features based on average values per petrophysical categories, 25x25 m/pixel resolution

R értéke	UCS (MPa)	Lejtés (%)	Magasság (m)	Erózió-bázis táv (m)	Kopás-állóság (%)	Víz-felvevő-képesség	Denudáció (m/mó év)	Fagy-állóság (%)	Kitettség (°)	Costpush	Lefolyás
UCS	1,000	0,833**	0,931**	0,548	0,781*	-0,661	-0,810**	0,741*	-0,312	0,771**	0,595
Lejtés	0,833**	1,000	0,831*	0,701*	0,781*	-0,657	-0,740*	0,748*	0,033	0,772**	0,471
Magasság	0,931**	0,831**	1,000	0,667*	0,662*	-0,723*	-0,850**	0,784*	-0,176	0,832**	0,734*
Erózáb. táv	0,548	0,701*	0,667*	1,000	0,291	-0,438	-0,394	0,407	-0,066	0,309	0,095
Kopásáll.	0,781*	0,781*	0,662	0,291	1,000	-0,703*	-0,607	0,606	0,103	0,747*	0,446
Vízfelvev.	-0,661	-0,657	-0,723*	-0,438	-0,703*	1,000	0,636	-0,648	0,096	-0,740*	-0,551
Denudáció	-0,810**	-0,740*	-0,850**	-0,394	-0,607	0,636	1,000	-0,973**	0,139	-0,834**	-0,784*
Fagyállóság	0,741*	0,748*	0,784*	0,407	0,606	-0,648	-0,973**	1,000	-0,014	0,861**	0,712*
Kitettség	-0,312	0,033	-0,176	-0,066	0,103	0,096	0,139	-0,014	1,000	0,163	0,053
Costpush	0,771*	0,772**	0,832**	0,309	0,747*	-0,740*	-0,834**	0,861**	0,163	1,000	0,857**
Lefolyás	0,595	0,471	0,734*	0,095	0,446	-0,551	-0,784**	0,712	0,053	0,857**	1,000

* p= 0,05   ** p= 0,01

Table 2. The result of factor analysis (principal components) of 11 morphologic and lithological features

Rotated Component Matrix

	1	2	3	4	5
height	**0,555**	0,325	**0,577**	0,311	-0,017
steepness	0,210	**0,834**	-0,004	-0,195	0,026
exposition	-0,008	0,026	0,043	0,004	**0,998**
base level	0,099	0,019	**0,953**	-0,032	0,050
costpush	0,236	**0,758**	0,137	0,317	0,008
runoff	0,059	0,012	0,016	**0,941**	0,004
ucs	**0,861**	0,192	0,249	0,079	-0,031
frost resist.	**0,918**	0,212	0,084	0,066	-0,007
porosity	**-0,787**	-0,058	-0,061	-0,043	-0,004
attrition res.	**0,859**	0,135	0,000	-0,054	0,031
denudation	**-0,919**	-0,205	-0,117	-0,088	0,018
KMO=0,77	45%	11%	9%	9%	8%

St. coefficient		St. coefficient	
	STEEPNESS		HEIGHT
heigth	0,051	*Base levels*	*0,329*
Base level	0,013	*UCS*	*0,643*
UCS	*0,300*	Steepness	0,020
	BASE LEV.		UCS
height	*0,672*	*heigth*	*0,767*
UCS	-0,227	Erózióbázis	-0,133
Steepness	0,011	Steepness	0,142

Table 3. Standardized coefficients of regression-analysis: the role of morphometric parameters
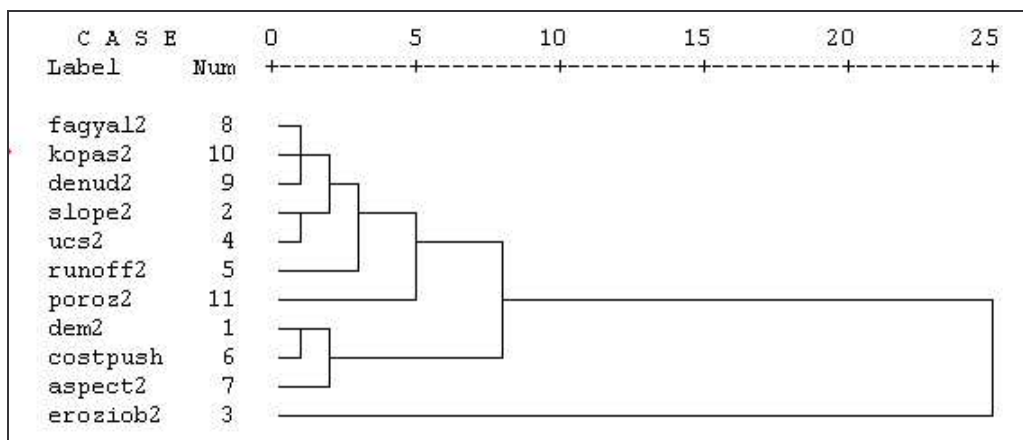

Fig. 1 The connection between morphometric and lithologic features based on the cluster analysis of the database
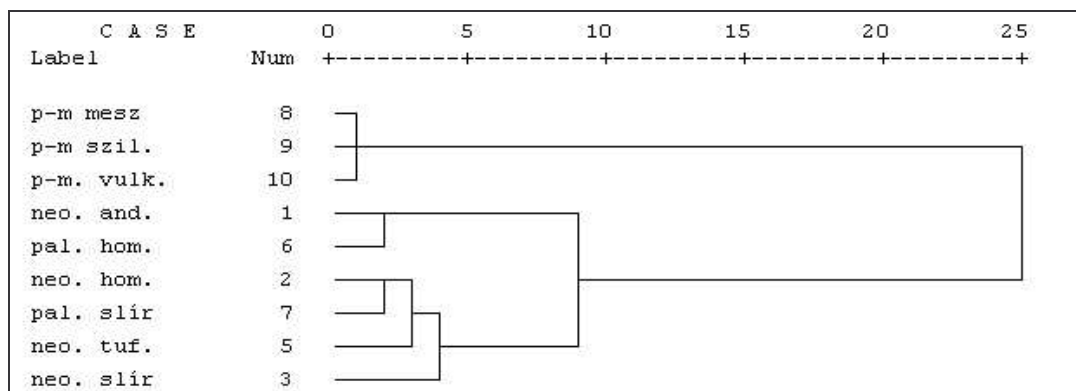

Fig. 2 The connection between rock types based on cluster analysis using mean values (dendrogram, standardized)
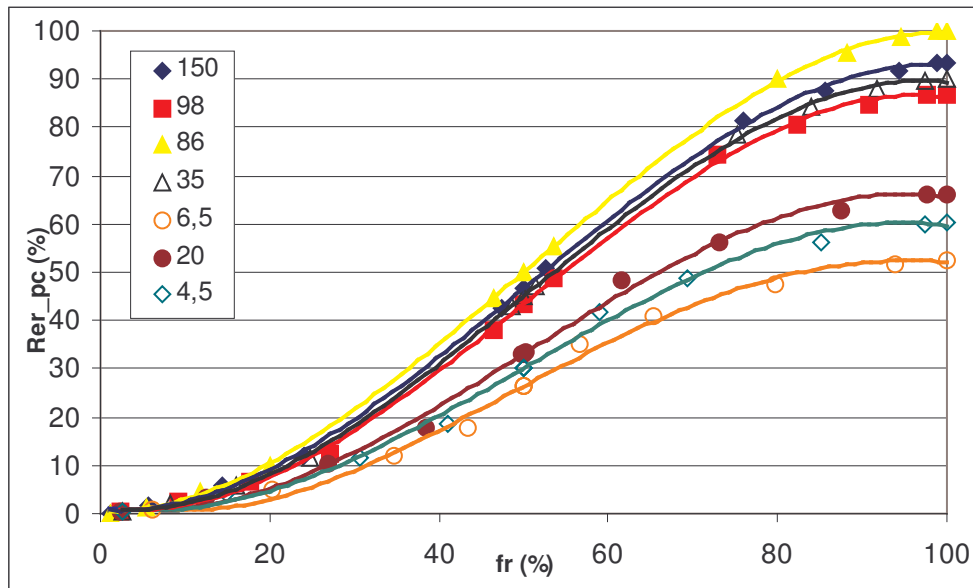
Fig. 3 The statistical slope profile of different rocks with different UCS (Bükk foreland) assuming common base level
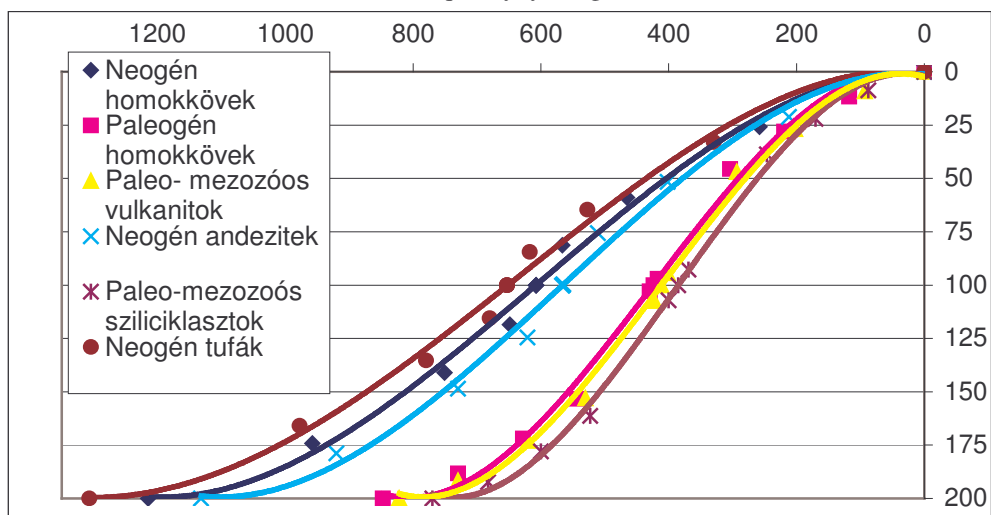
(x: frequency, y: height)

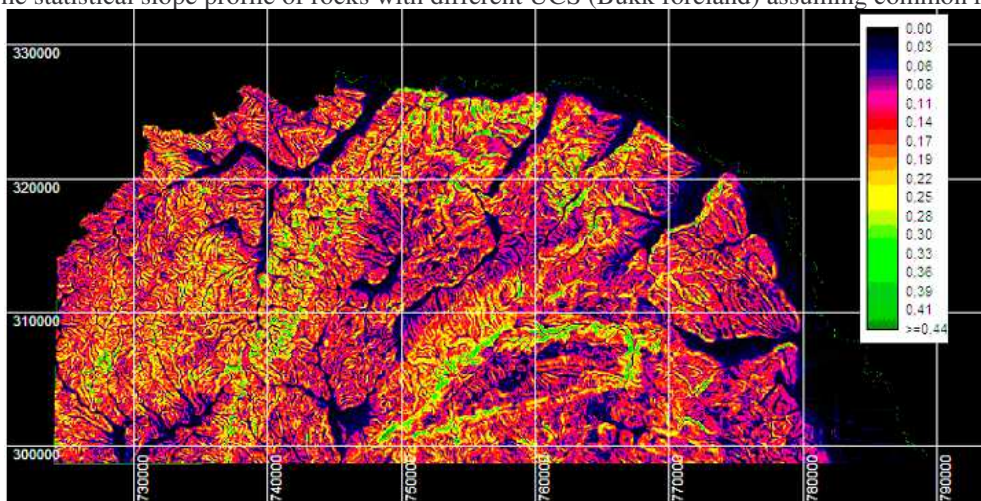**Fig. 4** The statistical slope profile of rocks with different UCS (Bükk foreland) assuming common ridge level

Fig. 5 The potential denudation map based on the quotient of slope gradient and rock strength (Bükk foreland)

Table 4 Correlation between parameters for 9 landscapes

	relief	valley dens.	precipitation	rock	steepness
relief	1,00	**0,836****	0,380	**0,656***	**0,827****
valley dens.	**0,836****	1,00	0,282	0,426	0,341
precipitation	0,380	0,282	1,00	0,462	0,153
rock type	**0,656***	0,426	0,462	1,00	**0,730**
steepness	**0,827***	0,341	0,153	**0,730**	1,00

** p=0,01   *p=0,05 szignifikancia

Table 5 The standardized coefficients based on regression-analysis for several parameters

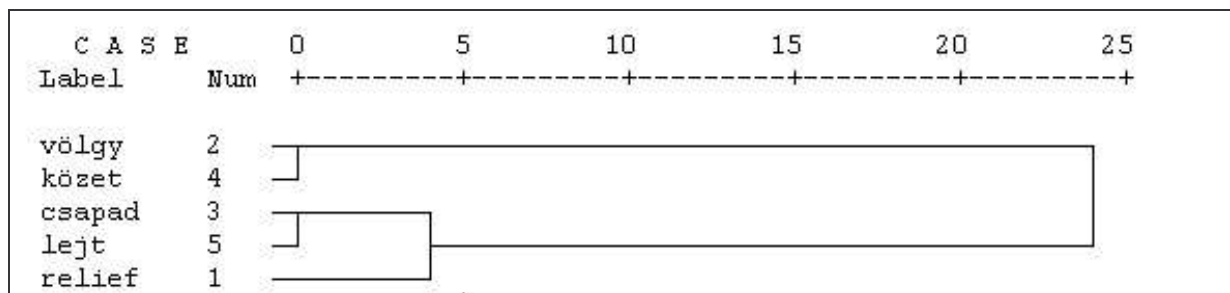| Relief (r=0,948)	St. koeff.	valley dens. (r=0,9)	St. koeff.	rock type (r=0,66)	St. koeff.	steepness (r=0,917)	St. koeff.
valley d.	*0,524*	*precipit.*	-0,509	*precipit.*	0,003	*precipit.*	*0,846*
precipit.	*0,222*	rock	-0,020	*steep*	1,000	relief	-0,129
rock	-0,108	*steep*	-0,155	relief	-0,501	rock	*0,300*
steep	*0,645*	*relief*	*0,822*	*valley d.*	-0,060	*valley d.*	-0,020

Fig. 6 The proximity between morphometric parameters based on 9 landscapes (dendrogram based on clusterization)
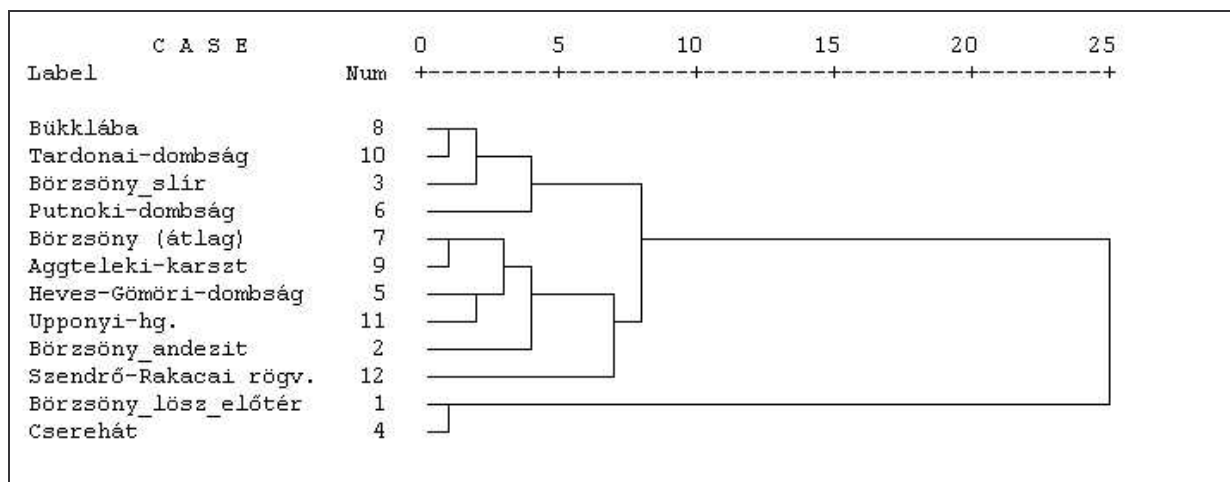

Fig. 7 Proximity between different landscapes based on morpometric and lithological parameters (dendrogram, hierarchic clusterization)