Identifying lithological features using morphometric parameters derived from DEM

Litológiai tulajdonságok azonosítása DTM-ből kivont morfometriai paraméterek alapján

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Abstract – The study focuses on the identification of lithological features based on morphometric variables derived from a 25x25m/pixel resolution DEM of the Bükk Mts., N-Hungary. Statistical methods using SPSS were applied to evaluate a database containing 20 million data in order to promote the cost-effectiveness of geological mapping. Using IDRISI software the derived morphometric parameters were altitude above base level (m), distance from base level (m), slope steepness (in degrees), slope aspect, runoff and costpush. Using TAS and SAGA softwares additional variables were chosen as sediment transport rate, wetness index, altitude above channel network. We investigated whether geological features (rock type, rock strength, resistance) can be identified or measured from these morphometric parameters. The reliability of the 3 softwares in this process was also tested, while the most sensitive morphometric parameters referring to geology were also identified. To test our hypothesis a control area with known geological background was selected, and the reclassification of data was carried out. Using IDRISI 70% of the pixels was successfully regrouped into the original rock type using morphometric data, while TAS and SAGA-type variables resulted more than 66%. Using correlation matrices some elements of surface evolution were also traced emphasising the differences between rock types.

Összefoglaló – Tanulmányunkban kőzettípusok és felszínfejlődési sajátosságok azonosítását kíséreltük meg morfometriai paraméterek statisztikai módszerekkel (SPSS) történő vizsgálatával, elősegítve a terepi kutatások hatékonyságát azáltal, hogy a vizsgálatok megtörténte előtt információt nyerünk a kutatott terület geológiai sajátosságaira vonatkozóan. Adatbázisunk 25x25m/pixel felbontású, 2 millió pixelt tartalmazó digitális terepmodellből kivont változókon alapult. A vizsgálatba bevont morfometriai változók az erózióbázistól való távolság, magasság, lejtőmeredekség, lefolyási értékszám, kitettség voltak, amelyeket Idrisi segítségével elemeztünk, míg az üledékszállítás, nedvességi index és egyéb változók kivonására a TAS és a SAGA segítségével került sor. A szoftverek hatékonyságának, megbízhatóságának összevetését a kívánt cél elérése érdekében szintén elvégeztük, miként azonosítottuk a kőzetminőségre leginkább érzékeny morfometriai változókat is. Hipotézisünk tesztelésére egy ismert geológiai adottságú kontrollterületet, a Bükk hegységet választottuk ki. A diszkriminancia analízis segítségével megvalósított visszaosztályozás 70%-os sikerességet mutatott a kőzettani kategóriák azonosítása terén IDRISI-t használva (elsősorban a keménységet, denudációs ellenállást szimbolizáló változók alapján jellemeztük a kőzettípusokat), míg a TAS és SAGA változói esetében a pixelek 66%-át sikerült visszasorolni az eredeti kőzettani kategóriába a morfometriai tulajdonságok alapján.

Keywords – DEM, lithological features, morphometric parameters, clusterisation, PCA, TAS, SAGA, IDRISI
Tárgyszavak – DTM, litológiai tulajdonságok, morfometriai paraméterek, klaszter-analízis, PCA, TAS, SAGA, IDRISI

Introduction

This study focuses on the identification of lithological features based on morphometric variables derived from DEM. During the last decades both remote sensing and GIS techniques have developed quickly making it possible to evaluate even fine resolution databases for the purposes of terrain analysis. From the perspective of geological applications, the former makes it possible to have a general overview on the lithology of a certain site before detailed geological mapping takes place, making geological surveys more cost-effective, while GIS-techniques, like computer-aided evaluation made possible the setting of enormous databases for quantitative analysis, making evalution faster and more effective.

It has been known for a long time that data on the lithological character of a given area can be derived from composite satellite images, but in our study we tried to elaborate the basis of a different method and test it. We aimed to identify rock types (concentrating on age, resistance to denudation, fault zones, etc.) based on morphometric variables derived from a DEM (and not satellite images). Since DEM can be produced not only from topographic maps, but from stereophotos as well, this method would also promote cost- and time-effectiveness of a geological research.

The derived morphometric parameters were processed by different software (IDRISI, TAS, SAGA), and the reliability of this software in identifying rock types was also tested to optimize both the selection of software and morphometric variables.

Methods and material

Area

To test our hypothesis a study area was chosen, where not only the geology was well-known, but data of other measurements referring to lithology (UCS, unconfined compressive strength, resistance to transport medium, frost resistivity, porosity) were also collected (*Fig.1*).

The investigation was carried out in an area of about 1500km^2 in northern Hungary. The area contains two regions of the uplifted Palaeozoic and Mesozoic basement and their extended forelands connected to an independent hilly region that is composed mainly of Palaeogene and Neogene molasse sediments. The Palaeozoic and Mesozoic series represent strongly diagenized, slightly metamorphosed formations. The Paleogene is well consolidated while the Neogene is usually semi-consolidated. The spatial distribution of the three main geological units is 21%, 29%, and 50% respectively.

The petrophysical category of Neogene sandstone consists of moderately cemented sand, pebble and conglomerate with clay and silt intercalations. Neogene silt is dominantly clay, marl and silt. Neogene Schlieren deposits (sands) consist of slightly-cemented shallow marine sandstones. Neogene tuff is represented by rhyolite–rhyodacite tuffs. Neogene andesite is an andesite agglomerate and lavabreccia. Palaeogene Schlieren deposits contain sand-bearing, micaceous clayey siltstone, claymarl and clay. Palaeogene sandstone frequently contains glauconitic, siliceous and carbonate cementation. Palaeozoic and Mesozoic siliciclastic rocks are represented by silicified sandstones, schistose siltstones, radiolarites. Palaeozoic and Mesozoic limestones are represented by marine limestone. Palaeozoic and Mesozoic igneous rocks are gabbro, dolerite, and basalt.

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.

Some remarks should be noted regarding the constraints of the forthcoming examination and evaluation. This investigation is considered to be relevant on upthrust, imbricated nappe systems, where the different rock types are separated from each other by valleys (evolved on fault lines in this case), thus the base level can be considered the same for all rock types, and positive forms are dominated by a certain rock type (the structure of hills is not layered, but nearly homogeneous). The model is relevant in areas where the core mountain (composed of crystalline rocks, or other hard rocks) is surrounded by semi- or unconsolidated rocks (flysch, molasse sediments), like the Pyrenees.

Methods

To identify rock types based on morphometric data, statistical methods, like correlation matrices, clustering, factor and regression analysis, and finally discriminance-analysis were applied using SPSS 15.0.

The DEM was derived from a topographic map, with a scale 1:50 000, contour lines by 10 metres. The resolution of the raster-type output was set to 25x25 metres/pixel as offered by HUTCHINSON & GALLANT (2000). Using IDRISI software, the derived morphological parameters (serving the base of identification) were: altitude above base level (m), distance from base level (local base of erosion, m), slope steepness (in degrees), slope aspect, runoff and costpush (*Fig. 2*).

Using TAS and SAGA additional parameters were chosen as sediment transport capacity, wetness index, network index, relative stream power (for definitions see *Table 10*). These were the variables used in our investigation. The 25x25m/pixel resolution resulted 2 million pixels, each characterised by the above mentioned 9 morphometric variables, producing 18 million cells in the database (beside co-ordinates and variables referring to rock type).

Producing variables representing rock features was a bit different and more difficult, since the amount of available data did not enable us to attach data on rock quality for each pixels, thus extrapolation was needed. First, the 67 formations of the territory were grouped into 10 petrophysical categories (for details see PÜSPÖKI et al 2005), then the averages for each formation were calculated using the available experimental data. The mean values were attached to each pixel of a given petrophysical category, resulting in smaller variance for these data-types (*Table 1*).

To provide data for rock types (to create numeric variables for geology in the database for quantitative analysis) 357 data regarding unconfined compressive strength (UCS, see YASAR-ERDOGAN 2004) from the archives of MAFI were collected, and additional 30 measurements were carried out at the Faculty of Engineering, University of Debrecen.

Since the territory is dominated by the Darnó fault zone, based on the examination of 44 outcrops, UCS values were corrected by the distance of lithoclases for the 10 rock types, using a nomograph given by GÁLOS-VÁSÁRHELYI (2006).

Further 100 rock samples were tested for resistence to attrition at the laboratory of the Institute of Earth Sciences, University of Debrecen using Los Angeles-cylinder, and 50 samples were tested for resistance against freezing and for porosity at the frost box of the laboratory.

Samples in the Los Angeles cylinder were tested for 30 minutes representing 900 rotations or 1500–1600 metres. (The average velocity of the rotation was 0.5 rotation/sec around a horizontal axis, the diameter of the cylinder was 0.7 metre, its depth was 0.6 metre). The average sample size was around 1kg, specimens were cubic, and 3 samples of the same rock type were tested at the same time. The inner perimeter of the cylinder was covered by foamy plastic, to prevent attrition on the steel surface of the cylinder – we decided rather to test the attrition of rock samples observed on the parent rock constituting the surface, then to measure attrition on steel. By measuring the weight loss of the samples the average resistance to the transporting medium was calculated in percents, the rock type with the highest resistivity represented 100%.

In the frost chamber the temperature varied between 20°C and +20°C within 24 hours. All the tested specimens were wet, their pores filled with water. Our aim was to produce the maximum weight loss within the shortest period, and not the reconstruction of the possible climatic conditions at which weathering occurs, that's why the testing circumstances were set in such a manner. Water sucking capacity was also measured.

Results

After these examinations three correlation matrices were created both for the lithological and morphometric parameters to analyze differences of surface evolution on different rock types.

The first matrix (*Table 2*) was created for the separate groups of rock types using altitude, slope steepness and distance from base level. The correlation coefficient remained low in most of the cases. This is not surprising if we accept the presumption that i.e. between distance from base level and slope steepness one cannot expect strong correlation, since supposing a normal slope with one inflexion point, the least steep slopes can occur both near the base level (valleys, terraces), and quite far from it (surface remnants), and the steepest slope occur between these. The same is true for the relationship between altitude and slope steepness.

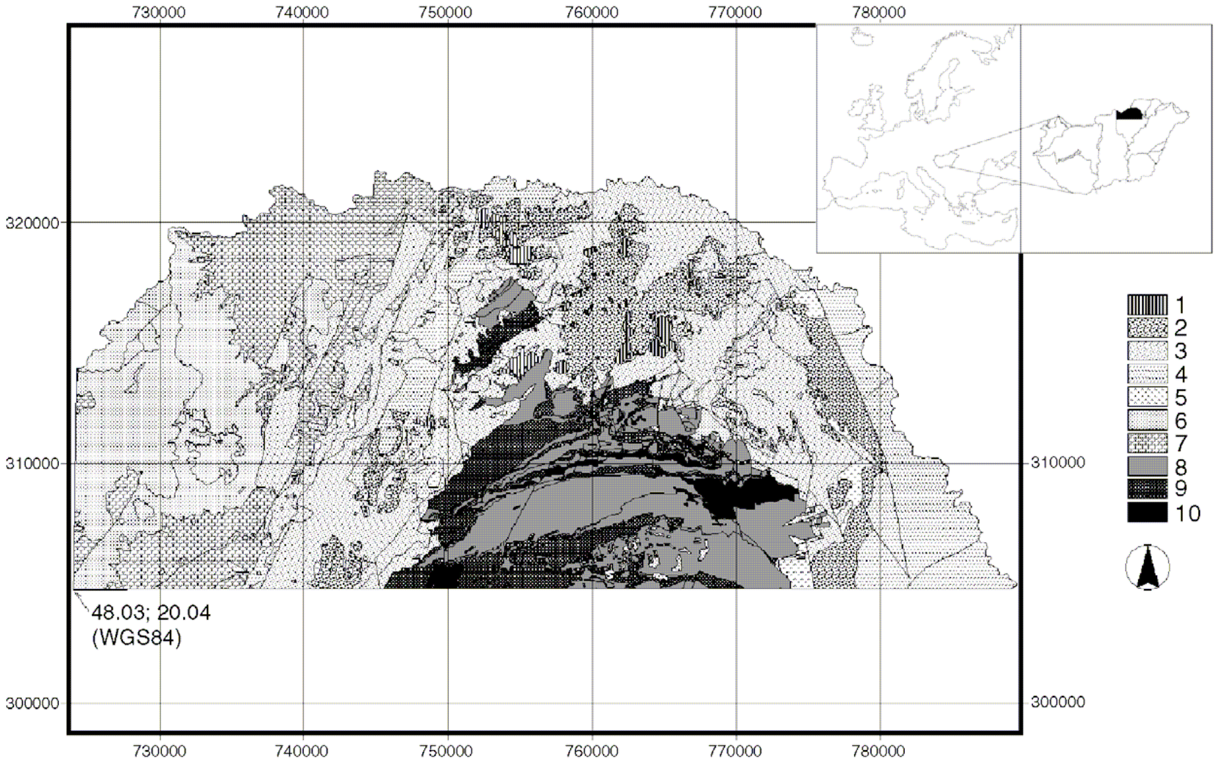


Figure 1 The geologic background of the investigated control area
Legend: 1. Neogene andesites, 2 Neogene sandstone, 3. Neogene schlieren, 4. Neogene silts, 5. Neogene tuffs, 6. Palaeogene sandstone, 7. Palaeogene schlieren, 8. Palaeo-Mesozoic limestones, 9. Palaeo-Mesozoic siliciclast, 10. Palaeo-Mesozoic volcanics (after BUDINSZKY et al. 1999 compiled by Püspöki & Szabó)

1. ábra A vizsgálati terület egyszerűsített földtani térképe a kőzetfizikai kategóriák bemutatásával (BUDINSZKY et al. 1999. alapján szerk.: Püspöki Z. – Szabó Sz.)
Jelmagyarázat: 1: neogén andezit; 2: neogén homokkő; 3: neogén slír; 4: neogén aleurolit; 5: neogén tufa; 6: paleogén homokkő; 7: paleogén slír; 8: paleo-mezozóos mészkő; 9: paleo-mezozóos sziliciklaszt; 10: paleo-mezozóos vulkanit

1:costpush 15,71774

	d	dem	slope	aspect	distance	costpush	runoff	ucs	frostres	porosity	attritio	denud	var
1633997		580,982	13,818	254,836	8207,076	341,178	27,000	86,00	96,00	1,00	66,00	25,00	
1633998		583,830	11,442	242,713	8185,091	341,183	28,000	86,00	96,00	1,00	66,00	25,00	
1633999		586,065	10,577	220,899	8163,123	344,418	28,000	86,00	96,00	1,00	66,00	25,00	
1634000		587,292	11,849	189,396	8141,172	350,599	33,000	86,00	96,00	1,00	66,00	25,00	
1634001		587,032	14,109	167,423	8119,240	354,198	68,000	86,00	96,00	1,00	66,00	25,00	
1634002		585,756	17,617	159,830	8097,325	351,390	23,000	86,00	96,00	1,00	66,00	25,00	
1634003		583,996	19,485	158,429	8075,427	344,087	38,000	86,00	96,00	1,00	66,00	25,00	
1634004		582,175	19,026	161,693	8053,548	335,557	31,000	86,00	96,00	1,00	66,00	25,00	
1634005		581,009	15,788	167,878	8031,687	329,643	21,000	86,00	96,00	1,00	66,00	25,00	
1634006		580,518	11,849	172,134	8009,844	325,272	41,000	86,00	96,00	1,00	66,00	25,00	
1634007		580,198	7,898	170,115	7988,020	320,121	27,000	86,00	96,00	1,00	66,00	25,00	
1634008		579,841	4,142	155,531	7966,214	315,048	22,000	86,00	96,00	1,00	66,00	25,00	
1634009		579,341	2,191	71,985	7944,427	314,005	25,000	86,00	96,00	1,00	66,00	25,00	

Figure 2 Part of the database with the values of morphometric and lithologic variables for some pixels

2. ábra Az adatbázis egy részlete a morfometriai és litológiai változókkal

	Frost resist (%)	Porosity (%)	Attrition resist. (%)	Slope steepness (%)	Altitude (m)	Distance base level (m)	Denudation (m/million years)	Runoff	Costpush
Neogene andesite	81.0	8.0	59.0	16.28	326	3877	30	59	476
Neogene sandstone	55.0	6.4	38.0	14.72	282	3789	45	48	370
Neogene schlieren	15.0	3.4	47.0	13.70	284	6979	60	32	247
Neogene siltstone	n.a.	n.a.	n.a.	12.83	293	7671	45	31	218
Neogene tuffs	66.0	12.5	15.5	12.91	268	6494	35	33	219
Palaeogene sandstone	82.0	2.5	72.0	22.30	316	6705	30	36	371
Palaeogene schlieren	15.0	20.0	35.3	14.93	236	6349	60	27	199
Palaeo-Mesozoic limestone	100.0	1.0	61.1	22.40	571	9576	10	72	507
Palaeo-Mesozoic siliciklastics	97.0	1.0	63.4	25.66	510	13224	25	44	495
Palaeo-Mesozoic volcanites	100.0	0.1	99.2	23.40	528	7573	15	52	502
	UCS (MPa)	Sediment transport rate TAS	network index TAS	Relative stream power TAS	wetness index TAS	wetness index SAGA	relative stream power SAGA	sediment transport SAGA	pixels
Neogene andesite	20.0	7.400	6.650	53.400	6.700	7.070	49.650	2.070	31489
Neogene sandstone	4.8	6.570	7.050	56.330	7.100	7.590	88.080	1.800	196936
Neogene schlieren	6.6	n.a.							529553
Neogene siltstone	6.5	6.280	7.180	51.970	7.220	8.080	258.930	1.800	112907
Neogene tuffs	7.3	5.950	7.400	66.420	7.450	8.070	132.480	1.630	31592
Palaeogene sandstone	35.0	10.630	6.460	78.500	7.080	7.080	156.220	3.020	356651
Palaeogene schlieren	5.0	n.a.							301105
Palaeo-Mesozoic limestone	98.0	13.130	6.650	122.380	6.690	7.350	403.350	3.620	306467
Palaeo-Mesozoic siliciklastics	86.0	16.710	6.610	174.500	6.630	7.270	374.470	4.380	159121
Palaeo-Mesozoic volcanites	150.0	14.140	6.500	140.810	6.550	7.090	358.920	3.840	37369

Table 1 Average values of litological and morphometric parameters for petrophysical groups

1. táblázat Az előállított litológiai és morfometriai változók átlagértékei kőzettípusonként

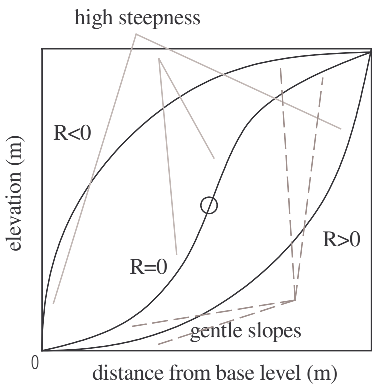


Figure 3 Relation between slope types and R correlation coefficient values based on the relations distance from base level – slope steepness and elevation – slope steepness

3. ábra A lejtőtípus és a korrelációs koefficiens értéke a lejtés – magasság és lejtés – erózióbázistól való távolság kapcsolata esetén

This provides a possibility to identify slope types based on these correlation coefficients. R=0 when the slope is normal. The high R value means, that the steeper the slope, the greater the distance is from the base level. Or, the steeper the slope, the greater the elevation is, both referring to a concave slope. Negative R values mean, that the steeper the slope, the nearer the base level is (the same is true for altitude-steepness relation: the lower the altitude, the steeper the slope is), referring to convex slopes.

Results indicate that Palaeogene Schlieren deposits tend to constitute concave slopes (correlation coefficient = 0.45 meaning that the inflexion line tended to occur near the peaks and ridges), while other rock types usually constitute convex slopes (*Fig. 3*).

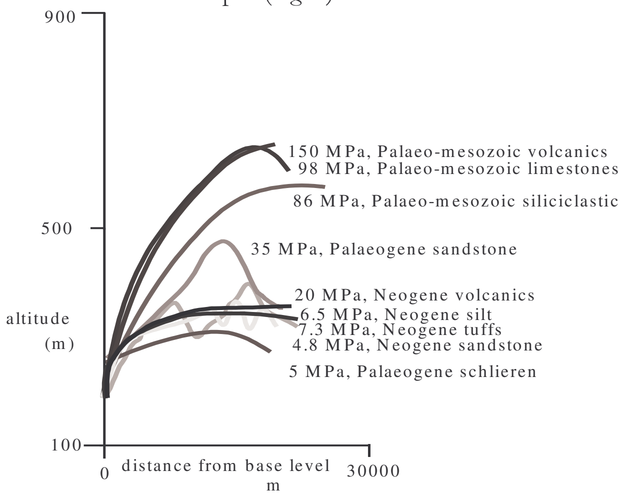


Figure 4 Relation between altitude and distance from base level for petrophysical groups with different UCS

4. ábra Kapcsolat az erózióbázistól való távolság és a magasság között különböző keménységű (UCS) kőzetek esetén

R value	Neogene volcanics	Neogén sandstone	Neogene schlieren	Neogene siltstone	Neogene tuffs	Palaeogene sandstone	Palaeogene schlieren	Palaeo-Mesozoic limestones	Palaeo-Mesozoic siliciclastic	Palaeo-Mesozoic volcanics
Altitude-steepness	-0.104	0.113	0.167	0.087	0.148	0.152	**0.530**	-0.024	0.058	-0.055
Altitude-distance	**0.629**	**0.522**	**0.701**	**0.716**	**0.837**	**0.503**	**0.521**	**0.734**	0.400	**0.615**
Steepness-distance	-0.171	-0.138	-0.054	-0.014	0.116	0.181	-0.072	0.095	0.133	0.156

Table 2 Correlation between morphometric variables for each petrophysical group

2. táblázat Korreláció a morfometriai paraméterek között kőzettípusokra lebontva

	altitude (m)	slope (%)	aspect (o)	distance (m)	costpush	runoff	UCS (MPa)	frost resist. (%)	porosity (%)	attrition res. (%)	denudation (mm/MA)
altitude	1	0.278	0.025	**0.507**	**0.576**	0.254	**0.738**	**0.621**	-0.496	0.437	-0.674
slope	0.831**	1	0.036	0.104	0.407	-0.010	0.340	0.351	-0.217	0.337	-0.341
aspect	-0.176	0.033	1	0.079	0.038	-0.003	-0.012	-0.002	0.009	0.010	0.009
distance	0.667*	0.701*	-0.066	1	0.012	0.058	0.263	0.182	-0.165	0.162	-0.188
costpush	0.832**	0.772*	0.163	0.309	1	0.189	0.378	0.400	-0.305	0.292	-0.400
runoff	0.734*	0.734*	0.053	0.095	0.857**	1	0.120	0.120	-0.088	0.063	-0.129
UCS	0.931**	0.833**	-0.312	0.548	0.771*	0.595	1	**0.844**	**-0.588**	**0.700**	**-0.894**
frost resistivity	0.784*	0.748*	-0.014	0.407	0.861**	0.712*	0.741*	1	**-0.660**	**0.751**	**-0.978**
porosity	-0.723	0.657	0.096	-0.438	-0.740	-0.551	-0.661	-0.648	1	**-0.680**	**0.635**
attrition res.	0.662	0.781*	0.103	0.291	0.747*	0.446	0.781*	0.606	-0.703*	1	**-0.737**
denudation	-0.850**	-0.740**	0.139	-0.394	-0.834**	-0.780*	-0.810**	-0.973**	0.636	-0.607	1

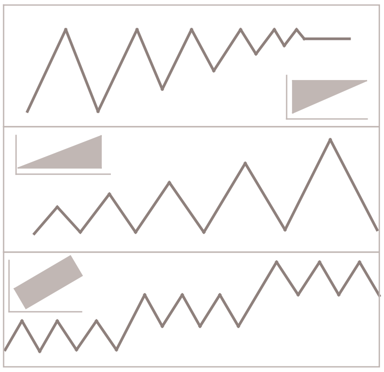
Table 3 Correlation matrix of DEM derived morphometric and lithologic parameters. Note that numbers right from number 1 represent correlation coefficients based on the original database using 2 million pixels (Pearson bivariate correlation), while numbers with italic figures represent correlation coefficients of average values counted for the 10 rock types.
*In the latter case tailed coefficients represent significance of *p<0.05 and **p<0.01*

3. táblázat A morfometriai és litológiai paraméterek korrelációs mátrixa a teljes adathalmaz felhasználásával (Pearson korreláció) 25x25 m/pixel felbontás esetén (saját szerk.). A számok az átlótól jobbra a teljes adatbázis 2 millió pixelje alapján mért korrelációt mutatják, az átlótól balra lévő számok a 10 kőzettípusra számított átlagértékek korrelációját mutatják be.
*Az utóbbi esetben a szignifikáns korrelációt * p<0.05 és ** p<0.01 jelenti*

	sediment transport capacity TAS	network index TAS	relative stream power TAS	wetness index TAS	wetness index SAGA	stream power SAGA	sediment transport SAGA	altitude	slope	aspect	UCS
sediment transport capacity TAS	1	0.240	**0.790**	0.220	0.010	0.050	**0.630**	0.160	0.430	0.030	0.220
network index TAS	**-0.750**	1	0.350	**0.990**	**0.700**	0.100	-0.070	-0.190	-0.490	-0.040	-0.120
relative stream power TAS	**0.970**	-0.560	1	0.350	0.170	0.070	0.290	0.040	0.010	0.010	0.220
wetness index TAS	**-0.750**	1.000	-0.570	1	**0.700**	0.100	-0.080	-0.190	**-0.510**	-0.040	-0.120
wetness index SAGA	0.620	0.95**	-0.450	**0.950****	1	0.250	-0.040	-0.200	**-0.500**	-0.040	-0.090
relative stream power SAGA	**0.800**	-0.360	**0.830**	-0.370	-0.140	1	0.300	-0.020	-0.040	-0.010	0.030
sediment transport cp. SAGA	**1.000**	**-0.770**	**0.950**	**-0.780**	-0.640	**0.800****	1	0.220	**0.670**	0.040	0.320
altitude IDRISI	0.91**	**-0.690**	0.520	-0.690	-0.600	**0.810****	**0.910****	1	0.280	0.025	**0.738**
slope IDRISI	0.96**	**-0.870**	**0.870****	**-0.880**	**-0.740**	**0.710****	**0.980****	0.83**	1	0.036	0.340
aspect IDRISI	0.050	-0.400	-0.080	-0.400	-0.420	-0.230	0.060	-0.176	0.030	1	0.010
UCS	**0.870****	-0.660	0.85**	-0.670	-0.570	**0.800****	0.870	0.93**	0.93**	-0.310	1

*Table 4 The correlational matrices for all data and for averages were also created for variables derived by TAS and SAGA. Unlike in IDRISI, the reclassification was not so convincing using TAS or SAGA. Note that numbers right from number 1 represent correlation coefficients based on the original database using 2 million pixels while numbers with italic figures represent correlation coefficients of average values counted for the 10 rock types. In the latter case tailed coefficients represent significance of * p<0.05 and **p<0.01*

*4. táblázat A TAS és SAGA segítségével kivont morfometriai tényezők korrelációs mátrixa (Pearson-korreláció) az átlagértékek felhasználásával 25x25m/pixel felbontás esetén (saját szerk.). Az eredmények nem olyan meggyőzőek, mint az előző esetben. Az átlagtól jobbra található értékek a teljes adathalmaz 2 millió pixelén alapuló korrelációs együtthatóit mutatják be, az átlótól balra lévő értékek a kőzettípusonként átlagolt értékek korrelációját ábrázolják. Az utóbbi esetben a szignifikáns korreláció jelölése * p<0.05 és ** p<0.01*



Increasing minimum, stagnating maximum: valley regression and incision is still in progress. Initial phase of dissection: lowering is still in progress, surface remnants can be traced, decreasing relief towards the core area.
Neogene volcanics

Stagnating minimum, increasing maximum. Incision and regression has ended, the lowering of ridges takes place, increasing relief
Palaeogene sandstone

Increasing minimum and maximum, uplift in the center is quicker than incision and regression, the center is uplifting,, margins are lowering, /or tectonically dissected surface remnant
Palaeo-Mesozoic limestone, volcanics

distance from base level (m) vs. altitude (m)

Figure 5 Denudation types in the Bükk Mts. on different rocks based on distance-altitude relations

5. ábra Lepusztulási típusok különböző kőzeteken a Bükkben a magasság és az erózióbázistól való távolság függvényében

As CLAYTON & SHAMOON (1998a,b 1999) has already proved, more consolidated (or older) rocks tend to constitute higher forms, then forms evolved on unconsolidated rock types at the same distance measured from the base level of erosion. Our investigation also confirms their results (*Fig. 4*). Irrespective of differences in rock hardness an equation can be set for average elevation using the distance from base level (using 60 000 randomly selected data), which was tested to avoid autocorrelation:

$$y = 7234{,}4\mathrm{Ln}(x) - 36844 \quad (R=0.65)$$

x= altitude/magasság (m),
y= distance from base of erosion/erózióbázistól való távolság

Based on the patch-type of distance-altitude diagrams drawn for different types of rocks, 3 main types of surface evolution can be distinguished in our sample area (*Fig. 5*). The type with increasing minimum and stagnating maximum (regarding distance-altitude relations) represents a young surface where neither the dissection of the area, nor the incision of valleys has ended. Lowering is still in progress Valley regression is in initial phase. Neogene volcanics relatively hard to other Neogene rocks are grouped into this type.

The patch type with increasing maximum, and constant minimum regarding distance-altitude relations represents a dissected area with higher peaks in the center and equalised valley profiles. Valley incision and retrogradation has ended, lowering is backstepping, but has not reached the core area yet. Palaeogene sandstones are comprised in this category.

The third type has increasing maximums and minimums, representing a tectonically dissected area elevated at different heights, or different generation of surface remnants (plateaus, pediments, etc.) Palaeozoic-Mesozoic limestones show this type of patch in distance-altitude diagrams (*Fig. 5*).

As *Table 3* shows, correlation is more significant, if the averages of the variables are compared instead of separate pixels (average represents an optimal statistical parameter, and can substitute standard deviance in this case). *Table 4* shows correlation values for parameters derived from TAS and SAGA.

Rotated Component Matrix/faktorok					
	1	2	3	4	5
Magasság Altitude	**0.555**	0.325	**0.577**	0.311	-0.017
UCS	**0.861**	0.192	0.249	0.079	-0.031
Fagyállóság Frost resist.	**0.918**	0.212	0.084	0.066	-0.007
Vízfelvevő Porosity	**-0.787**	-0.058	-0.061	-0.043	-0.004
Kopásállóság Attrition resist	**0.859**	0.135	0.000	-0.054	0.031
Denudáció Demudation	**-0.919**	-0.205	-0.117	-0.088	0.018
Lejtés Slope	0.210	**0.834**	-0.004	-0.195	0.026
Costpush	0.236	**0.758**	0.137	0.317	0.008
Erozióbázis Distance.b.l.	0.099	0.019	**0.953**	-0.032	0.050
Lefolyás Runoff	0.059	0.012	0.016	**0.941**	0.004
Kitettség Aspect	-0.008	0.026	0.043	0.004	**0.998**
KMO=0.77	45%	11%	9%	9%	8%

Table 5 The result of PCA: variables are grouped into factors (principal components)

5. táblázat Főkomponens-analízis során varimax rotációval létrejött mátrix, mely a változók faktorba sorolását és a faktorral való korrelációját mutatja

To trace independent variables and to avoid the use of variables with multicollinearity in the further examinations, hierarchical clusterisation of variables was applied. Data were standardized, Ward's method was used to create the dendrograph for the variables. We can conclude that among the variables used, parameters referring to similar physical background can be found. The factor analysis (applied method – principal component with varimax rotation) confirmed our suspect and created only 5 factors, grouping variables referring to lithology into one group, while slope aspect and runoff were regarded as separate factors (independent variables) (*Fig. 6, Table 5*).

Hierarchical clusterisation of data based on morphometric variables (without lithological variables) and on extracted factors grouped rocks into three major groups, separating consolidated Palaeo-Mesozoic rocks from unconsolidated Neogene (except Neogene volcanics), and from Palaeogene sandstones of intermediate hardness (grouped together with Neogene volcanics). This classification is almost equivalent of the age of rock types (*Fig. 7*).

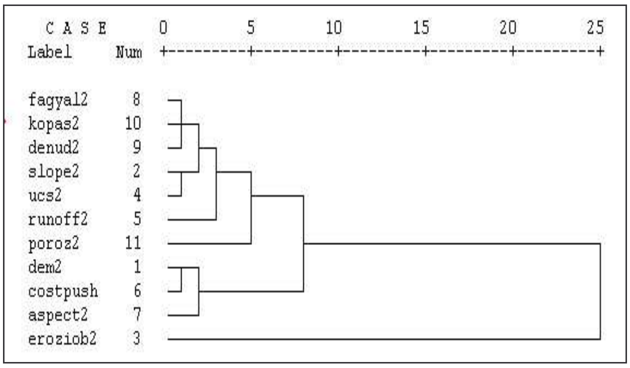


Figure 6 Clusterisation of morphometric and lithological variables

6. ábra A morfometriai és litológiai tényezők kapcsolata a teljes adatsor klaszteranalízise alapján

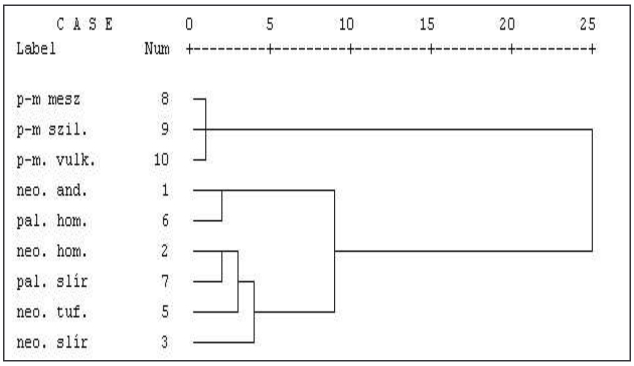


Figure 7 The hierarchical clusterisation of rock types based on morphometric parameters resulted 3 main groups, diferring in hardness

7. ábra A kőzettípusok hierarchikus klaszterezése a morfometriai változók alapján 3, kőzetkeménység szerint különböző csoportba osztotta szét a kőzeteket

This means, that there is enough difference between rocks to try to identify them without using variables referring to lithological characteristics, using only morphometric variables. To test this idea discriminant function analysis was carried out. We tried to reclass the pixels into the original lithological group using the morphometric variables derived from the DEM. Supposing 10 rock groups, the reclassification brought success only in 61% of all cases, but the reliabilty reached 75% when instead of using all rock groups, only the 3 main clusters (as seen in *Fig. 7*) were used, rendering prediction more convincing. From among morphometric parameters even distance from base level, slope steepness and elevation were enough to reach this value. Costpush, aspect, runoff did not modify the result significantly. Adversely, based on the latter 3 variables the success of reclassification also reached 70% without using slope steepness, elevation, and distance data. The reliability of reclassification exceeded 75% in the case of unconsolidated and Palaeo-Mesozoic rocks, while in the case of transitional, semiconsolidated rocks the success remained around 50% (this limit value represents random success).

Using variables of SAGA for the 3 major rock groups, Palaeogene rocks still remained poorly classified, however successfully reclassed pixels among Palaeogene rocks reached 50% (*Table 7*). TAS seems to be the least applicable software to identify lithology based on morphometric parameters (*Table 8*).

(%) Original group	Reclassification results by IDRISI		
	Neogene	*Paleogene*	*Palaeo-Mesozoic*
Neogene	**97.7**	2.2	0.1
Palaeogene	76.8	**18.0**	5.2
Palaeo-Mesozoic	21.3	5.4	**73.4**

Table 6 The result of reclassification (discriminate-analysis) by IDRISI – identifying lithology based on morphometric data

6. táblázat A visszaosztályozás eredménye 3 kőzettani nagycsoport esetén IDRISI segítségével – a litológia azonosítása a morfometriai változók felhasználásával

(%) Original group	Reclassification by SAGA variables		
	Neogene	*Palaeogene*	*Palaeo-Mesozoic*
Neogene	**88.8**	11.2	0
Palaeogene	49.2	**48**	2.8
Palaeo-Mesozoic	9.2	11.7	**79.1**

Table 7 The result of reclassification (discriminant-analysis) by SAGA variables – identifying lithology based on morphometric data

7. táblázat A visszaosztályozás eredménye 3 kőzettani nagycsoport esetén – a litológia azonosítása a morfometriai változók felhasználásával

(%) Original group	Reclassification by TAS variables		
	Neogene	*Palaeogene*	*Palaeo-Mesozoic*
Neogene	**81.2**	1.5	17.3
Palaeogene	50.2	**3.5**	46.2
Palaeo-Mesozoic	46.7	2.6	**50.6**

Table 8 The result of reclassification (discriminant-analysis) by TAS variables – identifying lithology based on morphometric data

8. táblázat A visszaosztályozás eredménye 3 kőzettani nagycsoport esetén – a litológia azonosítása a morfometriai változók felhasználásával

Conclusions

In this study we proved that the geology/lithology of a certain site can be predicted by morphometric parameters derived from DEM, if the investigated site consists of rocks with different age and degree of consolidation, and if the number of rock types do not exceed a certain limit. However the method is yet not enough sophisticated to predict lithology in fine resolution – making difference between rocks with quite similar characteristics, and can be used for rocks with quite different features (age, consolidation). In our case the originally 67 formations were grouped into 10 petrophysical categories, but the method was not able to reclass pixels into these 10 groups, success was brought only when categories were limited to 3 groups. In the latter case the 70% of pixels were successfully regrouped into their original petrophysical category using DEM derived morhometric parameters.

The geological settings of the site are also constraints of the examination. Yet, we are convinced, that the method can be developed to make geological surveys more cost-effective – used as preliminary investigations prior to field investigations – without using digitised topographic maps or satellite pictures, just based on stereophotographs, from which DEM can be produced, that serve as basis to derive morphometric features.

R=0.871	*Altitude*	*R=0.471*	*Steepness*	*R=0.577*	*Distance*	*R=0.775*	*UCS*
Beta	Standardised coefficient		Standardised coefficient		Standardised coefficient		Standardised coefficient
Steepness	-0.092	Aspect	0.023	Aspect	0.062	Aspect	-0.021
Aspect	-0.003	Distance	0.104	Costpush	-0.303	Costpush	-0.181
Distance	**0.315**	**Costpush**	**0.437**	Runoff	-0.071	Runoff	-0.061
Costpush	**0.353**	Runoff	-0.068	UCS	-0.287	**Altitude**	**0.892**
Runoff	0.104	**UCS**	**0.364**	**Altitude**	**0.873**	Steepness	0.190
UCS	**0.539**	Altitude	-0.292	Steepness	0.091	Distance	-0.171

R=0.110	*Aspect*	*R=0.300*	*Runoff*	*R=0.683*	*Costpush*
	Standardised coefficient		Standardised coefficient		Standardised coefficient
Costpush	0.043	Costpush	0.060	**Altitude**	**0.785**
Runoff	-0.006	**Altitude**	**0.392**	**Steepness**	**0.306**
Altitude	-0.012	Steepness	-0.081	Distance	-0.243
Steepness	0.030	Distance	-0.097	UCS	-0.243
Distance	0.091	UCS	-0.139	Aspect	0.023
UCS	-0.052	Aspect	-0.006	Runoff	0.035

Table 9 The result of regression analysis: the role of variables in influencing, determining other variables' values

9. táblázat A regresszió-analízis eredménye: az egyes változókat leginkább befolyásoló/meghatározó változók

Relative Stream Power	RSP = As^ 1.0 × tanS As= vízgyűjtő, S= lokális lejtő	As = catchment area S= local slope
Wetness Index	WI = ln(As/tanS) As= vízgyűjtő, S= lokális lejtő	
Sediment Transport Capacity Index	= USLE egyenlet LS faktora LS = (As/22.13)^0.6 x (sinS/0.0896)^1.3	LS factor of the USLE equation

Table 10 The meaning of some variables used in TAS and SAGA

10. táblázat A TAS és SAGA néhány változójának mögöttes tartalma

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