



HAL
open science

Investigation of the relationship between subsurface structures and mass movements of the high loess bank along the River Danube in Hungary

G. Mentés, B. Theilen-Willige, G. Papp, F. Síkhegyi, G. Újvári

► **To cite this version:**

G. Mentés, B. Theilen-Willige, G. Papp, F. Síkhegyi, G. Újvári. Investigation of the relationship between subsurface structures and mass movements of the high loess bank along the River Danube in Hungary. *Journal of Geodynamics*, 2009, 47 (2-3), pp.130. 10.1016/j.jog.2008.07.005 . hal-00531890

HAL Id: hal-00531890

<https://hal.science/hal-00531890>

Submitted on 4 Nov 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Title: Investigation of the relationship between subsurface structures and mass movements of the high loess bank along the River Danube in Hungary

Authors: G. Mentés, B. Theilen-Willige, G. Papp, F. Síkhegyi, G. Újvári



PII: S0264-3707(08)00062-8
DOI: doi:10.1016/j.jog.2008.07.005
Reference: GEOD 859

To appear in: *Journal of Geodynamics*

Received date: 16-11-2007
Revised date: 23-7-2008
Accepted date: 23-7-2008

Please cite this article as: Mentés, G., Theilen-Willige, B., Papp, G., Síkhegyi, F., Újvári, G., Investigation of the relationship between subsurface structures and mass movements of the high loess bank along the River Danube in Hungary, *Journal of Geodynamics* (2007), doi:10.1016/j.jog.2008.07.005

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Investigation of the relationship between subsurface structures and mass movements of**
2 **the high loess bank along the River Danube in Hungary**

3 G. Mentés^{a*}, B. Theilen-Willige^b, G. Papp^a, F. Síkhegyi^c, G. Újvári^a

4 ^a Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences;
5 Csatkai E. u. 6-8., H-9400 Sopron, Hungary

6 ^b Berlin University of Technology, Institute of Applied Geosciences, Department of
7 Hydrogeology and Bureau of Applied Geoscientific Remote Sensing (BAGF); Birkenweg 2,
8 D-78333 Stockach, Germany

9 ^c Geological Institute of Hungary, Stefánia út 14, H-1143, Budapest

10 * Fax: +36-99-508-355

11 E-mail: mentes@ggki.hu

12 **Abstract**

13 Relationships between regional tectonics, subsurface structures and mass movements are
14 investigated on the high loess bank of the River Danube at Dunaföldvár based on remote
15 sensing data, gravity and tilt measurements. The geology and morpho-tectonics of the area
16 were derived from remote sensing images. The basement structure under the high loess bank
17 and in its surroundings was revealed by gravimetric measurements. On the basis of these data
18 a model for the surface mass movements was developed and compared to the results of the
19 surface tilt measurements. Two explanations for the measured tilt have been considered, a
20 tectonic one and a geomorphologic one. The data in the former are treated as being the
21 consequence of recent tectonic movements. According to this approach the SSW tilt on the
22 top of the high bank originates from the very slow movements of Felső-Öreg-hegy towards
23 the southwest as a result of an ENE-WSW compression. In the geomorphologic explanation
24 the movements are the consequence of erosion and undercutting of the riverbank caused by
25 the Danube, which has led to the slow loss of the base support of the high bank, resulting in

26 slow sliding eastwards accompanied by counterclockwise rotation of the Felső-Öreg-hegy
27 block. In accordance with these explanations, most probably the measured tilt rate is the
28 consequence of both tectonic and geomorphologic processes. In order to prove active
29 tectonism on the territory long-term tilt and geodetic deformation measurements are necessary
30 on a wider area than the recent test site.

31 **Keywords:** High bank; Recent tectonic movements; Remote sensing; Gravity measurement;
32 Tilt measurement

33

34 **1. Introduction**

35 In Hungary there are several regions prone to landslides, among which the high banks along
36 the right hand side of the River Danube are especially endangered (Kleb and Schweitzer,
37 2001). Landslides in this area cause considerable damage and they result in severe human
38 casualties, property losses and environmental degradation. Landslides and other surface
39 movements arise as a consequence of interaction between various processes. The monitoring
40 of slope surface displacements and other geophysical, geological, hydrological,
41 meteorological, etc. phenomena by a multi-sensor measurement system can provide valuable
42 information about the causes of abrupt slope movements and can serve as a basis for
43 development of a knowledge-based, early warning system. In Dunaföldvár a test site has been
44 established by the Geodetic and Geophysical Research Institute of the Hungarian Academy of
45 Sciences (GGRI) with the objective of monitoring the movements and deformations of the
46 high bank and to study the interactions between the different natural factors. Research work
47 was started in 2001 with the support of the Hungarian Academy of Sciences. First a geodetic
48 monitoring system was established, based on yearly repeated geodetic measurements (GPS,
49 EDM, precise levelling) and continuous tilt measurements. The investigations were continued
50 between 2003 and 2006 in the frame of the EU5 OASYS project. The geological structure, the

51 geomorphologic and hydrological conditions, the seismic hazard of the test site and
52 meteorological influences were investigated in detail during this project (Mentes and Eperné,
53 2004). Besides the deformation measurements, temperature, precipitation, ground water table
54 variations and water level fluctuations of the River Danube were also monitored.

55

56 Among others, active tectonics can also influence the development and the onset of mass
57 movements as they are able to modify the gravity field, structural discontinuities, and the
58 slope geometry by means of uplifting, folding and erosion. Since the rate of tectonic
59 movement is generally very low, long-term and high accuracy deformation measurements are
60 necessary to detect these displacements and their indirect effects. This is the reason why the
61 relationship between landslides and tectonics has been mostly investigated on the basis of
62 geomorphology until now (Sorriso-Valvo, 1991). The aim of this paper is to study this
63 relationship by means of gravity and high accuracy tilt measurements and to compare the
64 results with satellite imagery, Digital Elevation Model (DEM) obtained by the Shuttle Radar
65 Topography Mission (SRTM) – all compiled in a Geographic Information System (GIS).

66

67 **2. Test site**

68 The western bank of the River Danube is one of the largest landslide endangered areas in
69 Hungary. The walls of the high bank are steep, 20-40 m high and composed of loose
70 sediments that are exposed to river erosion. Landslides cause a lot of problems in the small
71 town of Dunaföldvár where many houses are built on the top and at the toe of the high bank.
72 Dunaföldvár is situated at the eastern margin of the loess covered Mezőföld geographical unit
73 on the bank of the River Danube where the loess highland falls nearly vertically to the flood
74 plain of the river (Fig. 1). A part of the town is built on Felső-Öreg-hegy (Upper Old Hill) and
75 Alsó-Öreg-hegy (Lower Old Hill) (Fig. 2). These two units are separated by a 150-200 m

76 wide, N-S orientated, erosion-derasion valley and they are bordered by the NNW-SSE
77 orientated, 1-1.5 km wide Bölcskei valley on west. The northern part of the high bank is
78 Felső-Öreg-hegy measuring 120-130 m above sea level; its border-line along the Danube is
79 very steep and about 20-30 m high. This 400 m long section of the loess bank is prone to mass
80 movements. Some landslides have occurred here; the largest mass movement was in 1994.
81 For this reason this area was selected as a test site for high precision geodetic (GPS, precise
82 levelling), gravimetric and continuous tilt measurements. The network of the geodetic and
83 gravimetric measurement points and the location of the tiltmeters are shown in Fig. 2.

84

85 **3. Geomorphologic and geological overview**

86 Most of Hungary's surface is lowland, one third is covered by hills between 200 and 400 m
87 height and only a very small part of the country rises above 400 metres. The River Danube
88 divides Hungary into two general regions. The lowland east from the Danube is the Great
89 Hungarian Plain. The area west of the Danube is known as Transdanubia. Figure 1 presents a
90 height map showing the main geomorphologic units. The height map reveals distinctly
91 expressed, NW-SE oriented, linearly and parallel arranged south-east draining valleys and
92 ridges and intervening flat-topped plateaus in Transdanubia. This linear geomorphologic
93 structure occurs in solid rocks as well as in unconsolidated sedimentary cover, even in those
94 of the River Danube itself. It can be assumed that the orientation of the valleys and ridges in
95 Central Hungary is influenced by Alpine compression in the subsurface as their orientation is
96 perpendicular to the main compression direction. Wind and water erosion have formed the
97 surface and they have played an important role in landscape development. Their influence is
98 demonstrated by the occurrence of ventifacts and distribution of wind-blown sands and loess
99 deposits.

100

101 Crustal convergence within the Alpine collision zone has been and is still the driving force for
102 the tectonic structures causing compression and a block-wise tectonic structure. The recent,
103 strike-slip to compressive stress regime in the Pannonian domain is primarily governed by the
104 northward drift and counterclockwise rotation of the Adriatic micro-plate (Bada et al., 1999,
105 2001). As a result of the “Adria-push”, significant compressive stresses are concentrated in
106 the underlying lithosphere. Since the Late Oligocene and Early Miocene, the ongoing north-
107 south oriented compression of the Eastern Alps has been accompanied by vertical and lateral
108 extrusion and tectonic escape of large crustal wedges towards the unconstrained margin that is
109 represented by the Pannonian domain in the east. Inter-plate collision, tectonic extrusion and
110 escape processes since the Tertiary are still active, as inferred from seismicity and geodetic
111 observations. GPS data suggest that crustal blocks in the Alpine-Carpathian orogenic belt
112 should move from NW to NE with a velocity of about 1-2 mm/year with respect to stable
113 Europe (Bada et al., 2007). The compression of the subsurface due to these movements seems
114 to be traced on hillshade maps. The tectonic units are displaced along major transform faults
115 that are mainly reactivated structures of Miocene origin. The significantly heterogeneous
116 distribution of the extension is accommodated by transfer faults, bounding regions of different
117 polarity and direction or, for example, by the Mid Hungarian Line (MHL), an important SW-
118 NE trending fault zone (Csontos and Nagymarosy, 1998). The internal deformation is
119 manifested in late-stage subsidence anomalies of the entire basin system and the presence of a
120 set of seismically active shear zones imaged by a combined analysis of high-resolution
121 seismic profiling and earthquake epicentre distribution (Bada et al., 2007). The main fault
122 structure in the surroundings of Dunaföldvár is shown in Fig. 3.

123 The deeper geological structure of the test site was studied by new acquisition of gravity data
124 (see Section 5) and the structure of the high bank (Fig. 4) was revealed by drilling boreholes.
125 Figure 2 illustrates the profile (Dfv-1, Dfv-2, Dfv-3, Dfv-4) of the boreholes.

126

127 **4. Methods and approaches**

128 For a better understanding of the complex processes that cause and trigger landslides and for a
129 better knowledge of their interactions, special emphasis was put on a spatially accurate, GIS
130 integrated representation of landslide influencing parameters and determining factors as far as
131 data were available. Such parameters are, for example, height, slope degree and/or curvature
132 of slopes that can be derived from a digital elevation model (DEM). The evaluation of digital
133 topographic data is of great importance as it contributes to the detection of the specific
134 geomorphologic/topographic settings of landslide prone areas. For studying the relationship
135 between landslides and tectonics the following digital elevation data have been evaluated:
136 Shuttle Radar Topography Mission - SRTM, 90 m resolution data provided by the University
137 of Maryland, Global Land Cover Facility (<http://glcfapp.umiacs.umd.edu:8080/esdi/>). For the
138 sake of acquiring a geomorphologic overview and for deriving the characteristic,
139 geomorphologic features of the Dunaföldvár area, terrain parameter and morphometric maps
140 were extracted from SRTM DEM data, such as shaded relief, aspect and slope degree,
141 minimum and maximum curvature or profile convexity maps using ENVI 4.3 / CREASO and
142 ArcGIS 9.2 / ESRI software (Fig. 5). A systematic GIS approach is based on SRTM data from
143 which geomorphometric maps and parameters were extracted. Digital image processing
144 procedures, such as NDVI, histogram stretching, filter techniques, etc. were carried out to
145 enhance the LANDSAT ETM data. Linear morphologic features (lineaments) visible on
146 hillshade and slope maps and on LANDSAT imageries are often related to traces of faults and
147 fractures in the subsurface. Different colours of the lineaments were used to delineate linear
148 image features visible on LANDSAT and SRTM morphometric maps. Black lines indicate
149 linear image elements as neutral terms. The origin of these linear features may have different
150 reasons. Red lines are those lineaments on LANDSAT imageries that are assumed to be

151 related to fault zones – derived from anomalies in the drainage pattern, colour and grey tone
152 anomalies, vegetation anomalies, and due to abrupt, linear changes in the surface morphology
153 – while green lines are linear geomorphologic anomalies mapped on SRTM data based
154 morphometric maps. The information derived from the different data sets is summarized in
155 lineament maps (e.g. Fig. 6), which were compared with geological maps and topographic
156 data in order to verify the mapped lineaments as far as possible.

157

158 A dense network of new gravity field measurements was acquired to reveal any structural
159 anomalies that could be contributing to the triggering of mass movements on the high bank. A
160 LaCoste & Romberg G949 relative gravimeter was used for the gravity survey. Six gravity
161 base stations were chosen to coincide with points (100 - 600) of the GPS monitoring network
162 (Fig. 2). The datum point 10G was connected to the Hungarian National Gravity Network. In
163 the course of the general gravity survey in the area a further 20 points, numbered from 1 to
164 21, were used. The distribution of the points was adjusted to the local variation of the
165 topography. The 3D geodetic positioning of these points was done by GPS using the fast
166 static method.

167

168 The movements and deformations of the high bank were observed by continuous tilt
169 measurements. For this purpose two dual-axis borehole tiltmeters (Model 722A with a
170 resolution of 0.1 μ rad) made by Applied Geomechanics Inc. (AGI), Santa Cruz, California
171 were applied. Both tiltmeters were installed in shallow boreholes with a depth of 3 m which
172 ensure suitable temperature stability for the instruments. One tiltmeter (I) was installed on the
173 top of the high loess bank at about 8 m far from its edge. The other instrument (V) was placed
174 at the toe of the high bank about 50 m far from the river (Fig. 2.). The height difference
175 between the tiltmeters is about 30 m. The positive y axes of the tiltmeters are perpendicular to

176 the River Danube, while the positive x axes are directed to south and are parallel with the
177 Danube. The temperature was also measured by means of the thermometers built-in the
178 tiltmeters. The data were collected with a sampling rate of 1 sample/hour from 06 June 2002
179 till 31 December 2007. From the hourly recorded data daily averages were calculated by a
180 moving average method. The more than five year long data series made it possible to reduce
181 the meteorological and seasonal effects in the tilt data, which is a basic requirement for the
182 investigation of very low rate tectonic movements.

183

184 **5. Gravity measurements**

185 The whole gravity network (Fig. 2) was measured in 2003 in order to determine a detailed
186 Bouguer gravity anomaly map of the investigated area. The precision of the gravity
187 differences between the survey points was estimated to be better than 20 μGal . The g values
188 of the network points were determined relative to the fixed gravity value of point 10G. Then
189 these were reduced to the datum level of the Hungarian National Height System using the
190 conventional free-air reduction. Based on the reduced gravity acceleration data free-air (Δg_{fa})
191 and Bouguer anomalies, both simple (Δg_B) and complete (Δg_{Bc}), were calculated (Papp et al.,
192 2004).

193 For the computation of the terrain correction in a planar approximation a 20 m x 20 m digital
194 elevation model (DEM) of the surrounding area was used. This detailed model was merged
195 with the 3D rectangular prism based model of the topography to represent the distant terrain
196 effects up to the usual distance of 167 km.

197

198 On the basis of the known geology of the area and an earlier gravity investigation (Papp et al.,
199 2004), the application of the usual average crustal density of $\rho_i = 2670 \text{ kg/m}^3$ was not used in
200 the Bouguer reduction, because it proved to be too high producing a “ghost” anomaly

201 correlated by the topography (Fig. 7). In order to obtain a realistic value of ρ_t for both the
202 Bouguer reduction and the terrain correction some surface rock samples of loess were
203 analysed in laboratory. The determinations of the volume density of the samples gave an
204 average value of 1610 kg/m^3 with a standard deviation of $\pm 100 \text{ kg/m}^3$ at a low (3.7%) water
205 content. The porosity of the samples varied between 32% and 47% indicating that the water
206 table and/or the soil moisture may significantly increase the in situ volume density of the
207 topographical masses up to 2000 kg/m^3 . Fixing the density between its “dry” and waterlogged
208 values ($1610 \text{ kg/m}^3 < \rho_t = 1800 \text{ kg/m}^3 < 2000 \text{ kg/m}^3$) the “ghost” anomaly disappeared (Fig.
209 8) and it became clear that no small-scale (local) geological/tectonic structures representing
210 horizontal density variation are covered by the topographical masses. The complete Bouguer
211 anomaly pattern shows only a dominant NW dipping trend connected to the tilt of the pre-
212 Tertiary basement surface in the same direction (Kilényi et al., 1991).

213

214 **6. Tilt measurements**

215 The daily averaged tilt data are plotted in Fig. 9. VX, VY and IX, IY denote the x and y tilt
216 components at the toe and on the top of the high bank, respectively (Fig. 2). It can be seen that
217 tilt data are disturbed by local and seasonal variations. To concentrate only on the tilts caused
218 by possible movements of tectonic origin, correlation between tilt and other recorded data
219 were investigated. The analysis of tilt data showed that there is no long-term correlation
220 between tilt and temperature, as well as precipitation data. Similar results were found when
221 the influence of the Danube’s water level variations, the changes of the ground water table
222 and the effect of the loess moisture content on tilt measurements were investigated (Mentes,
223 2008). In this way, the linear trend of the tilt data could be estimated by fitting a regression
224 line to the tilt curves. The steepness of this line gives the rate of the long-term tilt. The
225 obtained tilt rates in the X and Y directions in $\mu\text{rad}/\text{year}$, the error of the tilt rate

226 determinations and the correlation coefficients are given in Table 1. The correlation
227 coefficients between the tilt and the time obtained on the top of the high bank (tilt
228 components: IX and IY) are higher than 0.7. This means that the connection between the tilt
229 and the time can be assumed to be linear in spite of the fact that the tilt data are strongly
230 disturbed by local and seasonal effects. The tilt measurements were statistically significant
231 and good for data processing at the top of the high bank location, while at the foot of the high
232 bank (tilt components: VX and VY) the error was too high and the correlation coefficient was
233 low; thus the results there are not reliable. These outcomes are mainly the consequence of
234 high disturbing effects relative to the low tilt rates. The resultant tilt rate on the top of the high
235 bank – calculated from the x and y components given in Table 1 – is $47.3 \mu\text{rad}/\text{year}$, while its
236 direction is SSW (see the arrow in Fig. 10).

237

238 **7. Remote sensing data**

239 Morphometric maps (Figs. 11 and 12) show that the valleys, hills and streams, i.e. the main
240 structural elements, are approximately NW-SE and NNW-SSE directed west from the
241 Danube. ENE-WSW and ESE-WNW directions could be also detected west- and southwards
242 from the test site on the basis of the drainage pattern and lineament maps (Figs. 12 and 13).
243 Statistical analysis of valley orientations and joint lines of strike in loess deposits on the
244 Mezőföld geographical unit indicate a main NW-SE and a secondary ENE-WSW structural
245 direction (Horváth et al., 1990). The former is called the Móri-valley direction, which is
246 distinctly visible in satellite imagery as well as in the field and agrees with the radial valley
247 network in Transdanubia (Síkhegyi, 2002). The latter is the basement direction, because it is
248 also seen in Bouguer anomaly maps (Kiss, 2006) and it was also detected by our gravimetric
249 measurements. There is a permanent debate about the origin of the radial valleys. They are
250 considered to be of aeolian origin by some researchers (e.g. Fodor et al., 2005) while others

251 (Jámbor et al., 1993; Síkhegyi, 2002) explain them as the result of regional tectonics. The
252 NW-SE and ENE-WSW directions are decisive west from the Danube, while a visible NNE-
253 SSW direction is characteristic on the Great Hungarian Plain east of the river. There is a
254 subsided area northwest of the test site with several possible/hypothetical faults and a
255 tectonically determined, NNW-SSE directed, and 1-1.5 km wide Bölcskei valley (Fig. 14). A
256 NW-SE orientated section of the Danube at Dunaföldvár follows a pre-existing weakness
257 zone that is parallel with the Bölcskei valley. These orientations fit with the radial pattern of
258 the hydrographic and valley network in Transdanubia (Síkhegyi, 2002). A NE-SW extension
259 was identified based on the morphological features of the Solt Plain, on the opposite side of
260 the Danube at the present test site (Fig. 14). Escarpments and sub-depressions are the result of
261 normal faulting according to Síkhegyi (2002). Csontos et al. (2005) also indicated a NNW-
262 SSE directed normal fault along this section of the Danube. In line with the above mentioned
263 NE-SW extension, Csontos et al. (2005) supposed a NW-SE (to WNW-ESE) shortening
264 induced dextral (right lateral) shear along ENE-WSW oriented faults near and southwards
265 from the test site. These linear features can be identified in Fig. 13 and some lineaments can
266 also be found directly on the test site (see the broken lines L1 and L2 in Fig. 10).

267

268 The NW-SE directions were regarded as sinistral (left-lateral) strike-slip faults by Rádai
269 (1978), Czakó (1980), Horváth et al. (1990) and Gerner (1992). Czakó (1980) and Horváth et
270 al. (1990) concluded that the ENE-WSW directions are the conjugate dextral pair of these
271 sinistral faults and they constitute a transcurrent fault system.

272

273 **8. Discussion**

274 The results of the gravimetric measurements show no structural discontinuities under the high
275 bank. So, we can assume that tectonic movements which may contribute to the evolution of
276 landslides in this area are of regional rather than of local origin.

277 The observed continuous tilting of the Felső-Öreg-hegy block, with a rate of $47.3 \mu\text{rad}/\text{year}$ in
278 a SSW direction, provides an explanation for the fact that most of the landslides and earth
279 falls occur at the south end of this high bank section (recently, in years 1994, 2005).

280 The measured tilt can be interpreted in two different ways: it is due to recent tectonic
281 movements or it is a result of geomorphologic processes. In the former case it is implied that
282 the L1 and L2 lineaments (Fig. 10) are active faults; however there is an ongoing debate about
283 this issue (see Section 7). The measured tilt direction is in accordance with recent tectonic
284 movements inferred from the results of the analysed morphologic, lineament and other remote
285 sensing data (Fig. 6). During late Pleistocene to Holocene times the Mid-Hungarian shear
286 zone (MHSZ) and the Kapos line displayed right lateral strike slip kinematics (Síkhegyi,
287 2002) according to the geomorphologic analysis of Middle and East Transdanubia. This idea
288 was supported by Horváth et al. (1990) and subsequently by Csontos et al. (2005) who
289 stressed that two distinct deformation regimes could have been active during the Quaternary
290 in the study area (see Fig. 12 in Csontos et al., 2005). In the eastern part of the MHSZ the
291 Tamási line is the sinistral step (bend) over of the Kapos line, implying that the territory
292 between the Móri graben and the River Danube is in a compressional, push-up neotectonic
293 regime. This compression triggers morphological uplift southwest of Dunaföldvár, where
294 changes in the tilt direction of valleys occur in the radial pattern (Fig 12). The uplift also
295 changes the very distinct strike of the Móri graben: the southern end of the valley is uplifted
296 and the valley bottom is shifted in a southwest direction by a minimum of 2 km (see Fig. 15).
297 According to the above described process the local main compression direction, which forms
298 push-up structures, is roughly parallel to the shear zone (ENE-WSW) in the vicinity of the

299 study area. As a consequence of this situation the Felső-Öreg-hegy block situated eastwards
300 of the L2 line moves onto the asymmetric Bölcskei valley located southwest from the L2 line
301 (Fig. 10) and that causes the measured tilt. This statement could be confirmed by long-term
302 tilt observations at the toe of the high bank. If the trend of this data series would be
303 maintained and becomes statistically robust, then it could be concluded that there are indeed
304 recent tectonic movements. Such measurements could also shed light on the dispute
305 mentioned in Section 7.

306 There exists an alternative plausible explanation for the obtained tilt direction. The mass of
307 Felső-Öreg-hegy is sliding slowly but steadily towards the Danube while it is also rotating
308 counter-clockwise. These movements and conditions would theoretically predict a SW-SSW
309 tilting coinciding with the results of our tilt measurements (Fig. 10). The detected tilts and
310 movements are presumably the indirect effects of old tectonic movements, as follows: a radial
311 pattern of valley networks in Transdanubia determines the orientation of many segments of
312 the Danube from Budapest to the south (Síkhegyi, 2002). The NW-SE orientated segments of
313 the Danube follow pre-existing weakness zones. At Dunaföldvár (Felső-Öreg-hegy), where
314 the Danube flows along a weakness zone, a receding river bank has evolved due to persistent
315 erosion and undercutting by the river. In this scenario, Felső-Öreg-hegy gradually loses its
316 base support and slowly slides into the Danube in an ENE-NE direction with counter-
317 clockwise rotation, causing a permanent SSW tilting with a high rate at the top of the high
318 bank and with a low rate at its base.

319 Probably, these two processes together determine the movements of the high bank. Besides
320 the tilt measurements, the continuation of GPS measurements could help to test this
321 hypothesis in the future.

322

323 **9. Conclusions**

324 The results confirm that precise remote sensing data are essential for a detailed
325 geomorphologic, geological and hydrologic study of areas prone to landslides. The advantage
326 of GIS lies in the possibility to assimilate different layers of geographical data and to correlate
327 these with each other. As a consequence, the design of a common GIS database structure
328 (always open to new data) can greatly contribute to the homogenisation of methodologies and
329 procedures.

330 To reveal any structural discontinuities very precise gravimetric measurements are necessary.
331 Development of special calibration methods would be useful in order to improve the accuracy
332 of the measurements and to decrease the excessive disturbance caused by the variation of the
333 water content of the loess.

334 The five year long tilt data series shows that the accuracy of tilt measurements is high enough
335 to detect very small movements but, because they are also very sensitive to direct and indirect
336 local and meteorological disturbances, a much longer period of measurement is required to
337 enhance the signal to noise ratio.

338 Despite the fact that the measured tilt can be explained in two different ways, it is very likely
339 that the movements are the consequence of the simultaneous effect of both tectonic and
340 geomorphologic processes. Installation of an additional tiltmeter farther from the high bank
341 and a longer duration of GPS measurements in a larger area than the present test site
342 (including some points at larger distances from the high bank) would be desirable in order to
343 prove unambiguously recent tectonic movements within the test area.

344

345 **Acknowledgements**

346 This research was partly supported by the EU5 OASYS project (project no.: EVG1-CT-2002-
347 00061) and partly by Deputy Under-Secretariat of Ministry of Education for Research and

348 Development and by its foreign contractual partner, Bundesministerium für Auswärtige
349 Angelegenheiten in the frame of the Scientific and Technological Cooperation between
350 Austria and Hungary (Hungarian project no. A-13/2005). The project received additional
351 financial support from the president of the Hungarian Academy of Sciences. We are very
352 grateful to the employees of the Geodetic Department in the GGRI for their kind assistance in
353 the field works.

354

355 **References**

356 Bada, G., Horváth, F., Gerner, P., Fejes, I., 1999. Review of the present-day geodynamics of
357 the Pannonian basin: progress and problems. *J. Geodyn.* 27, 501-527.

358 Bada, G., Horváth, F., Cloetingh, S., Coblenz, D.D., Tóth, T., 2001. Role of topography-
359 induced gravitational stresses in basin inversion: The case study of the Pannonian Basin.
360 *Tectonics* 20, 343-363.

361 Bada, G., Grenczy, Gy., Tóth, L., Horváth, F., Stein, S., Cloetingh, S., Windhoffer, G.,
362 Fodor, L., Pinter, N., Fejes, I., 2007. Motion of Adria and ongoing inversion of the Pannonian
363 basin: Seismicity, GPS velocities and stress transfer. In: Stein, S., Mazzotti, S., (Eds.),
364 *Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues*. Geological Society of
365 America Special Paper 425 (16), 243-262, doi: 10.1130/2007.2425.

366 Csontos, L., Magyar, Á., Van Vliet-Lanoë, B., Musitz, B., 2005. Neotectonics of the Somogy
367 hills (part II): Evidence from seismic sections. *Tectonophysics* 410, 63-80.

368 Csontos, L., Nagymarosy, A., 1998. The Mid-Hungarian line: a zone of repeated tectonic
369 inversions. *Tectonophysics* 297, 51-71.

370 Czakó, T., 1980. A törésvonalak és a szénhidrogéntartó szerkezetek feltárása a távérzékelés
371 módszerével. (Exploration of faults and hydrocarbon-bearing structures by the remote sensing
372 method.) *MTA X. Osztályának Közleményei* 13, 53-69. (in Hungarian)

- 373 Fodor, L., Bada, G., Csillag, G., Horváth, E., Ruszkiczay-Rüdiger, Zs., Palotás, K., Síkhegyi,
374 F., Timár, G., Cloetingh, S., Horváth, F., 2005. An outline of neotectonic structures and
375 morphotectonics of the western and central Pannonian Basin. *Tectonophysics* 410, 15– 41.
- 376 Gerner, P., 1992. Recens közetfeszültség a Dunántúlon. (Recent stress field in Transdanubia,
377 Western Hungary). *Földtani Közlöny* 122, 89-105. (in Hungarian with English abstract)
- 378 Horváth, F., Bada, G., Windhoffer, G., Csontos, L., Dombrádi, E., 2006. A Pannon-medence
379 jelenkori geodinamikájának atlasza: Euro-konform térképsorozat és magyarázó (Atlas of the
380 present-day geodynamics of the Pannonian Basin: Euroconform maps with explanatory text).
381 *Magyar Geofizika* 47, 133-137. (in Hungarian)
- 382 Horváth, F., Csontos, L., Erdélyi, M., Ferencz, Cs., Gábris, Gy., Hevesi, A., Síkhegyi, F.,
383 1990. Paks környezetének neotektonikája. (Neotectonics of the surroundings of Paks)
384 Kutatási Jelentés (Research Report), MÁELGI, Budapest, 71 p. (in Hungarian).
- 385 Jámbor, Á ., Bihari, D., Chikán, G., Franyó , F., Kaiser, M., Radócz, Gy., Síkhegyi, F., 1993.
386 Active Pleistocene fault in Hungary 1: 500,000 map and explanatory text (in Hungarian).
387 Manuscript, Archive of Dept. of Tectonics, Geol. Inst. Hungary.
- 388 Kilényi, É., Kröll, A., Oberhauser, D., Šefara, J., Steinhauser, P., Szabó, Z., Wessely, G.,
389 1991. Pre-Tertiary basement contour map of the Carpathian Basin beneath Austria,
390 Chechoslovakia and Hungary. *Geophys. Transact.* 36, 15-36.
- 391 Kiss, J., 2006. Bouguer anomaly map of Hungary. *Geophys. Transact.* 45, 99-104.
- 392 Kleb, B., Schweitzer, F., 2001. A Duna csuszamlásveszélyes magaspártjainak
393 településkörnyezeti hatásvizsgálata. (Assessment of the impact of landslide prone high banks
394 on urban environment along the River Danube) In: Ádám, A., Meskó, A., (Eds.),
395 *Földtudományok és a földi folyamatok kockázati tényezői.* Bp. MTA., 169-193 (in
396 Hungarian).

- 397 Mentés G., 2008. Investigation of different, possible agencies causing landslides on the high
398 loess bank of the River Danube at Dunaföldvár, Hungary. Proceedings of Measuring the
399 Changes, 13th FIG International Symposium on Deformation Measurements and Analysis,
400 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering, LNEC,
401 Lisbon, Portugal, May 12-15, pp. 1-10.
- 402 Mentés G., Eperné, I., (Eds), 2004. Landslide monitoring of loess structures in Dunaföldvár,
403 Hungary. Geodetic and Geophysical Res. Inst. Hung. Acad. Sci., Sopron, 84. pp.
- 404 Papp, G., Benedek, J., Kalmár J., 2004. Gravity investigations on Dunaföldvár test area. In:
405 Mentés G., Eperné, I. (Eds), Landslide monitoring of loess structures in Dunaföldvár,
406 Hungary. Geodetic and Geophysical Res. Inst. Hung. Acad. Sci., Sopron, pp. 37-46.
- 407 Pyrus Kft. (Ltd.), 1994. Részletes geotechnikai vizsgálat a dunaföldvári löszmagaspart Hősök
408 tere 20-21. sz. ingatlanok mögötti szakaszára. (Detailed geotechnical investigation of the high
409 loess wall in Dunaföldvár along a section behind the Hősök square 20-21.) 11 pp. (with
410 appendix, in Hungarian)
- 411 Rádai, Ö., 1978. Subsurface water environment and the reconnaissance of it by aerospace
412 methods in Hungary. Proceeding of the ISP-IUFRO Symposium in Freyburg
- 413 Síkhegyi, F., 2002. Active structural evolution of the western and central parts of the
414 Pannonian basin: a geomorphological approach. EGU Stephan Mueller Special Publication
415 Series 3, 203-216.
- 416 Sorriso-Valvo, M., 1991. Mass-movement and tectonics. In: Almeida-Teixeira, M. E.,
417 Fantechi, R., Oliveira, R., Gomes C.A., (Eds.), Prevention and control of landslides and other
418 mass movements. Commission of the European Communities, Brussels, Directorate-General
419 Science, Research and Development EUR 12918 EN, pp. 127-138.

420 **Figure captures**

421 **Fig. 1.** Height map showing the main geomorphologic units of west and central Hungary and
422 the location of the test site at Dunaföldvár (DEM is from Horváth et al., 2006).

423 **Fig. 2.** Contour map of the test site at Dunaföldvár. **Legend:** The contour lines denote the
424 elevation above Balti sea level in meters. Circles denote GPS points (100-600), triangles the
425 gravity points (1-21); 10G is the gravity reference point; V and I show the location of the
426 tiltmeters. The line that crosses points Dfv-1, Dfv-2, Dfv-3 and Dfv-4 indicates the geological
427 cross-section presented in Fig. 4.

428 **Fig. 3.** Fault pattern in the vicinity of Dunaföldvár (after Horváth et al., 2006 and Fodor et al.,
429 2005). MHSZ=Mid Hungarian Shear Zone.

430 **Fig. 4.** Geological cross-section between Felső-Öreg-hegy and the River Danube based on the
431 geotechnical survey performed by Pyrus Ltd. in 1994. **Legend:** 1 – recent fill mixed with silt,
432 affected by pedogenesis, 2 – sandy, pebbly fill, 3 – sandy gravel, 4 – sand, 5 – typical loess, 6
433 – palaeosol, 7 – alluvial meadow clay soil, 8 – clay, a.s.l – above (Balti) sea level, Dfv-1. –
434 Dfv-4.: exploratory drill holes, a – LW (lowest water lever), b – AW (average water level), c
435 – HW (highest water level).

436 **Fig. 5.** GIS integrated evaluation of morphometric maps.

437 **Fig. 6.** Derivation process of the lineament map from SRTM, ERS and LANDSAT ETM data.

438 **Fig. 7.** Bouguer gravity anomalies in the test area computed using a topographic density of
439 2670 kg/m^3 . The triangles mark the gravity stations. The contour interval is 0.1 mGal; the
440 plane co-ordinates are given in meters.

441 **Fig. 8.** Bouguer gravity anomalies in the test area computed using a topographic density of
442 1800 kg/m^3 . The triangles mark the gravity stations. The contour interval is 0.1 mGal; the
443 plane co-ordinates are given in meters.

444 **Fig. 9.** Daily mean values of the recorded tilt data. Legend: VX and VY – x and y tilt
445 components on the bank of the Danube, IX and IY – x and y tilt components on the top of the
446 loess wall.

447 **Fig. 10.** Detected tilt direction and rate on the top (I) of the high bank. The dashed lines (L_1 ,
448 L_2) indicate those lineaments which appear in Fig 13.

449 **Fig. 11.** SRTM based morphometric maps (shaded relief, overlay of shaded relief and slope,
450 aspect, slope). Brown quadrangles denote the study area.

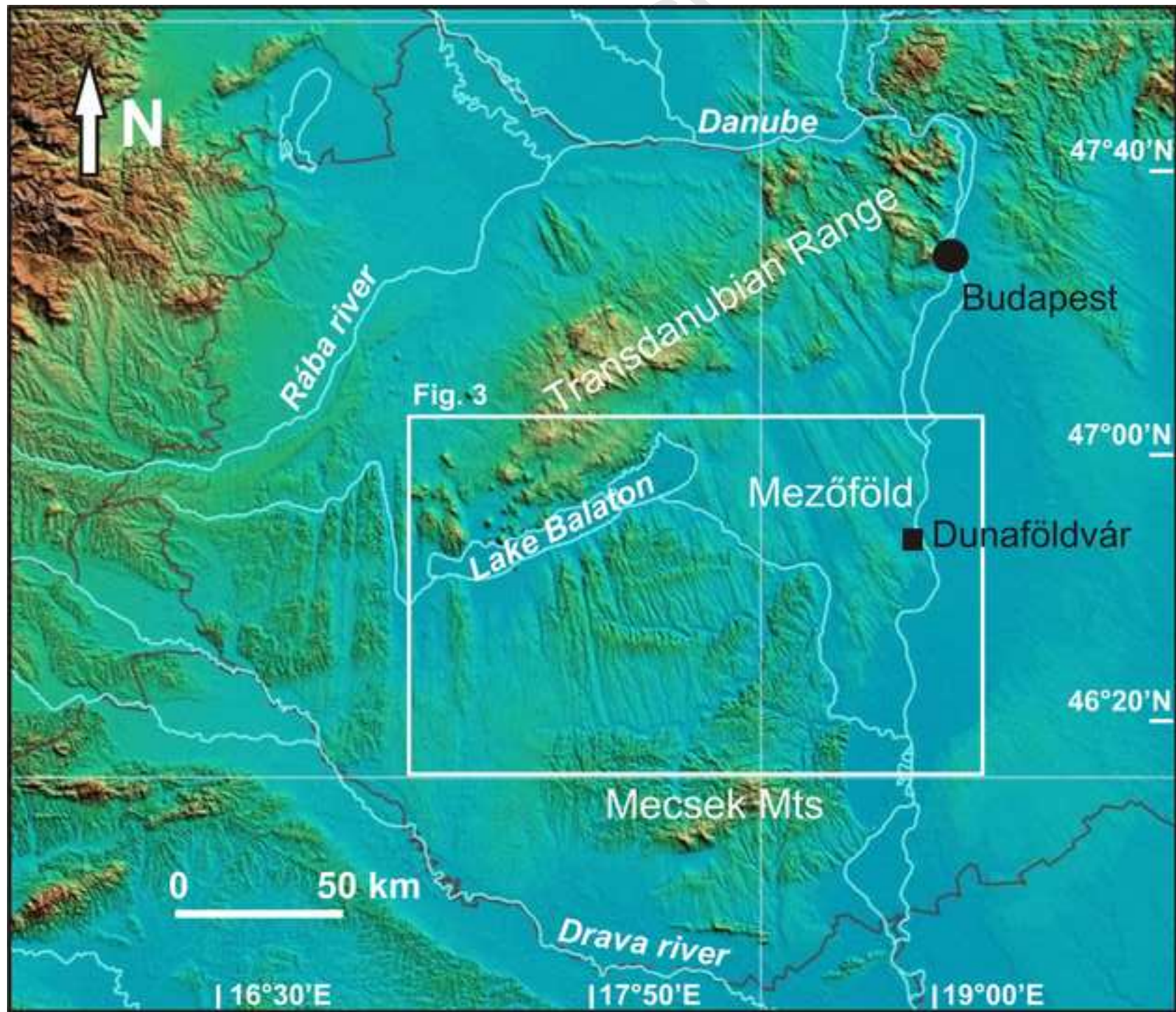
451 **Fig. 12.** Drainage pattern of the test site and its wider surroundings. The NW-SE oriented
452 linear and parallel arranged south-east draining valleys are clearly visible west of the Danube.

453 **Fig. 13.** Lineament map of the study area. Primary NW-SE and NNW-SSE directions are
454 characteristic west of the river.

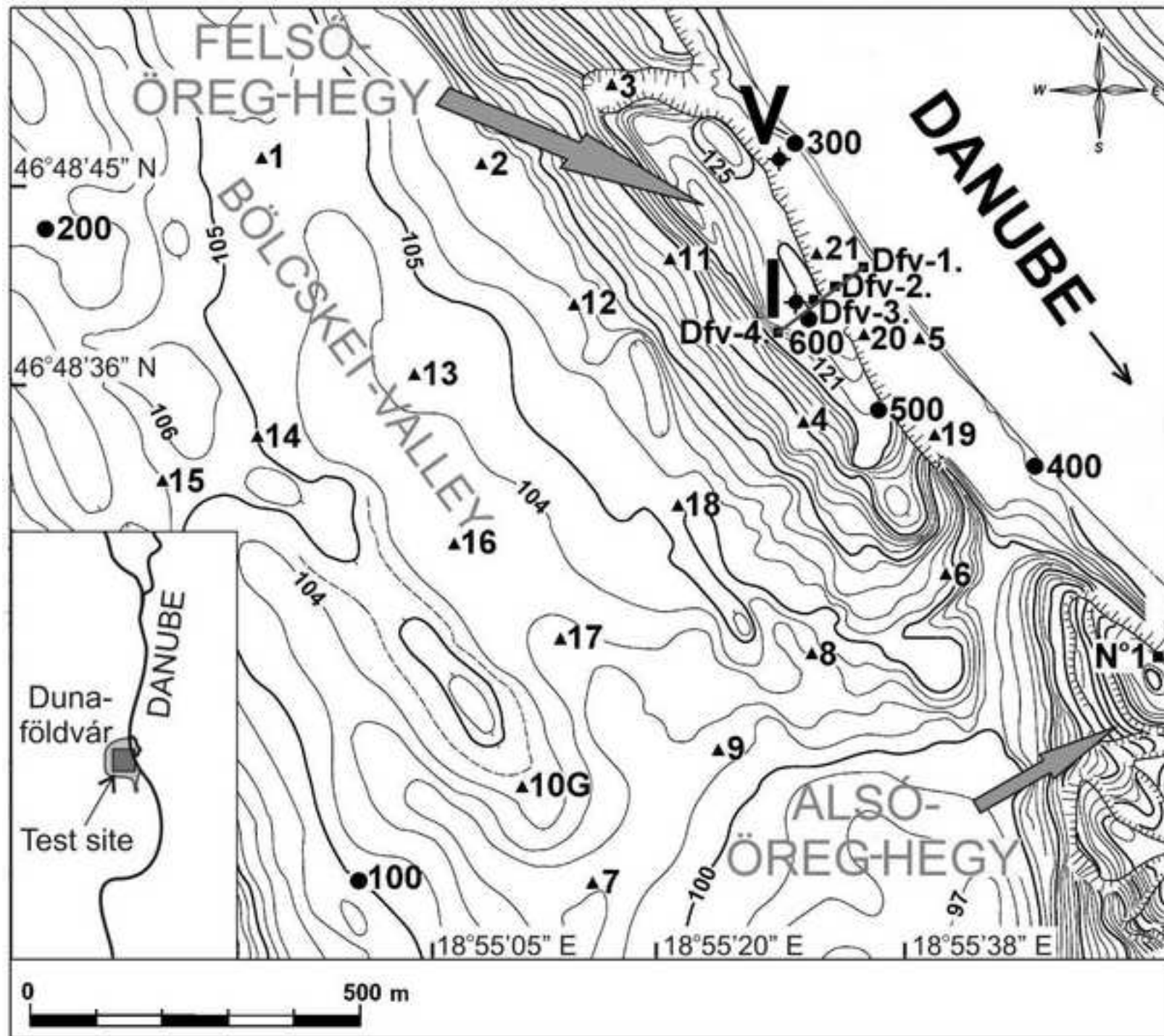
455 **Fig. 14.** Catchment and subsidence areas of the test site and its surroundings.

456 **Fig. 15.** Height map and supposed results of recent tectonics. Black arrows denote uplifted
457 areas southwest from Dunaföldvár; white arrows indicate the shift of the valley bottom of the
458 Móri graben. For further explanation see the text.

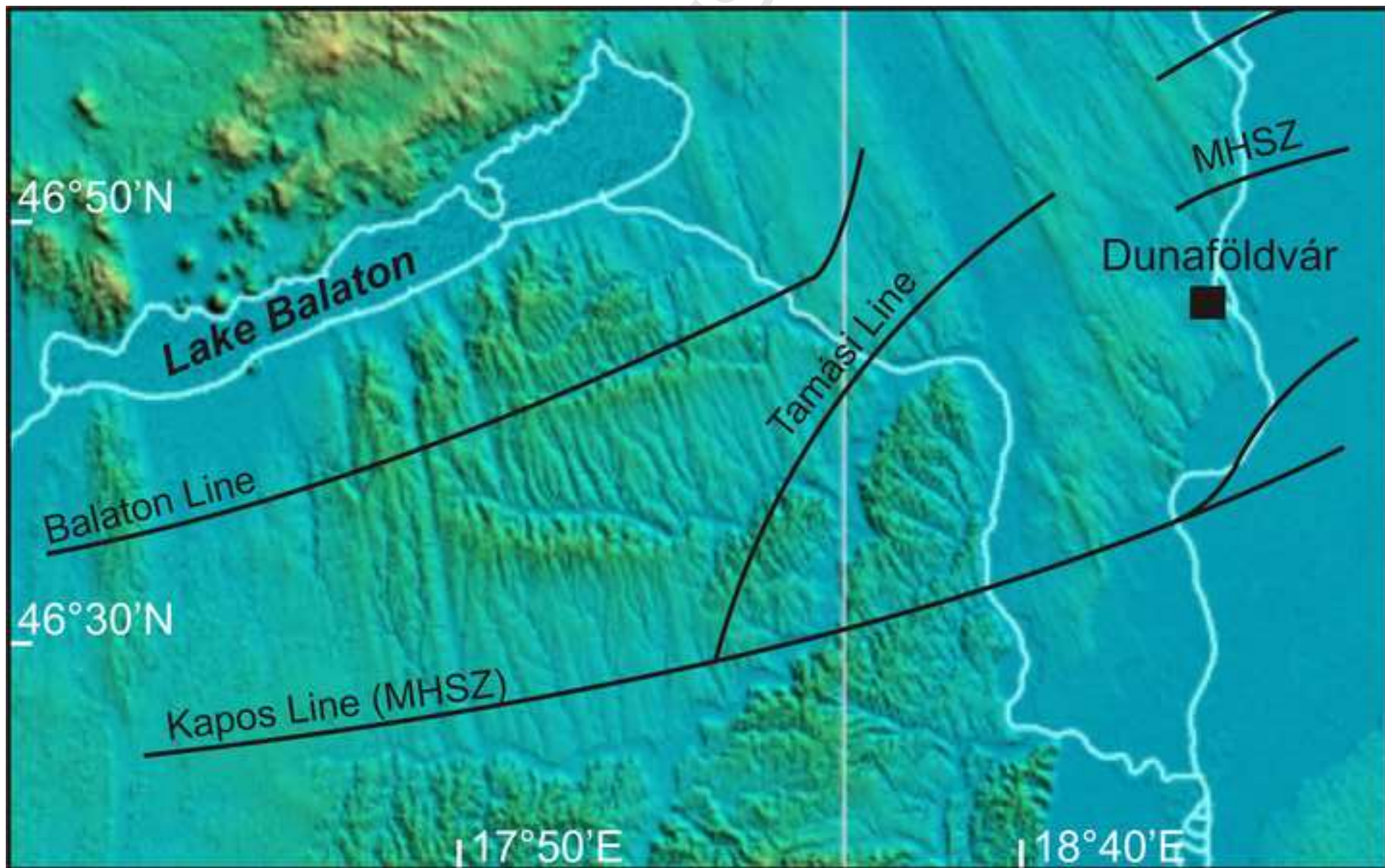
459



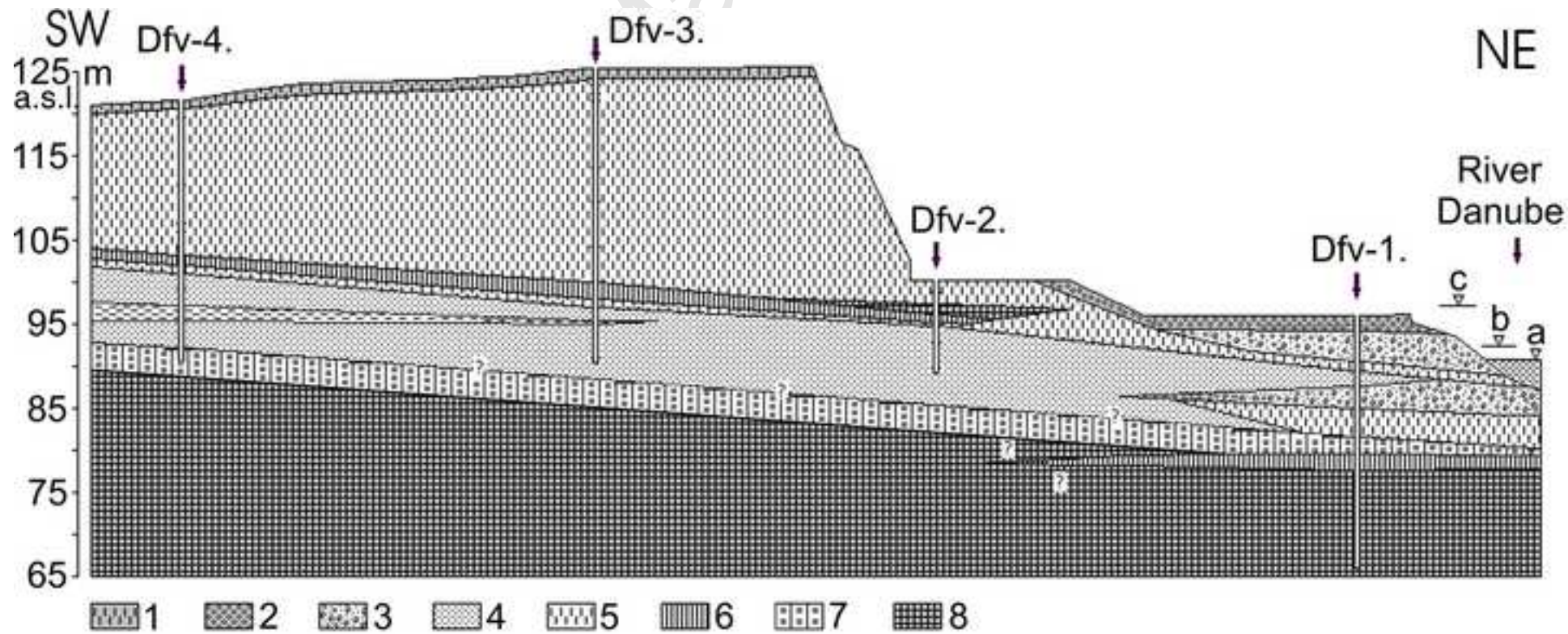
Figure

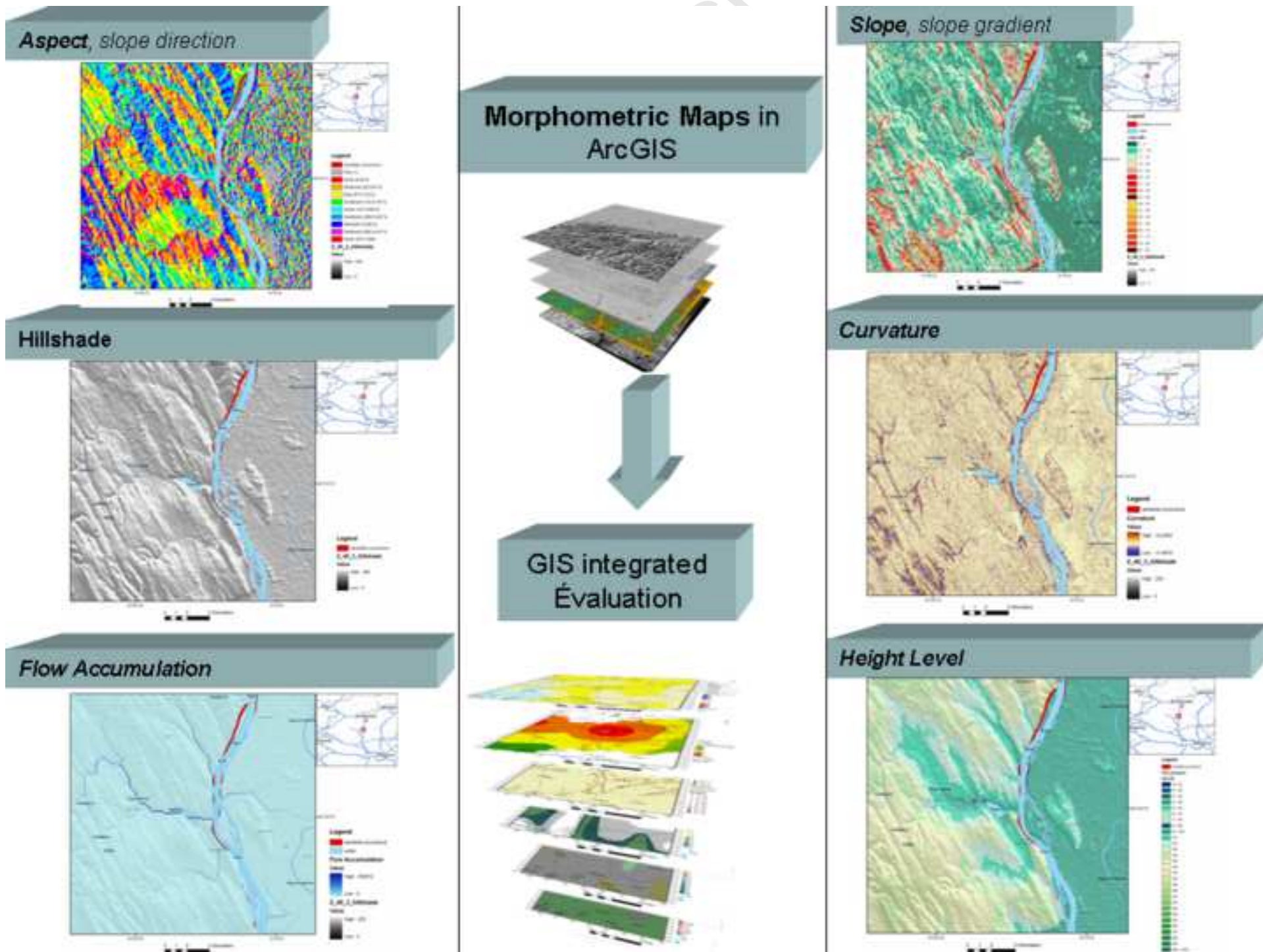


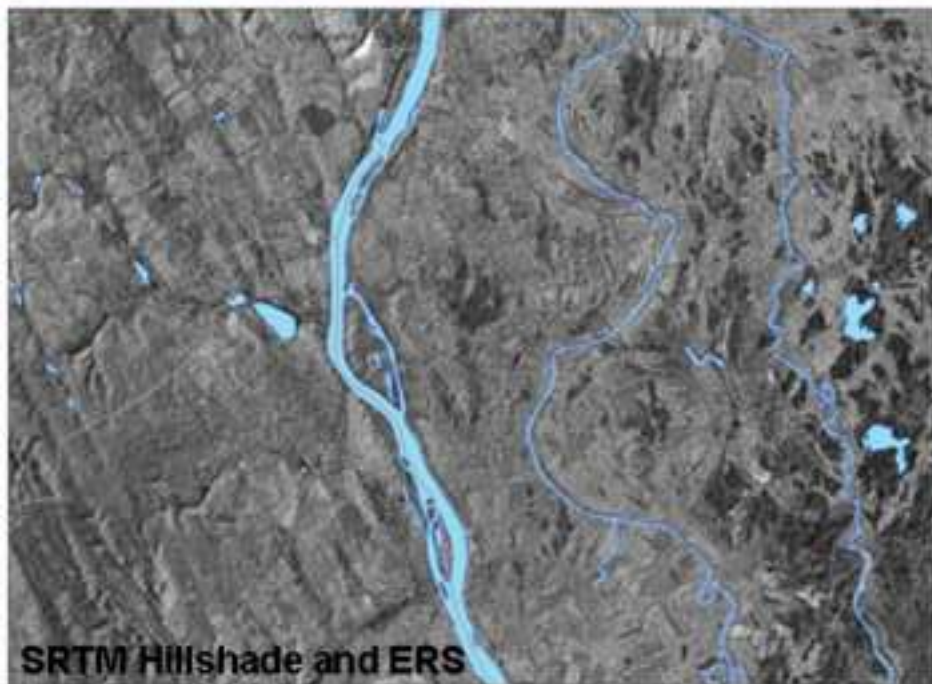
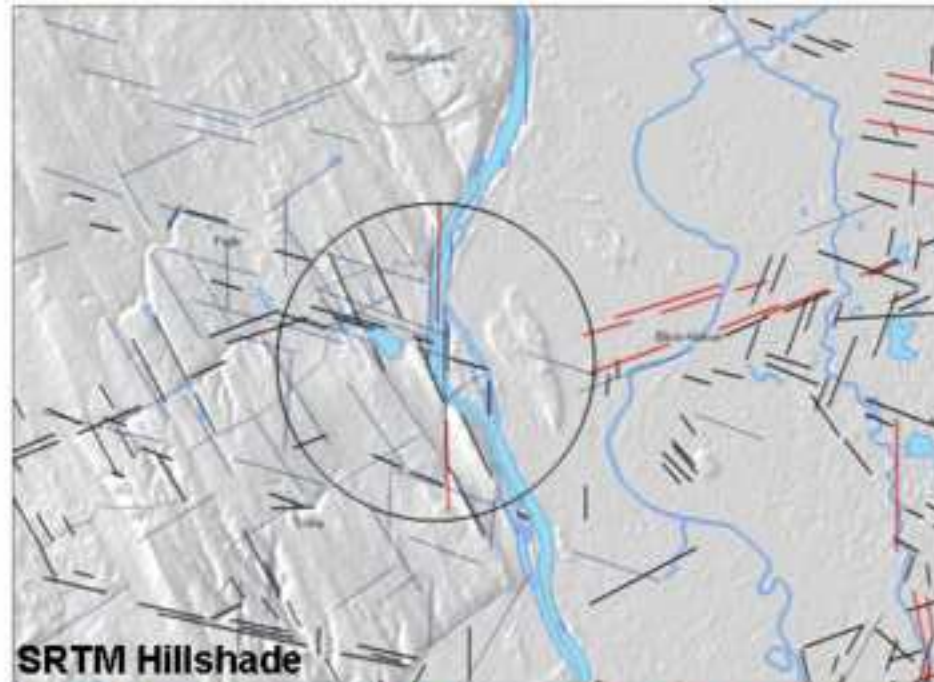
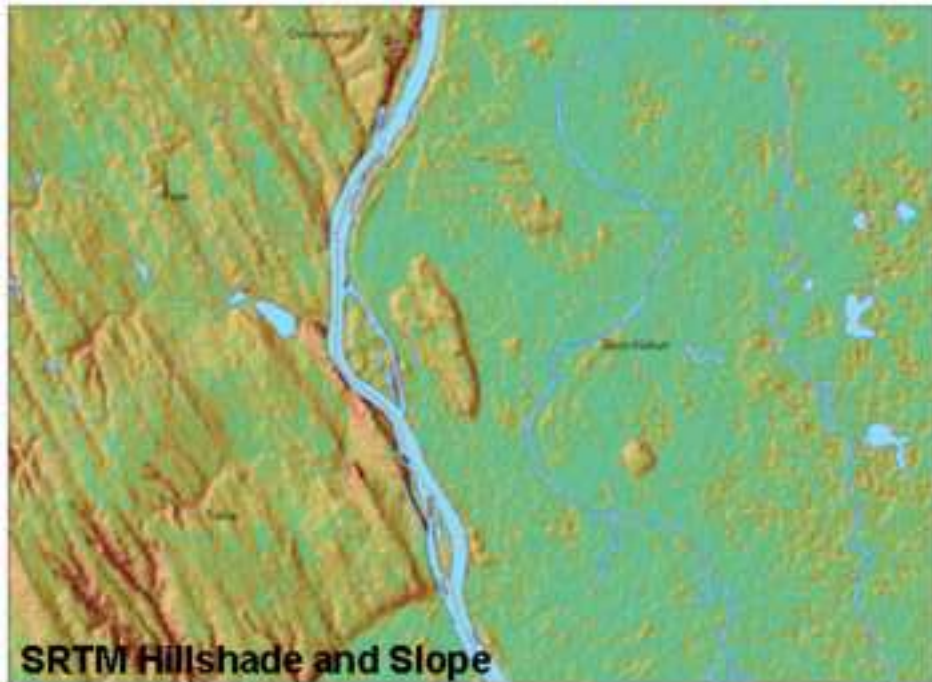
scrip



Figure



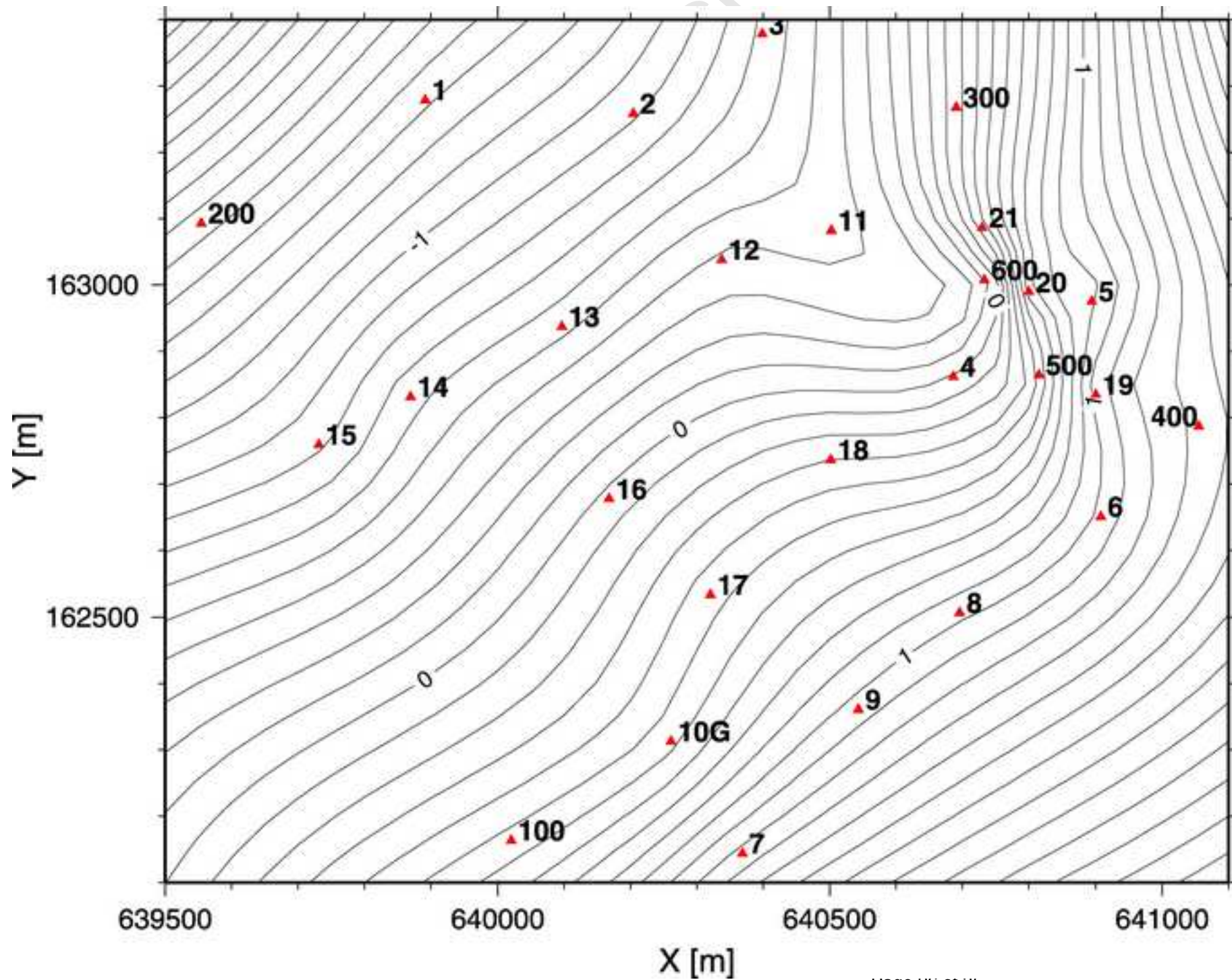


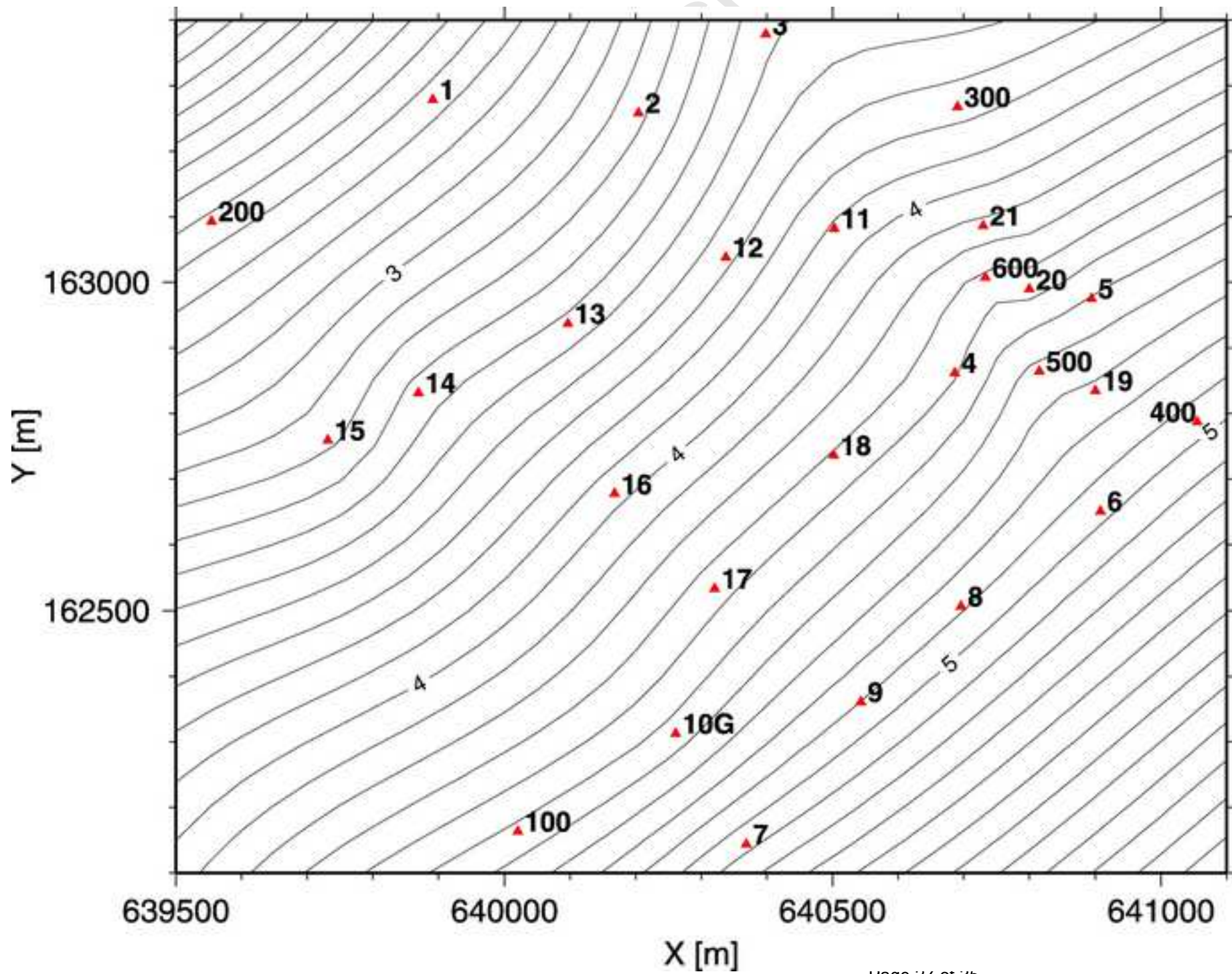


420 210 0 420 Meters

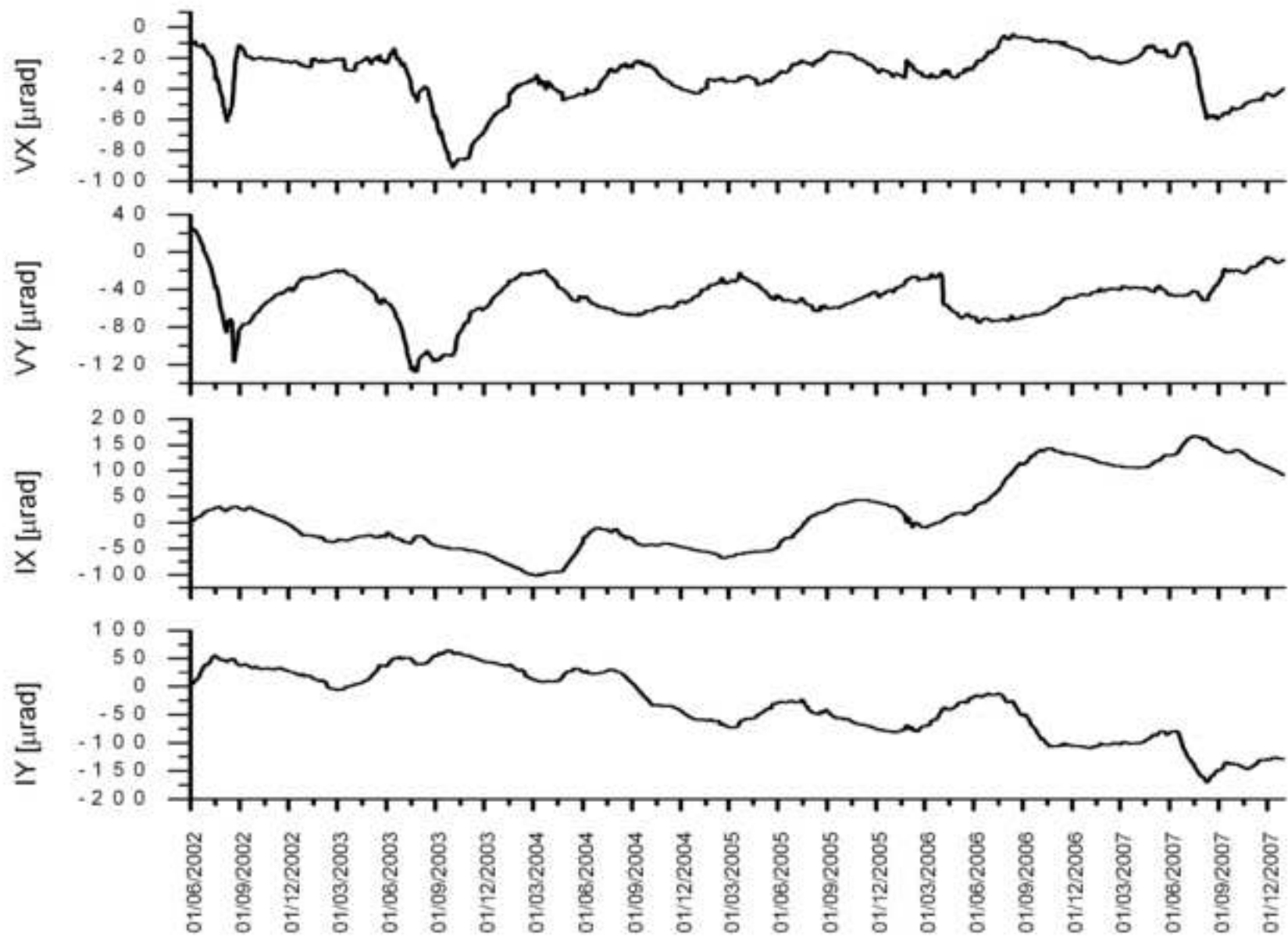
270 135 0 270 Meters

Figure





rip



Figure

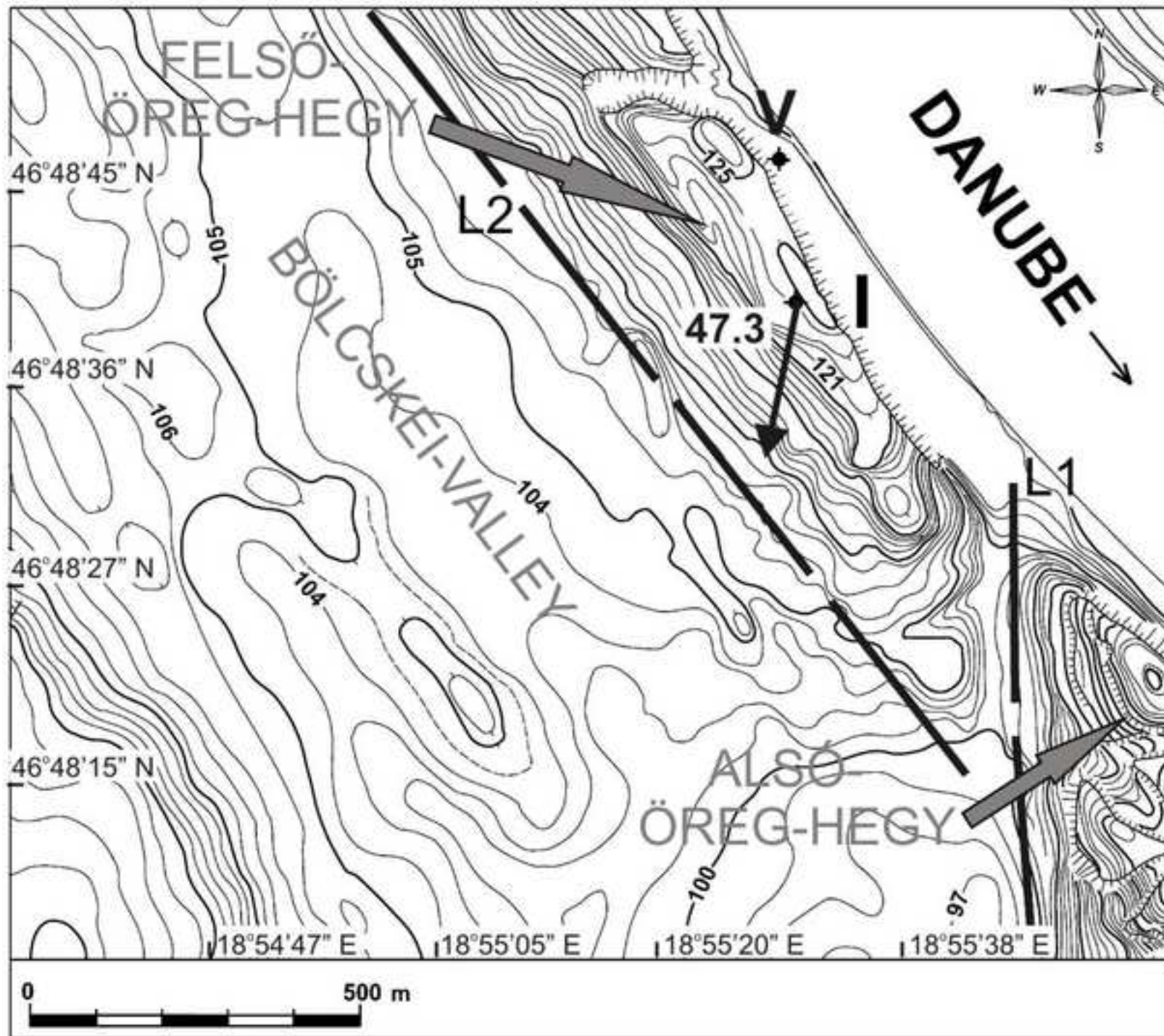
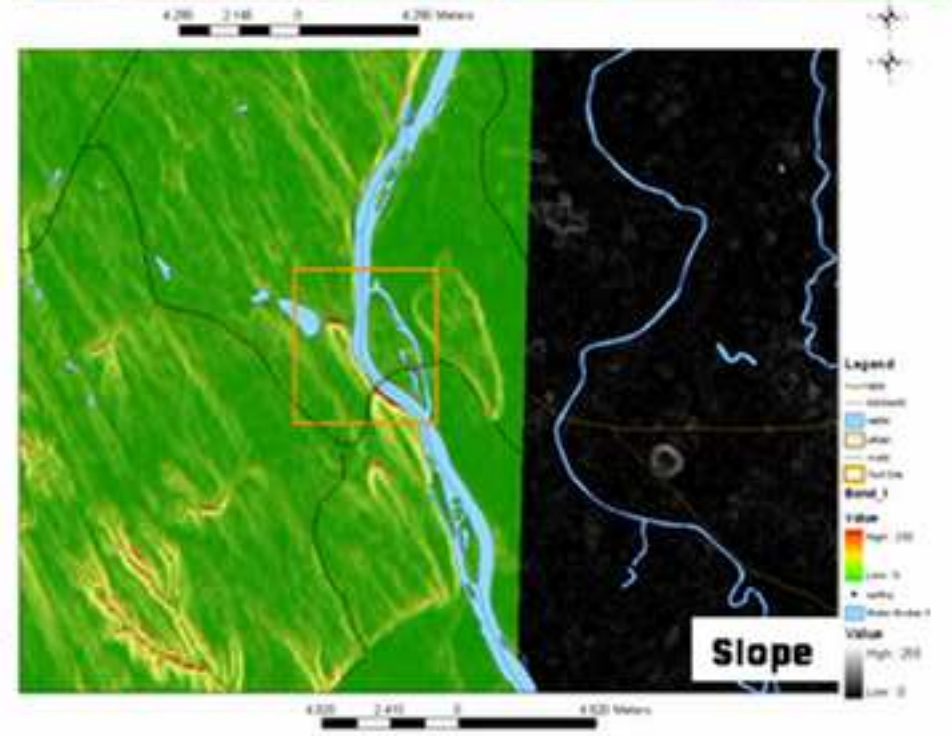
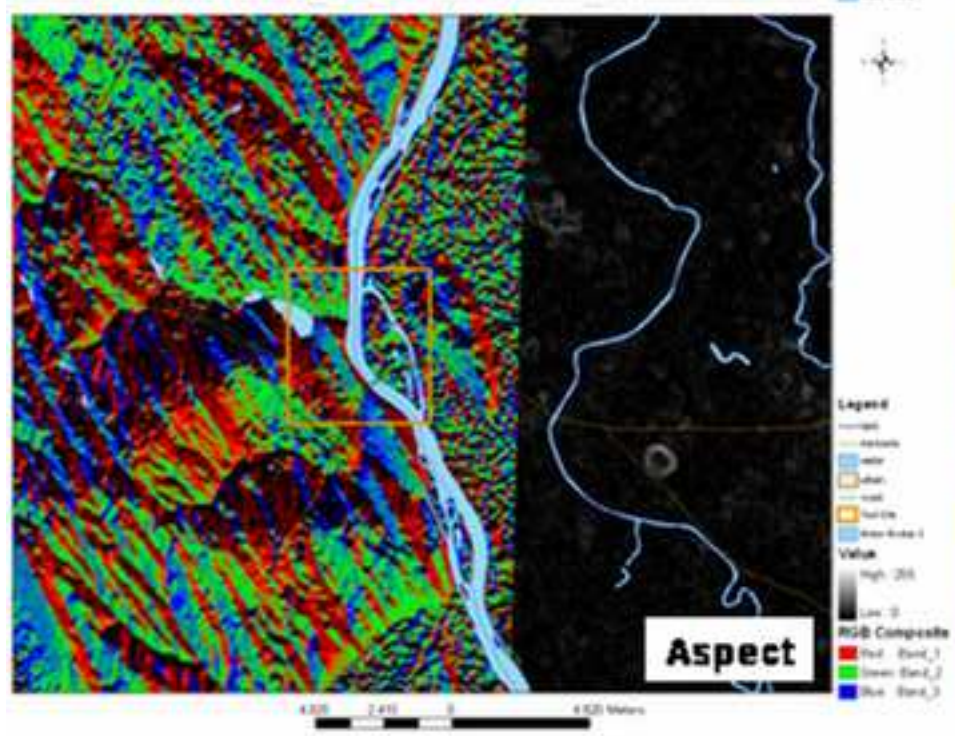
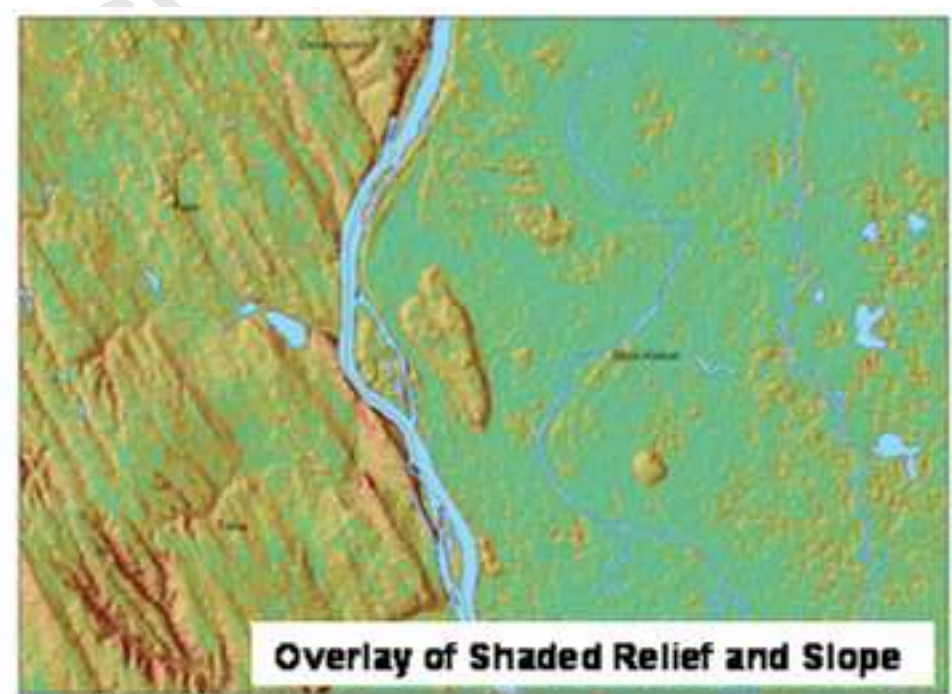
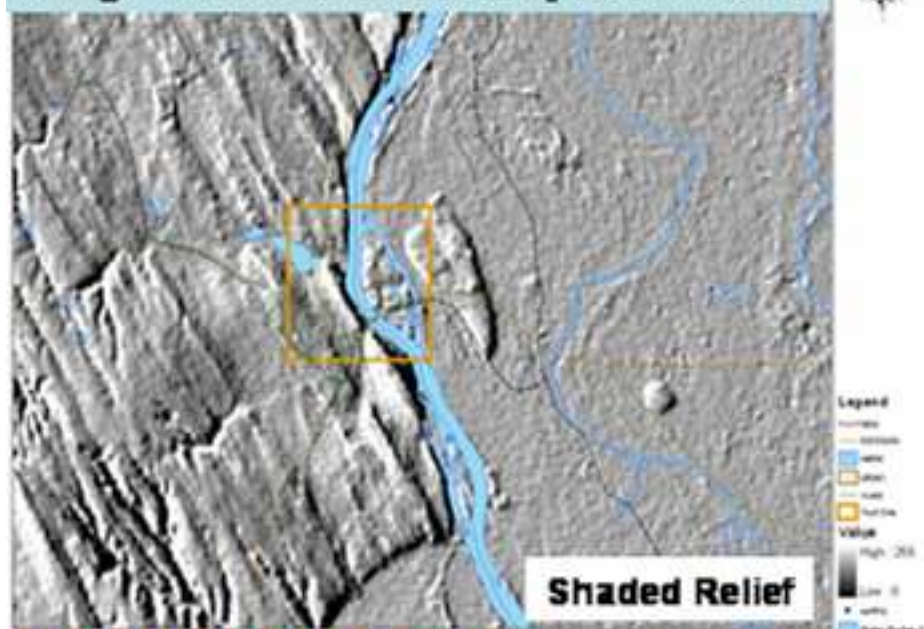
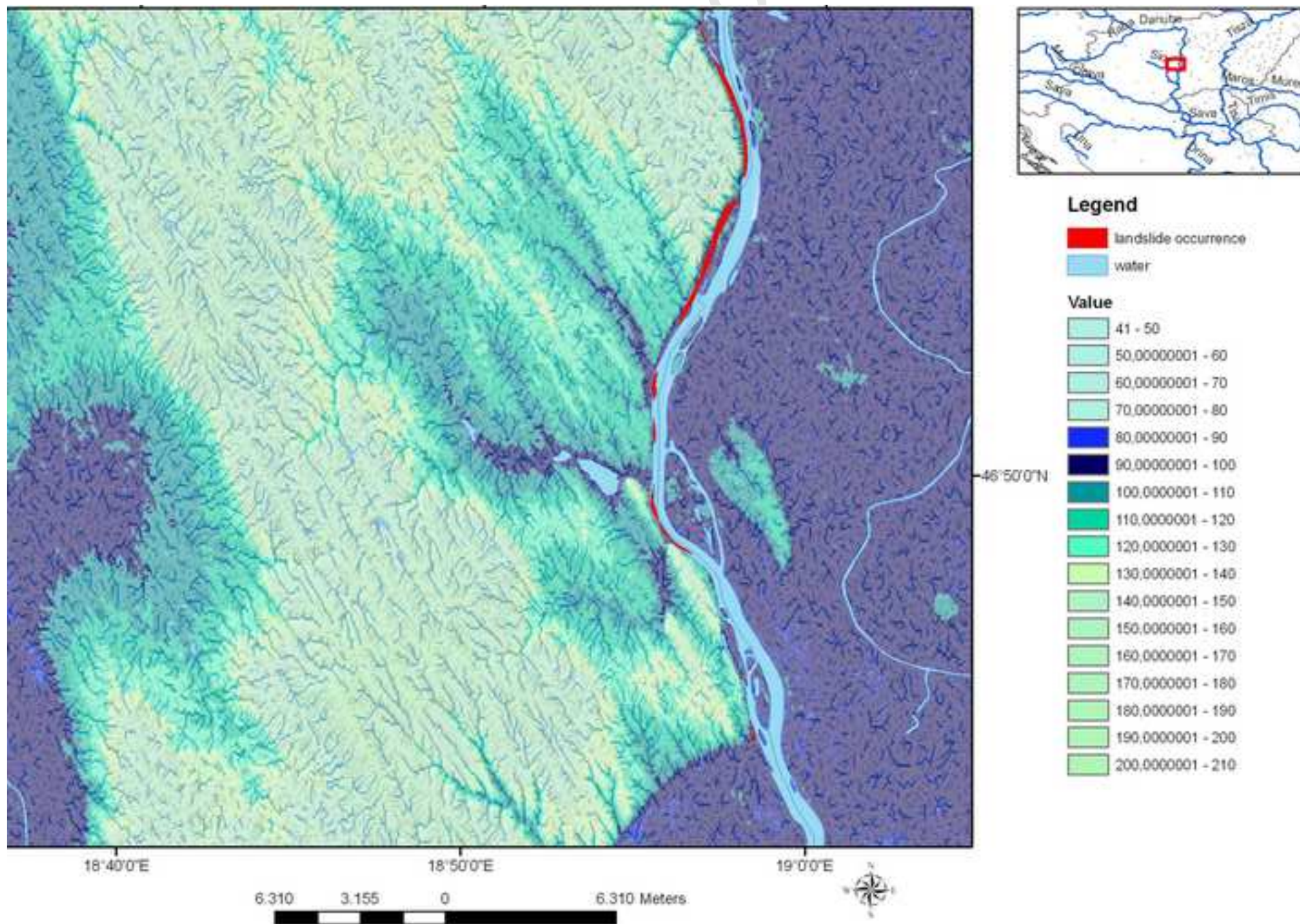
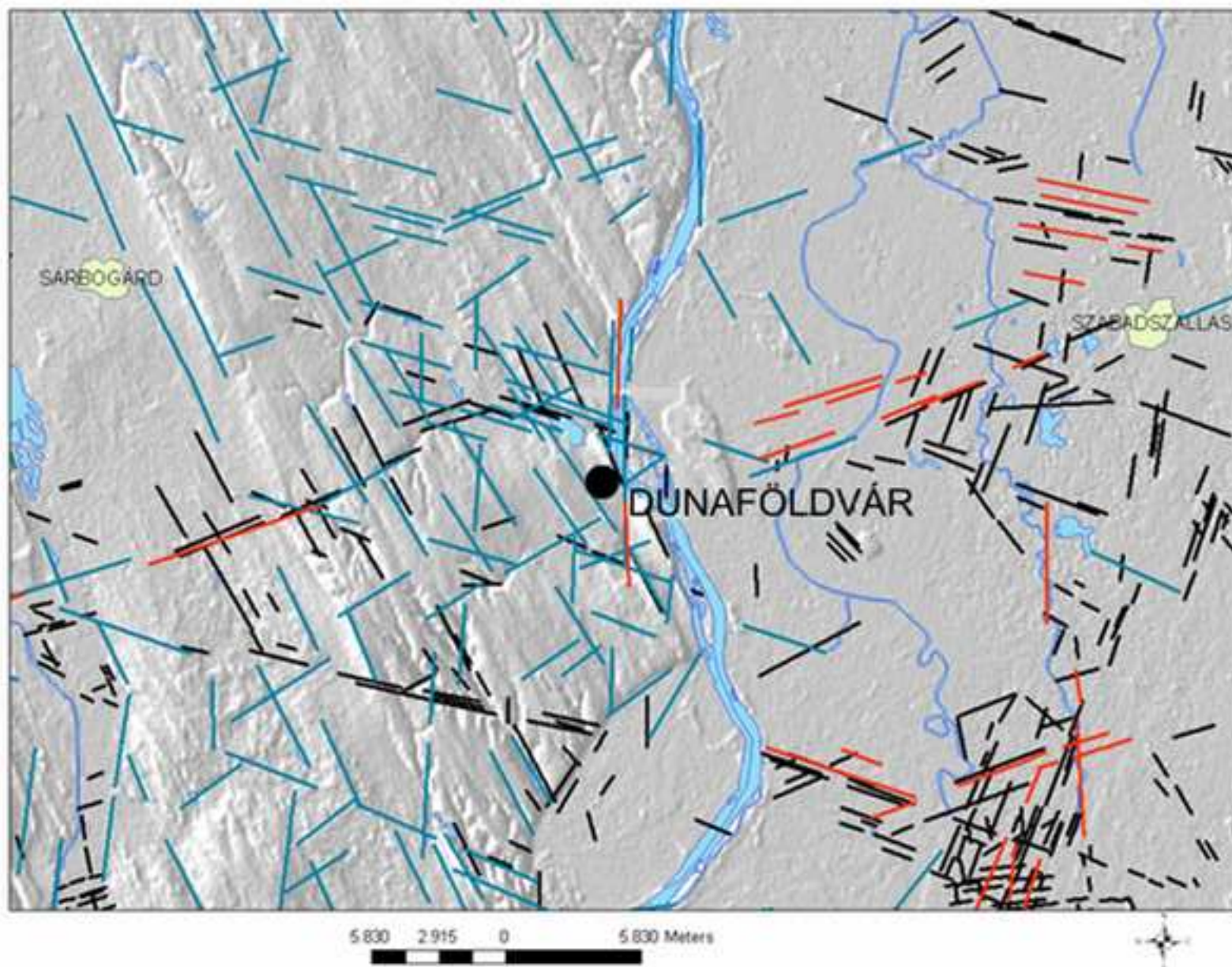





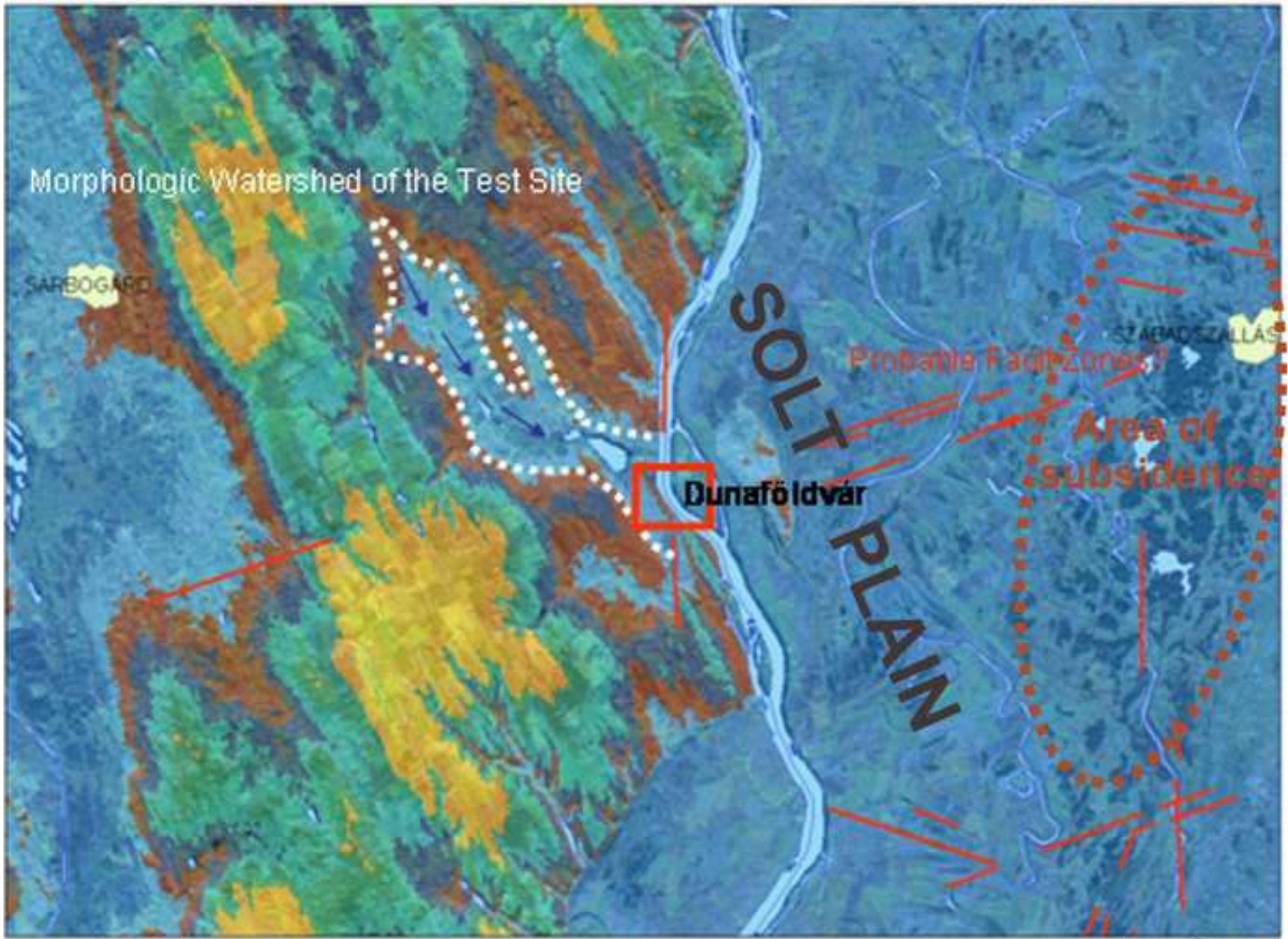
Image Products derived by SRTM Data







-  Lineaments supposed to be related to Probable Fault Zones
-  Lineaments
-  SRTM Lineaments



5140 2570 0 5140 Meters



Figure

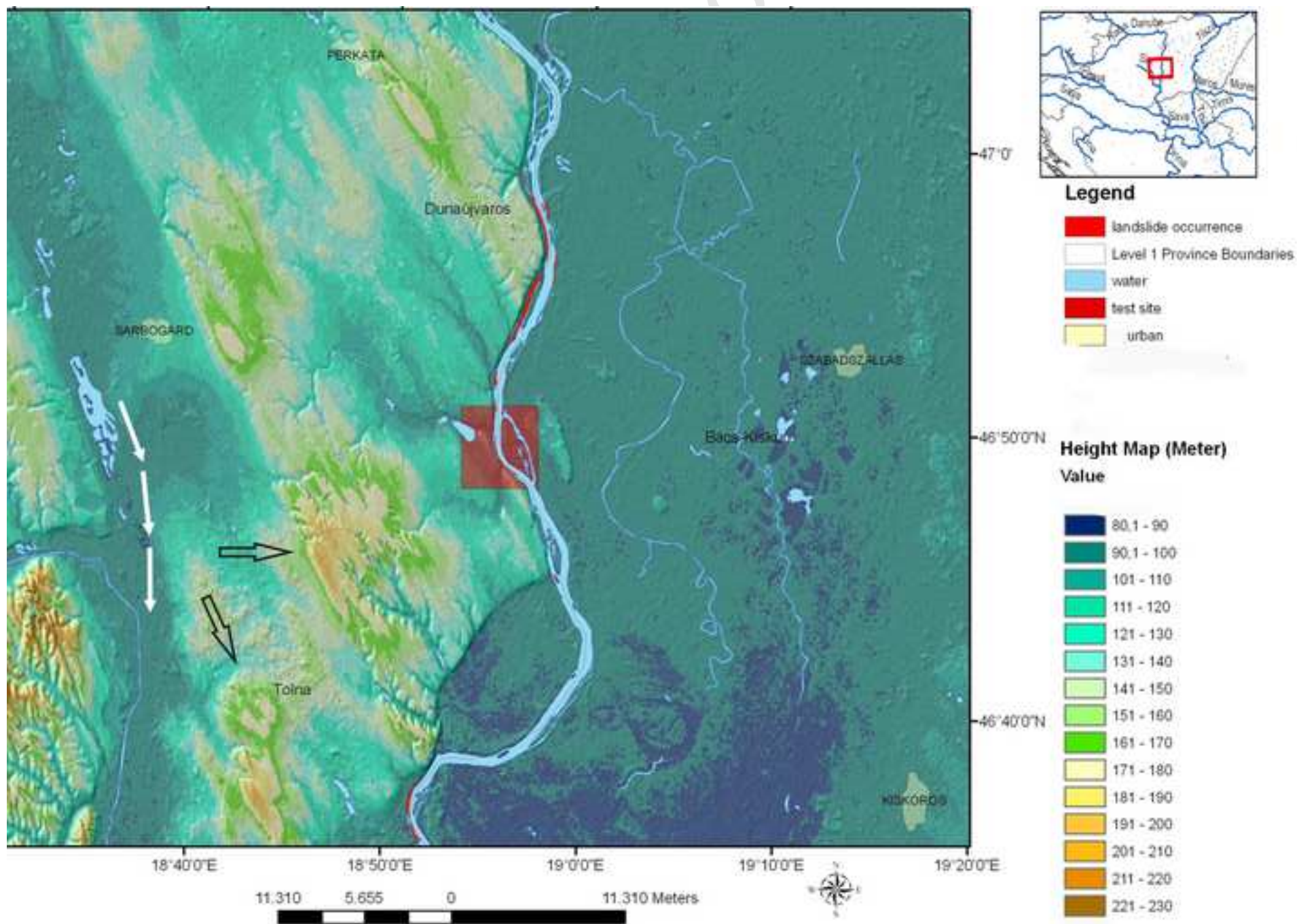


Table 1. Tilt rates calculated from the raw tilt data

Tilt components	Tilt rate	Error of the rate determination	Correlation coefficient
	$\mu\text{rad}/\text{year}$	$\mu\text{rad}/\text{year}$	
IX	33.3	0.68	0.733
IY	-33.6	0.37	-0.898
VX	1.5	0.22	0.152
VY	2.7	0.32	0.188

Accepted Manuscript