Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology 1031

Terrain Modelling with GIS for Tectonic Geomorphology

Numerical Methods and Applications

BY

GYOZO JORDAN

ACTA UNIVERSITATIS UPSALIENSIS
UPPSALA 2004

Dissertation presented at Uppsala University to be publicly examined in Konferensrum Dk 235, Geocentrum, Uppsala, Tuesday, November 23, 2004 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract
Jordan, G. 2004. Terrain Modelling with GIS for Tectonic Geomorphology. Numerical Methods and Applications. Acta Universitatis Upsaliensis. *Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1031. 41 pp. Uppsala. ISBN 91-554-6072-0

Analysis of digital elevation models (DEMs) by means of geomorphometry provides means of recognising fractures and characterising the morphotectonics of an area in a quantitative way. The objective of the thesis is to develop numerical methods and a consistent GIS methodology for tectonic geomorphology and apply it to test sites. Based on the study of landforms related to faults, geomorphological characteristics are translated into mathematical and numerical algorithms. The methodology is based on general geomorphometry. In this study, the basic geometric attributes (elevation, slope, aspect and curvatures) are complemented with the automatic extraction of ridge and valley lines and surface specific points. Evan's univariate and bivariate methodology of general geomorphometry is extended with texture (spatial) analysis methods such as trend, autocorrelation, spectral, wavelet and network analysis. Digital terrain modelling is carried out by means of (1) general geomorphometry, (2) digital drainage network analysis, (3) digital image processing, (4) lineament extraction and analysis, (5) spatial and statistical analysis and (6) DEM specific digital methods such as shaded relief models, digital cross-sections and 3D surface modelling. Geological data of various sources and scales are integrated in a GIS database. Interpretation of multi-source information confirmed the findings of digital morphotectonic investigation. A simple shear model with principal displacement zone in the NE-SW direction can explain most of the morphotectonic features associated with structures identified by geological and digital morphotectonic investigations in the Kali Basin. Comparison of the results of the DTA with the known geology from NW Greece indicated that the major faults correspond to clear lineaments. Thus, DTA of an area in the proposed way forms a useful tool to identify major and minor structures covering large areas. In this thesis, numerical methods for drainage network extraction and aspect analysis have been developed and applied to tectonic geomorphology.

Keywords: digital elevation model, digital terrain modelling, GIS, morphometry, tectonic geomorphology

Gyozo Jordan, Department of Earth Sciences, Environment and Landscape Dynamics, Uppsala University, Sweden

ISSN 1104-232X
ISBN 91-554-6072-0
urn:nbn:se:uu:diva-4635 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-4635)

To my parents from whom I learnt to wonder, respect and love Nature and Her humans.

List of Publications

This thesis is based on the following papers that are referred to by their Roman numerals. The publishers kindly gave their permission for reproduction of papers.

PART I. DIGITAL TECTONIC GEOMORPHOLOGY

I **Jordan, G., Meijninger, B.M.L., Szucs, A., van Hinsbergen, D.J.J., Meulenkamp, J.E., van Dijk, P.M., 2003.** A GIS framework for digital tectonic geomorphology: case studies. International Journal of Applied Earth Observation and Geoinformation, submitted.

II **Jordan, G., 2003.** Morphometric analysis and tectonic interpretation of digital terrain data: a case study. Earth Surface Processes and Landforms, **28**: 807 - 822.

III **Jordan, G., Csillag, G., Szucs, A., and Qvarfort, U., 2003.** Application of digital terrain modelling and GIS methods for the morphotectonic investigation of the Káli Basin, Hungary. Zeitschrift fur Geomorphologie, **47**:145-169.

PART II. DEVELOPMENT OF NUMERICAL METHODS FOR TECTONIC GEOMORPHOLOGY

IV **Jordan, G., 2004**. Adaptive smoothing of valleys in DEMs using TIN interpolation from ridgeline elevations: an application to morphotectonic aspect analysis. Computers and Geosciences, submitted.

V. **Jordan, G. and Schott, B., 2004.** Application of wavelet analysis to the study of spatial pattern of morphotectonic lineaments in digital terrain models. A case study. Remote Sensing of Environment, in press.

VI. **Jordan, G., 2004.** Extraction of high-density drainage and ridgeline network from DEMs by means of digital drainage analysis and mathematical morphology methods. (manuscript)

Other publications published as result of PhD research.

1. Jordan, G. and Csillag, G., 2003. A GIS framework for morphotectonic analysis - a case study. 4th European Congress on Regional Geoscientific Cartography and Information Systems, 17-20 June, 2003, Bologna, Italy. Proceedings, **2**: 516-519. Regione Emilia-Romadna, Servizio Geologico, Bologna.

2. Jordan, G. and Csillag, G., 2001. Digital terrain modelling for morphotectonic analysis: a GIS framework. In: H. Ohmori (ed). DEMs and Geomorphology. Special Publication of the Geographic Information Systems Association, **1**: 60-61. Nihon University, Tokyo.

3. Jordan, G. and Csillag, G., 2001. Digital terrain modelling for morphotectonic analysis: a GIS framework. 5th International Congress on Geomorphology, 23-28 August, 2001, Tokyo, Japan. Abstracts. Transactions, Japanese Geomorphological Union. p. 115.

4. Csillag G. and Jordan G. 2002. Geomorphological investigation of the Káli Basin with terrain modelling and 'traditional methods'. Annual Congress of the Hungarian Geological Association, June 27–29, 2002, Bodajk, Hungary. Abstracts, p. 4. (in Hungarian)

Acknowledgements

I would like to thank Ulf Qvarfort for giving continuous support during the years of my thesis work at the Uppsala University. He provided research facilities and a good working environment for thesis work and fruitful discussions. His outstanding ability of solving emerging problems immediately made my research work much efficient. I would like to express my gratitude to Keith Bennett, Head of Paleobiology Division for his patience and kind understanding during my PhD work at his department.

My sincere thanks to my friends at the Uppsala University. Bertram Schott, Lin Zhixun, Manhal Sirat and Barna Zsigmond. Bert, thanks for introducing me to wavelet analysis. Manhal, thanks for stimulating discussions on structural geology. Without the personal support of friends outside of the university I would not have been able to complete my thesis. Special thanks to Anikó and Edward Ledwaba and the Heszler family for providing true friendship during my stay in Sweden. Kind assistance of the Geobiblioteket in obtaining a great amount of international literature is gratefully acknowledged.

This thesis would not exist without the support of the Geological Institute of Hungary (MAFI). First of all, I would like to say thank you to Gábor Gaál, former MAFI director, and Károly Brezsnyánszky, Director of MAFI for their continuous interest in my work and their understanding support. I thank Emőke Jocháné Edelényi, Head of Regional Hydrogeology Department, István Horváth, Head of Geochemistry Department and György Tóth, Head of Hydrogeology Division for providing facilities and giving friendly support for the preparation of this thesis. It was a useful experience and great pleasure to collaborate with Gábor Csillag in developing some of the papers for this thesis. Enthusiasm of Ferenc Sikhegyi and fruitful discussions with him helped me to pursue the interesting topic of morphotectonics. The always ready and high quality work of the GIS Division team is much appretiated. Friendly assistance of the National Earth Science Library at MAFI in obtaining fundamental international literature is gratefully acknowledged.

The three months of stay as a visiting scientist at the International Institute for Geo-Information Science and Earth Observation (ITC) in Enschede, the Netherlands was essential for the success of my thesis. Professor Andrea

Fabbri, Head of Geological Survey Division, provided me a much welcoming environment, professional support and facilities of an international institute excelling at digital image process, terrain modelling and geoscientific applications. Discussions with Tseahaie Woldai Assistant Professor at ITC were much useful. This was where I met Bart Meijninger with whom collaboration was interesting and fruitful. My sincere thanks to Zoltán Vekerdy, Assistant Professor at Hydrology Division, for making my stay most pleasant and useful at ITC. I thank the Vekerdy family for being so friendly to me during my stay in the Netherlands. Dénes, thank you, too, for your friendliness.

My stay at the Joint Research Centre of the European Commission (JRC) meant a technical break in my thesis work that lead to more than two years of delay for completing my thesis. However, Giovanni Bidogliao, Head of Soil and Waste Unit, Stefan Sommer, Action Leader, and Marco D'Alessandro, Marc van Liedekerke, Tamas Hamor and Anca-Marina Vijdea provided a good working environment where finalising my thesis became possible. European Soil Bureau crew: thanks for being a friendly, nice and stimulating company around (in) my office! I would like to express my thankful gratitude to Pierre Soille for sharing enthusiasm about digital methods, terrain modelling and for the fruitful collaboration. I would like to say thank you to Jurgen Voght for providing friendly support for and sharing interest in terrain modelling and geo-environmental applications. There is no space here to list the dosens of friends and nice people who supported me and expressed interest in my thesis work during my stay at JRC. Doughlas Owen's help for checking the English of my papers is gratefully acknowledged. Kind help of Una Cullinan of JRC Library with obtaining relevant literature is also gratefully acknowledged.

Thank you Andika for being a helpful colleague; and a loving wife! 'Collaboration' is always a great pleasure with you! The period of my PhD work has brought the greatest success and happiness in my life: the birth of my two sons, Marcell and Milan. Thanks for being with me.

I would like to say thank you to my parents from whom I learnt to wonder, respect and love Nature and Her people.

Research has been carried out with the help of scholarships from the Swedish Institute, the Soros Foundation and the Hungarian National Science Fund (OTKA T32866). Their assistance is gratefully acknowledged.

Contents

1 Introduction

Structural analysis of topographic features is a well-established field of study in geomorphology, and aerial photographs and remotely sensed images have long been used for this purpose. Recent developments in information technology and digital elevation data acquisition have resulted in an increasing interest in digital terrain modelling for tectonic geomorphology. Surface methods such as remote sensing and morphological analysis provide fast and relatively cheap information, complementary to classical field geology in order to study subsurface geology. Morphological analysis of topographic features, in particular lineaments, has long been applied in structural and tectonic studies (Hobbs, 1912; Frisch, 1997), and has become a fundamental tool in tectonic analyses using (stereo-)aerialphotographs and other remotely sensed imagery (Siegal & Gillespie, 1980; Drury, 1987; Salvi, 1995; Woldai et al., 2000). Although the interpretation of land morphology in terms of geological structures is well-established (Fabbri, 1984; Prost, 1994; Keller & Pinter, 1996) there are relatively few examples of the use of Geographic Information systems (GIS) in such studies, and there is as yet no case study documented in the literature involving the consistent application of available digital methods for tectonic geomorphology.

Review of literature on digital morphotectonic analysis shows that a great variety of methods have been used, such as shaded relief models together with remotely sensed images, three-dimensional view with image drape, digital cross-sections, slope, aspect and curvature maps, DTM histograms, and trend and spectral analysis (**Paper I**). The most important limitations in general are that (1) most of the studies use a single method (or only a few methods) for feature recognition and description, (2) all of the studies are at the regional scale, although landform observations are at the local scale, (3) most of the studies use visual methods of feature (mostly lineament) extraction, (4) there are very few cases involving the analysis and extraction of landforms specific to tectonic structures, (5) most of the methods can be applied to neo-tectonic landforms only, and (6) there is a lack of rigorous study of the relationship between tectonic processes, secondary geological processes, and their representation in DEMs.

Systematic digital tectonic geomorphology analysis is hampered by (1) the lack of such studies in literature, and (2) the non-uniform description and use of relevant digital methods in different fields of the Earth Sciences. Essentially identical methods are often used in these different fields with different names and for different purposes that makes their adoption to digital tectonic geomorphology difficult. GIS software can easily perform most of the analyses but some procedures may be very difficult to implement. Digital analysis of the kind presented here requires the use of an integrated system of many analytical and software tools.

Digital tectonic geomorphology is the integration of three components: structural geology, geomorphology and digital terrain analysis (DTA) (Jordan & Csillag, 2001; Jordan & Csillag, 2003). Tectonic geomorphology has developed sophisticated methods for the integration of structural geology and geomorphology. The application of numerical methods in geomorphology has led to the field of geomorphometry, which has developed rapidly since the availability of digital terrain data. There is, however, a gap between structural geology and DTA. In this thesis discussion is limited to the analysis of faults. DTA of faults is carried out by (1) the study of landforms related to tectonic structures and translation of these morphological characteristics into mathematical and numerical algorithms (**Papers IV, V and VI**), and (2) implementation of detailed morphotectonic analysis using GIS technology (**Papers I, II and III**).

The basic geometric properties which characterise the terrain surface at a point are (1) elevation, (2) properties of the gradient vector: its magnitude defining slope, and its direction angle defining terrain aspect, (3) surface curvature, (4) convexity and (5) surface-specific points and lines, i.e. local maxima (peaks), minima (pits), saddle points (passes), inflection points, slope-breaks, ridge and valley lines (**Paper II**). The relationship of local geometric attributes and tectonic structures such as relationship between slope-breaks and fractures is often straightforward (Siegal & Gillespie, 1980; Drury, 1987; Prost, 1994; Salvi, 1995).

In contrast to local geometric analysis, general geomorphology also studies the statistical and spatial characteristics and relationships of point attributes (Evans, 1972; 1980). Relationships between point attributes were used by Evans (1980) to further characterise the terrain. For example, the elevation-average slope curve and the cumulative percentage area-elevation curve (‘hypsometric curve’) can be used to study slope conditions. By fitting a trend surface to the studied area or its parts, the overall tilt due to tectonic activity can be studied (Doornkamp,1972; Fraser et al., 1995; Guth, 1997). Autocorrelation, spectral, wavelet and variogram analysis can reveal anisotropy and periodicity present in the digital elevation model. Both features often result from tectonic control on terrain morphology (Harrison and Lo, 1996).

2 Aim of the Study

- The main objective of the thesis is to develop a systematic GIS procedure for digital tectonic geomorphology (**Paper I**).

- The second objective is that Evan's (1972, 1980) general geomorphology method is further developed by (1) complementing with automatic extraction of surface specific points and ridge and valley lines, and (2) extending its univariate and bivariate methodology with texture (spatial) analysis methods such as trend, autocorrelation, spectral and variogram analyses and topological analysis (**Paper II**).

- A third objective is to develop numerical methods for tectonic geomorphology such as adaptive valley smoothing (**Paper IV**), wavelet analysis (**Paper V**) and high-density drainage network extraction (**Paper VI**).

- The final objective is the application of DTA and GIS methods for detailed tectonic geomorphological investigation of study sites and apply it to test sites of local and regional scales (**Paper I and III**).

- Specific objectives of investigation are
  (1) the extraction and characterisation of morphological features associated with known faults using high-resolution (50 m) DEM on a local scale in the Káli Basin, Hungary (**Paper II and III**), and
  (2) identification of tectonic features from geomorphology using low-resolution DEM (1 km) on regional scale in north-western Greece (**Paper I**).

The hypothesis is that, based on the study of landforms related to faults, geomorphological characteristics can be translated into mathematical and numerical algorithms which in turn can be used to extract, describe and interpret terrain data in terms of structural geology and geomorphology.

In this thesis discussion is limited to the analysis of faults. Regarding the great diversity of tectonic geomorphology, only a limited selection of fault-related landforms can be discussed in the thesis. The emphasis is on digital data processing and implementation of GIS methods.

3 Study Areas

3.1 Káli Basin, Hungary

The Káli Basin is located in the south-western part of the Balaton Upland in the Transdanubian Range which is a part of the North Pannonian Unit of the Carpatho-Pannonian region (Trunko, 1995; Budai et al., 1999) (Fig. 1.A). The study area encompasses a 14 km by 18 km rectangle on the northern side of Lake Balaton. The southern border of the basin is formed by a series of hills made up by folded Permian red sandstone (Fig 1.C). Gentle slopes and shallow valleys are characteristic on the terrain of the fractured resistant red sandstone. In the middle of the basin and in the East gently folded Triassic carbonate sediment series are exposed. Tertiary clastic sediments, primarily sand, fill the majority of the basin. The basin is bordered by Pliocene (5-2.8 m.a.) basaltic volcanic masses in the North and West. Pyroclastic and lava rocks constitute the well-preserved volcanic edifices. The terrain is characterised by thick slope scree and valleys incised in the loose tuff. Quaternary deposits consist of wetland sediments in the majority of the basin area, while slope-foot scree, alluvial sediments and Pleistocene loess in valleys are characteristic of the area. The Liter and Veszprem SE-verging reverse faults in the North, the Kekkut Fault in the West and folds in the South were formed during the Cretaceous (Figs 1.B and C). Tertiary sediments cover both the reverse and the Kekkut faults. Left-lateral strike slip faulting was typical of the region during the Miocene. Extensional tectonics characterised the end of Tertiary times. At present, the area is seismically inactive.

The DEM of the Káli Basin was obtained from the Hungarian Defence Mapping Agency 1:50,000-scale DTM-50 digital grid terrain database. The DTM-50 elevation data was initially interpolated with a third-order spline function from scanned and automatically vectorised contour lines of 10 m interval in Gauss-Krüger projection. The elevation matrix was converted to a regular grid in the EOV (National Uniform Projection) projection. The horizontal resolution of the grid is 50x50 m and the vertical resolution is 1 m. Elevations above sea level are given as integers in metres.

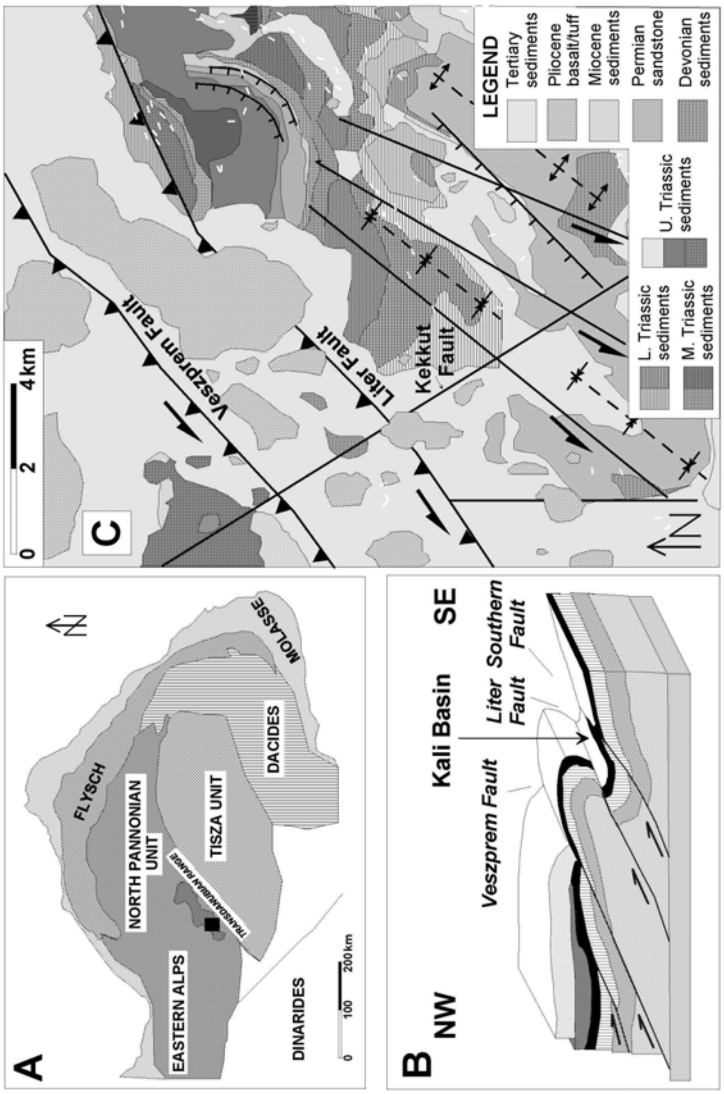

Figure 1. Káli Basin study area. A. Location of the study area in the Pannonian Basin. Solid box: location of the Káli Basin in the Transdanubian Range. B. Cartoon showing Cretaceous faulting and folding in the Balaton Highland (Dudko, 1999). C. Geological map of the Káli Basin. Fault lines and fold axes indicated in geological maps are shown. Short white lines show the strike of bedded sedimentary rocks.

3.2 North-western Greece

The north-western Greece study area exposes a NW-SE striking nappe pile (Fig. 2.A) associated with African-Eurasian convergence in the course of the Late Mesozoic and Tertiary. The nappes themselves are internally highly folded and thrusted. The age of nappe emplacement becomes progressively younger from east to west and are subdivided in the (pre-)Apulian zone (autochton) at the base of the tectonostratigraphy, overlain by the Ionian zone, the Tripolitza zone, and the Pindos zone (Aubouin, 1957; Bonneau, 1984) (Fig. 2.A). The nappe pile is cross-cut at high angles by a series of Late Tertiary extensional and strike-slip faults (**Paper I**). Some of these have been described before and two zones will be identified here. The Late Mio-Pliocene and still-active Aliakmon fault zone in Thessaly (Fig. 2.A) has been recognized as a major NE-SW trending NW-verging normal fault zone. The Servia fault, which belongs to the Aliakmon fault zone, bounds the Kozani Basin. It has an estimated vertical displacement of 2100 meters (Doutsos & Koukouvelas, 1998). The E-W trending Souli-fault in Epirus (**Paper I**) is a normal fault with a component of left-lateral strike slip. A still-active NE-SW trending NW-verging normal fault is identified near Konitsa, forming the northern limit of the Timfi block (IGRS-IFP, 1966) (Fig. 2.A) and a WNW-ENE trending, NNE verging normal fault system, associated with the formation of the Gulf of Amvrakikos (Clews, 1989). In the south-eastern part of north-western Greece, the intramontane basins of Karditsa and Larissa are filled with Late Neogene to Holocene terrestrial deposits.

Based on the geologic map of IGRS-IFP (1966) and Bornovas & Rontogianni-Tsiabaou (1984) and field observations, two fault zones are identified that have not been mentioned before in literature: the Thesprotiko Fault Zone runs NE-SW across Epirus and displaces a syncline filled with Lower Miocene sediments in a right-lateral sense by 15-20 km. Its age is post-Early Miocene. It interferes with the Kastaniotikos fault zone (Skourlis & Doutsos, 2003), which is a WNW-ESE trending, north-verging normal fault zone, bringing the Upper Unit next to the Mesozoic carbonate sequence of the Pindos Zone (Fig. 2.A) during an ill-defined time period after the Eocene.

A DEM of north-western Greece was obtained from the Global Land One-kilometre Base Elevation (GLOBE) model that has a 30 arc-second (approx. 800 m) grid spacing and 1 meter vertical resolution. DTA of the DEM of north-western Greece was carried out in combination with regional-scale remote sensing (Landsat TM satellite images).

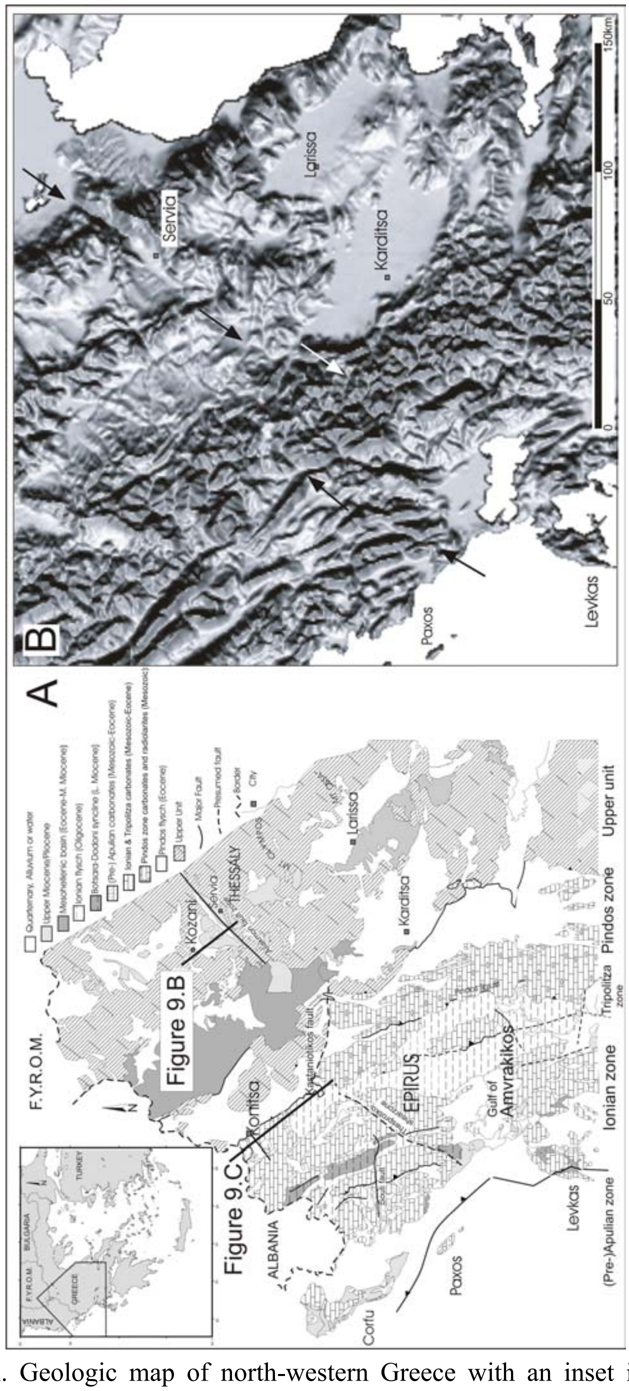

Figure 2. A. Geologic map of north-western Greece with an inset indicating its position in Greece. Thick solid lines are locations of cross-sections in Figures 9.B and 9.C. B. Shaded relief model of original DEM (13x vertical exaggeration). Arrows indicate main lineaments in the NE-SW direction.

4 Methods

4.1 Spatial analysis of morphological features associated with fractures

Structural discontinuities in rocks most often result in linear morphological features along the intersection of fracture plane and land surface. Linear morphological expressions of fractures include (1) linear valleys, (2) linear ridgelines and (3) linear slope-breaks. The main geometric characteristics of a *single* line are orientation, length (continuity) and line curvature (Fig. 3.A). Linear fracture traces are most obvious in the case of high-dip faults of normal, reverse and strike-slip type whilst thrust faults tend to appear irregular in topography (Prost, 1994; Drury 1997; Goldsworthy & Jackson, 2000). Intersection of topographic surface and fold structures can also result in linear and planar features depending on the geometry and orientation of the folds with respect to the erosion surface (Ramsay & Huber, 1987).

Planar features such as uniform hillsides also develop along fractures. Geometry of planar surfaces are described by uniform aspect and high and constant slope values (Fig. 3.A). Shape and areal extent are also important characteristics. Large elongated areas with linear boundaries can be associated with faults. The measure of curvature is important in case of complex curving fracture surfaces.

Specific geomorphological features forming along faults are diverse. Asymmetric geometry of slopes across valley and ridgeline axes, as measured by uniform slope angle differences, can result from tectonic influences on the morphology. Characteristic landforms, such as depressions, pressure bulges or tilt of flats are commonly seen in fault zones. Depressions and bulges are geometric locations of local elevation minima and maxima, respectively. Characteristic shape and slope conditions describe their geometry (Keller & Pinter, 1996). Tilt of flats result in uniform surface gradients.

Most of the above morphological features, such as linear valleys, asymmetric slopes and depressions may be caused by secondary processes or can be associated with lithology. For example, wind erosion may create linear patterns; planar surfaces, linear valleys and ridges and asymmetric slopes are often associated with bedding; and linear morphological features may arise from lithological contacts between different rock types (Way, 1973).

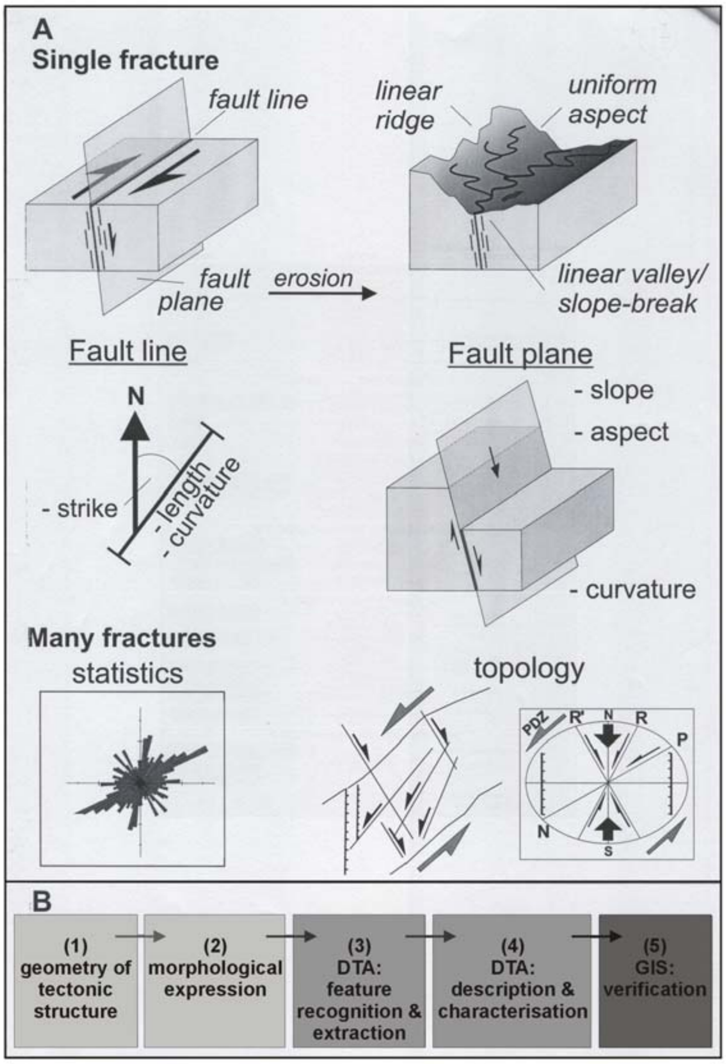

Figure 3. A. Geometric and spatial analysis of fractures. B. Analytical steps in digital tectonic geomorphology. See text for details.

The spatial relationships *among* fractures can be described either statistically by a spatial frequency analysis of the above characteristics or topologically

(Fig. 3.A). In statistical analysis, location of individual features is not considered within the studied population. For example, angular statistics (rose-diagrams) are used for analysis of orientation distribution in the study area. Spatial statistics of fault length and intersection densities are important in structural geology, too. Note also that the density number of lineaments is sensitive to the scale and resolution of the used imagery, relief and thickness of soil cover (Tirén & Beckholmen, 1992). Another approach in many-fracture analysis considers fracture populations as networks, and focuses on their pattern of intersection in terms of lengths, angle and frequencies, mutual dislocations and shape and size of fracture-bounded areas, from which the stress field can be quantified (Ramsay & Huber, 1987). This approach is commonly known as topological analysis, where the location and relationships of individual features are considered (Fig. 3.A). Intersecting lineaments define rock blocks of various scales identifiable by DTA (Tirén & Beckholmen, 1992), an important feature of, for example, shear zone regimes (Sylvester, 1988).

Lithological structures within rock units may also be represented by DEMs and their description might help clarifying geological and structural relationships, but these features can also obscure tectonic structures. Secondary geomorphological indicators of tectonic influence are dislocations of geomorphic surfaces, such as erosional surfaces and alluvial plains, and these surfaces are the result of uplift, subsidence or tilting. Fluvial networks are the most common indicators: the drainage network pattern often reflects the regional or even the local tectonic framework (Deffontaines & Chorowicz, 1991). In the absence of further morphological evidence, these morphological features can be distinguished from features of non-tectonic origin with the use of geological information. Geological data from various sources, such as geological maps, geophysical data, remotely sensed images and field measurements also have to be incorporated in the GIS database.

4.2 Feature recognition and parameter extraction: a GIS framework for digital tectonic geomorphology

In order to maximise the tectonic geomorphology information obtained from a DEM, a sequential modelling scheme is applied (Jordan & Csillag, 2001). The design of the modelling scheme has been based on the following considerations:

- the objective is the quantitative geometric characterization of landforms;
- the objective is providing reproducible outputs;
- analysis proceeds from simple to the more complex analysis;

- outputs from modelling steps are controlled by input data and parameters;
- the procedure integrates a wide-range of available methods;
- multi-source information is integrated in the database;
- DTA is implemented in a GIS environment.

The components of digital tectonic geomorphology implemented with GIS in this study are (1) numerical differential geometry, (2) digital drainage network analysis, (3) digital geomorphometry, (4) digital image processing, (5) lineament extraction and analysis, (6) spatial and statistical analysis and (7) DEM-specific digital methods such as shaded relief models, digital cross-sections and 3D surface modelling. Analysis of multi-source data uses GIS techniques in this study. Fig. 3.B illustrates the procedure of recognition and extraction of fault-related landforms and their tectonic interpretation. Based on the study of landforms related to faults (see previous section), geomorphological characteristics are translated into mathematical and numerical algorithms. Topographic features represented by DEM of test areas are extracted and characterised by DTA (Fig. 3.B). Verification of structural implications uses other data sources in GIS. The development and application of numerical methods in a GIS environment are discussed below.

The analysis presented in this study proceeds from simple univariate elevation studies, through differential geometric surface analysis and drainage network analysis, to the multivariate interpretation of results using GIS technology (Fig. 4). Reproducibility of morphological analysis is achieved by the application of numerical data processing algorithms. Each modelling module (Fig. 4) has a set of defined input parameters. Subsequent steps are based on output of previous terrain models. Prior to the spatial analysis of each terrain attribute, its histogram is studied for systematic error and statistical properties such as multi-modality. Histograms are interpreted in terms of morphometry and used for classification of terrain data. Image stretching for enhancement of visual interpretation is also based on histograms.

4.3 Digital geomorphometry analysis

Elevation and derivatives of altitude, called point attributes, form the bases for geomorphometric study of landscape (Evans, 1972). The five basic parameters calculated are elevation, slope, aspect, profile and tangential curvatures (Evans, 1980). For example, a peak in the elevation histogram that corresponds to a sharp increase in its cumulative graph indicates a flat planation surface. A peak in the aspect frequency histogram or a large petal in the rose diagram shows that a larger number of pixels have aspect in a preferred orientation. Where these pixels form one or more connected areas on hill-sides with linear boundaries, a tectonic origin can be inferred.

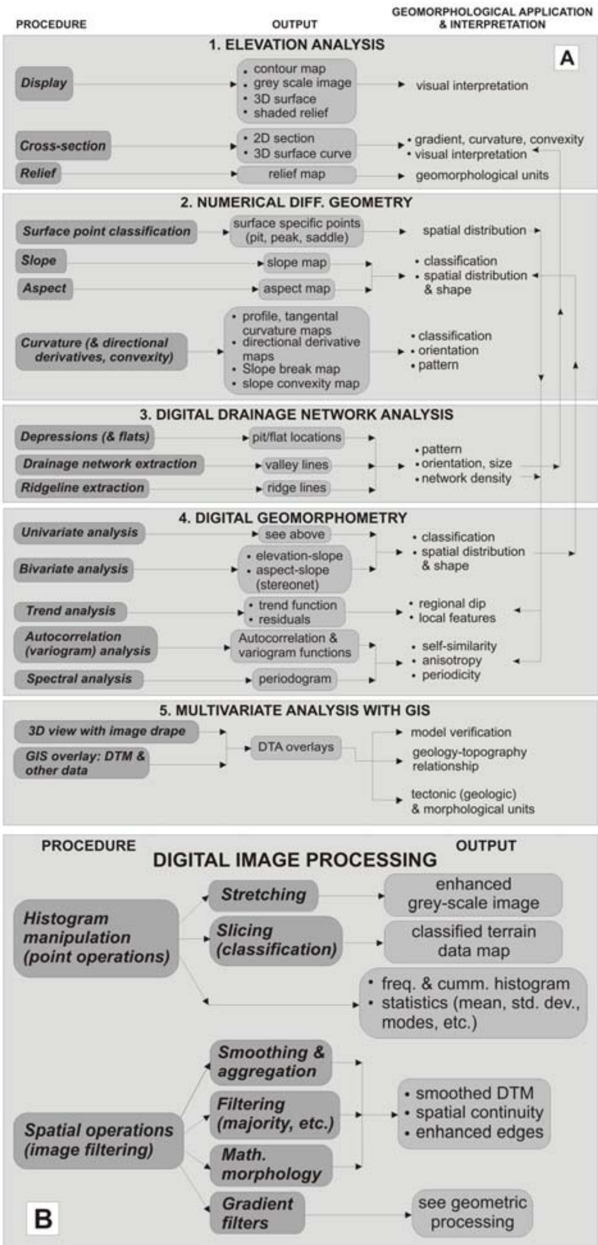

Figure 4. A GIS modelling scheme for systematic digital tectonic geomorphology analysis. A. Flow chart of numerical methods. B. Image processing methods applied to terrain models (Jordan & Csillag, 2003).

Next in the analysis, bivariate and multivariate relationships between variables (derivatives and moments) are studied (Fig. 4.A). Slopes and aspects are plotted in a stereonet to study if steep slopes have preferred orientations, as steep slopes with the same orientation may be associated with faulting.

Finally, terrain ‘texture’ is conveniently studied by means of spatial statistical methods and network analysis techniques (Fig. 4.A). Trend analysis, autocorrelation and spectral analysis are carried out for the entire area or specific parts of the area (e.g., basins only). The trend surface is fitted to all data points or to surface specific points, such as peaks or valley lines, to estimate regional dips, as the tilt of an area is often related to tectonic movements.

Autocorrelation, spectral and wavelet analyses reveal lineation (anisotropy) and periodicity of a landscape due to faulting or folding (**Paper V**). The autocorrelation property can also be studied by calculating semi-variograms in different directions (Curran, 1988). Problems emerge from the fact that valleys often curve and there are confluences down-valley and that ridge height and spacing may vary (Evans, 1972). In order to overcome the problem of converging ridges of alternating height, analysis in this study is limited to valley lines only. Valley lines were defined by the digital drainage network identification method described in **Paper VI**.

4.4 Digital image processing of terrain data

DEMs and each terrain attribute map derived by DTA can be viewed as raster images and hence be processed using digital image processing procedures to increasing the apparent distinction between features in the scene (Sauter et al., 1989; Fabbri, 1984; Woldai and Bayasgalan, 1999) (Fig. 4.B). Point operations of histogram slicing and contrast stretching have basically two applications. Slicing of an image histogram by dividing pixel values into specified intervals has been used here to display discrete categories of elevation, slope, aspect and other terrain attributes (Lillesand & Kiefer, 1994, Fig. 4.B). Aspect data have been displayed and analysed by means of rose diagrams and circular statistics (Wells, 1999; Baas, 2000). Areas of uniform geometric attribute were then examined for area distribution, continuity and shape whilst contrast stretching was performed on grey-level images to enhance visual interpretations of the terrain models (Lillesand & Kiefer, 1994) (Fig. 4.B).

Spatial operations of gradient filters are discussed in **Paper II**. In this study, local operators of gradient filters were applied only to terrain data and not to grey-scale images in order to preserve the original geometric information in terrain models. In this way, edges (valleys, ridges and slope-breaks) were extracted on geometric bases. For example, slope-breaks were recognised as edges if change in slope in the gradient direction (profile curvature) exceeded a predefined threshold. Low-pass filters such as median and average filters were used to reduce noise and emphasise areas of similar topographic attributes. For example, aspects calculated from a smoothed DEM could reveal a hill slope of uniform aspect related to faulting (**Paper IV**). The enhanced images were then used for analysis of shape, spatial distribution and for interactive lineament extraction.

Hill shading methods producing relief maps are peculiar to DEM images and are fundamental for morphostructural analysis (Simpson & Anders, 1992). Hill shading increases the contrast of very subtle intensity variations of an image, much more than contouring or pseudo-colour representation do (Drury 1987). Onorati et al. (1992) used multi-image operation of false colour composites (i.e. Red, Green, Blue colour components) in morphotectonic studies to simultaneously analyse three DTMs. In the present study colour-separated geological maps and remotely sensed images were combined with a shaded relief map. These in turn were draped on the three-dimensional view of the study areas to enable the study of the relationship between geology and morphology.

4.5 Spatial analysis of lineaments

Lineaments are defined as straight linear elements visible at the Earth's surface and which are the representations of geological and/or geomorphological phenomena (Clark & Wilson 1994). In geomorphometric analysis, a linear feature can have geometric origin only and represent a change in terrain elevation, such as a valley or ridgeline, slope-break or inflex line. In terms of digital modelling, a lineament is a continuous series of pixels having similar terrain values (Koike et al., 1998). Each line is characterised by length and orientation in this study (**Paper III**). Distribution and relationships among lines are described by length and orientation frequencies calculated for the entire area or a sub-area. In the present case studies, lineament intersection density, total length per area and frequency per area have been analysed. Two lineament extraction procedures have been applied in this study: (1) an automatic procedure using digital drainage extraction to identify valley and ridgelines and (2) interactive lineament interpretation of terrain models (**Paper III**). Wavelet analysis has been used to identify and measure periodicity and location of lineamant zones in the study area (**Paper V**).

5 Applications

5.1 Káli Basin, Hungary

The histogram of grid elevations shows systematic error in the DEM as pikes corresponding to the original contour lines at 10 m intervals (Fig. 5.B). Grey-scale elevation image shows a general increasing elevations from SW to NE indicating that the whole area is uniformly tilted towards the SW (Fig. 5.A). Cross-section across the whole basin in NE-SW direction also shows the general dip of the area to the SW (Fig. 5.D).

Lineaments intersecting the entire basin in the NE-SW direction are seen in the shaded relief image (b in Fig 5.C). The western boundary of basin is marked by a series of volcanic cones aligning in a narrow N-S zone. N-S slope edges in the same direction are sharp (d in Fig. 5.C). A third set of lineations consists NW-SE striking slope-break, ridges and valleys cross-cutting the study area (c in Fig. 5.C). Six-time vertical DEM exaggeration reveals a number of closed depressions in the basin area (D1 and S1 in Fig. 5.E). Asymetric depressions are marked 'd' and 'h' in Figs 5.E and 5.C, respectively. Note that closed depressions are artefacts resulting from spline interpolation error.

Due to large systematic errors in the aspect derived from the original spline DEM, aspect calculations discussed below used a new DEM interpolated by TIN from contour lines (**Paper IV**). Systematic error shown as peaks in the histogram at factors of 45° azimuth is due to numerical derivation over a rectangular grid (Fig. 6.A). Aspect rose diagram calculated only for hilly areas with slopes more than 1° (Fig. 6.B) displays two major directions: one facing SE (120°) and another pointing to the opposite direction (300°). The pronounced lack of land facets facing N and S shows that E-W oriented morphological features are not characteristic to the area. Based on the rose diagram (Fig. 6.B), aspects were divided into two classses between 110° and 160°, and between 290° and 340°, respectively. The two aspect frequency peaks correspond to the flanks of the northern and southern hill ranges running in the NE-SW direction (Fig. 6.C). Related areas are elongated and limited by sharp linear edges. Slopes of uniform aspect commonly have N-S and NW-SE edges.

Uniform slope is expected where contour lines are equidistant in the original map. On the basis of cumulative percentage area-slope curve (**Paper II**) areas have been classified plain, hilly and mountainous where slope is ≤1°, 1°-3° and 3°<, respectively. Slope map displayed in these classes shows sharp edges of the Káli Basin in the NE-SW, NW-SE and N-S directions.

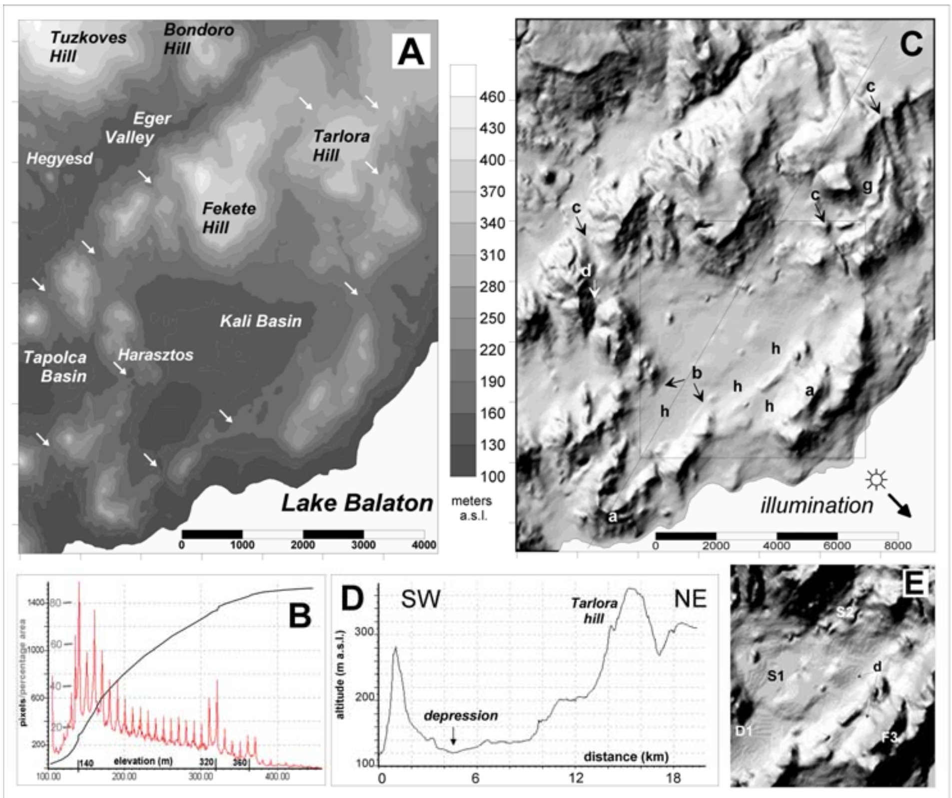

Figure 5. A. Grey-scale elevation image. Arrows indicate saddle points. B. Light curve: elevation histogram; heavy curve: cumulative percentage area curve of elevation. C. Shaded relief model for the Káli Basin. Letters highlight specific features. Black line: cross-section trace in Fig. D. Rectangle: area in Fig. E. D. Digital cross-section. Note strong vertical exaggeration. E. Shaded relief image of the basin (20x vertical exaggeration). Key: D1: main depression; S1 and S2: S-shaped depressions; F3: Permian folds; d: asymmetric depressions; k: short, deep valley.

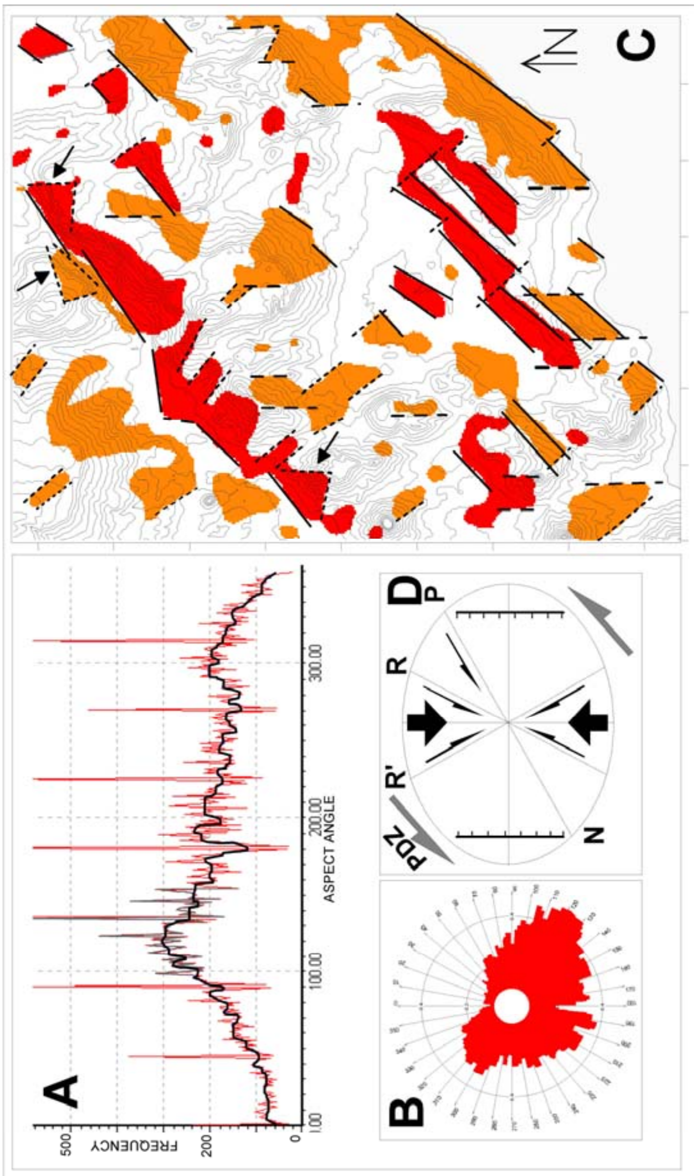

Figure 6. A. Histogram of aspects for slopes>1°. Solid line is the five-term median smooth of diagram. B. Rose diagram for the smoothed aspect frequencies. C. Classified aspect image after 11x11 majority filtering. Dark and light shaded areas have aspects between 290° and 340°, 110° and 160°, respectively. Lines are drawn to highlight edges of hill slopes. Solid lines: NE-SW direction; dashed lines: N-S direction; Dotted lines: NW-SE direction. 20 m elevation contours are also shown. D. Simple shear model for the basin (after Dudko, 1999).

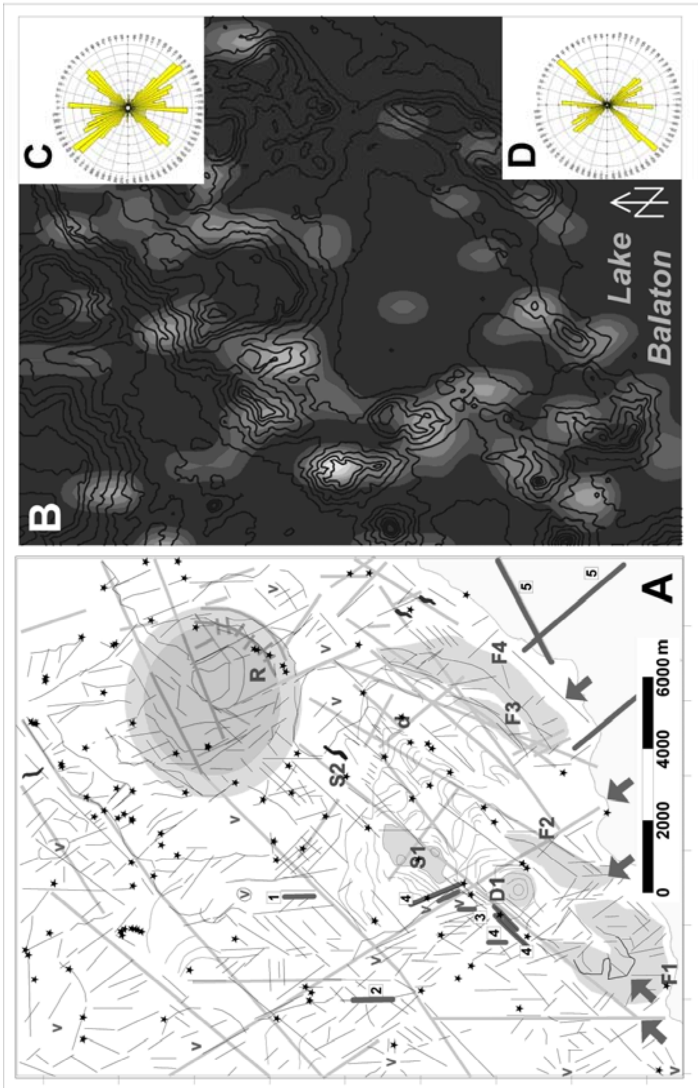

Figure 7. A. Lineament map. Black lines are line features (valleys, ridges and slope-breaks) digitised from terrain images. Grey polygons emphasise major morphological features. Thick light-grey lines show fracture lines shown in geological maps. Thick dark-grey lines show fracture lines recognised by other studies. Asterisks are springs. Large arrows show zones of springs. Key: D1: main depression; S1 and S2: S-shaped depressions; F1-F4: fold features; R: ring structure; d: asymmetric depressions; v: volcanic features. B. Lineament density map for N-S (N±10°) lineaments. Light tones indicate higher densities. Topographic contours are also shown. C. and D. Frequency and length rose diagrams of lineaments, respectively.

The DEM, smoothed twice with 3x3 moving average filter, has been the input for 2nd order derivatives. Tangential curvature map displays valleys and ridges as white and black lines corresponding to positive and negative values, respectively (**Paper II**). The major NE-SW, NW-SE and N-S directions are apparent. Second-order derivatives in the X direction revealed prominent N-S linear features. The mixed second derivatives show NE-SW and NW-SE running linear features representing valleys, ridges and slope breaks.

Plotting average slope against elevation displays peaks at factors of ten metres and pits in between (**Paper II**). Coherent with the elevation histogram analysis, the DEM is characterised by flats around original contours and steep slopes between yielding the wavy patterns observed in the derivative maps. The plot of average slope against aspect for hilly areas (slope>1º) shows if slopes tend to be steeper in certain directions. Results show that higher densities of gradients are found in the NW and SE directions, NE and SW directions and the E and W directions (**Paper II**). Scatter is higher in the southerly directions. The steepest slopes are associated with hill slopes in the NW and SE directions. Together with the aspect-average slope plot and stereonet, it can be deduced that the NW-SE, E-W and NE-SW directions not only represent higher frequencies of aspect orientations (see Fig. 6.B) but they are also associated with greater slopes.

The regional tilt of the area was analysed by linear trend surface fitting to the whole basin area, to its parts only or to surface specific points (**Paper II**). An overall dip of about 1° to the SE is apparent if the trend plane was fitted to basin areas only (below 140 m a.s.l. and defined by slope ≤ 1%). The hence obtained orientation is consistent with the SW tilt found in elevation analysis. The same tilt was found by field measurements on Tertiary sea-shore sediments.

Autocorrelation analysis was performed after extraction of a linear trend and subsequent 5x5 average smooth of the DEM in order to study lineation (anisotropy) and periodicity due to faulting or folding (**Paper II**). The main anisotropy direction was parallel to the main NE-SW lineation orientation found by the previous DTA procedures.

Lineaments defined by sharp grey-scale edges in the above terrain images were digitised on screen (**Paper III**). According to the rose diagram of lineaments (Fig. 7.A, C and D), all linear features are oriented in one of the three main directions, i.e., (1) NE-SW, (2) N-S, and (3) NW-SE. Valleys, ridgelines and slope-breaks corresponding to the three directions cross-cut the whole study area indicating the regional origin of these features. The three major orientations are consistent with the findings above. Since most of the valleys with these orientations cross-cut different rock types in the area they cannot be related to bedding only. Digitally extracted drainage network and segment orientations were also analysed (**Paper II**). Low scatter of segments around these directions implies that related valley lines are well-defined.

The binary image of extracted channel network (**Paper VI**) was used in this study to create an artificial elevation model of valleys (**Paper II**). Single-pixel wide channel lines were widened with morphological dilatation using a 3x3 structuring element (Gonzalez & Woods, 1993). Background pixels were assigned zero and channel pixels received a constant value and the resulting three pixel-wide drainage lines were then smoothed with a 3x3 average filter. The resulting valley network had uniform depth and it was used for analysis of periodicity. Variogram in the E-W direction for the drainage-based artifical DEM displayed periodic shape (**Paper II**). This suggests that the N-S running valleys are periodic with about 3000 m separation on average. This periodicity was also confirmed by wavelet analysis (**Paper V**). The investigation of the periodogram calculated for the same DEM revealed that large-scale valleys have a clear orientation in the NE-SW direction.

Finally, lineaments were extracted from a 1:100,000 DEM (100x100 m resolution) covering half of the Balaton Upland in order to check if morphological features found in the Káli Basin are also present at a regional scale. The major lines in the three principal directions are all present in the smaller scale DEM (**Paper III**). NE-SW and NW-SE running linear valleys are predominant at the regional scale and can be followed far beyond the study area.

The gravity anomaly map of the area displays a pronounced NE-SW anisotropy (Vertessy & Kiss, 1995) (**Paper III**). Lineaments extracted from the map using digital edge detection methods (Vertessy & Kiss, 1995) coincide with lineaments identified by the terrain modelling in this study. Previous studies (e.g. Nemeth & Martin, 1999) in the Kali Basin have recognized N-S orientations of volcanic structures such as dykes associated with faults ('1, 2, 3' in Fig. 7.A). Digitised lineament maps of two remotely sensed image analysis studies using aerial photographs (Csillag, 1989) and satellite images (Marsi & Sikhegyi, 1985) also show a fair correspondence with the DEM-based lineament map. In addition, springs align along some of the identified morphological lineaments and known fault lines (Fig. 7.A).

5.2 North-western Greece

For the digital tectonic geomorphology analysis of north-western Greece shaded relief models and differential geometry models such as aspect, slope and curvature models were used. Morphological cross-sections were calculated perpendicular to significant fault lines. Satellite images were draped over the DEM to create three-dimensional views. Lineaments observed in shaded relief, aspect, slope and curvature models were manually digitised on the screen. Notwithstanding the relatively poor resolution of the DEM used, the results provide an acceptable regional morphotectonic view of the study area.

The histogram of the grid elevation shows a systematic error in the DEM as small pikes corresponding to 50 m intervals resulting from the primary grid cell processing of the GLOBE model. Pikes at 10 m and at 110 m are related to the topographically low coastal regions in Epirus and Macedonia and to the Larissa and Karditsa basins in Thessaly, respectively (Fig. 2.B).

The relief map, which is the quotient of the local standard deviation and average elevation, shows high relief variability values in coastal regions and in highly deformed areas as Epirus and along the borders of the Larissa and Karditsa basins. Shaded relief models, which were smoothed by 3x3, 5x5, 7x7, 11x11 and 21x21 average filters, have been displayed at 4 different illumination angles at 45° interval (Fig. 8.A). The lineament rose-diagram of the shaded relief map shows a subtle trend to the north and east, whilst there are few lineaments with NE-SW to WSW-ENE orientations (**Paper I**).

A lineament map of the aspect analysis has been constructed on the basis of the presence of fault facets, ridge cut-offs and uniform dips of hill slopes. Eight classified aspect maps were calculated from a DEM smoothed with a 7x7 average filter. Subsequently, the classified aspect maps were filtered with a 5x5 pixel majority matrix to reduce noise and increase interpretability. For example, Fig. 8.C illustrates an overlay map of two classified aspect images for the angles between 280º and 350º, one of which was filtered with a 3x3 majority matrix and the other with a 5x5 majority matrix. Fig. 8.C illustrates the differences obtained when using different majority filters, and shows that the choice of majority filter to obtain an optimal result is a matter of trial and error. On the other hand, the map in Fig. 8.C illustrates that corresponding areas are elongate and bounded by sharply defined linear edges in the NE-SW direction. In general, the resulting lineament map of the aspect analysis illustrates two pronounced lineament orientations trending NW-SE and NE-SW (Fig. 8.B).

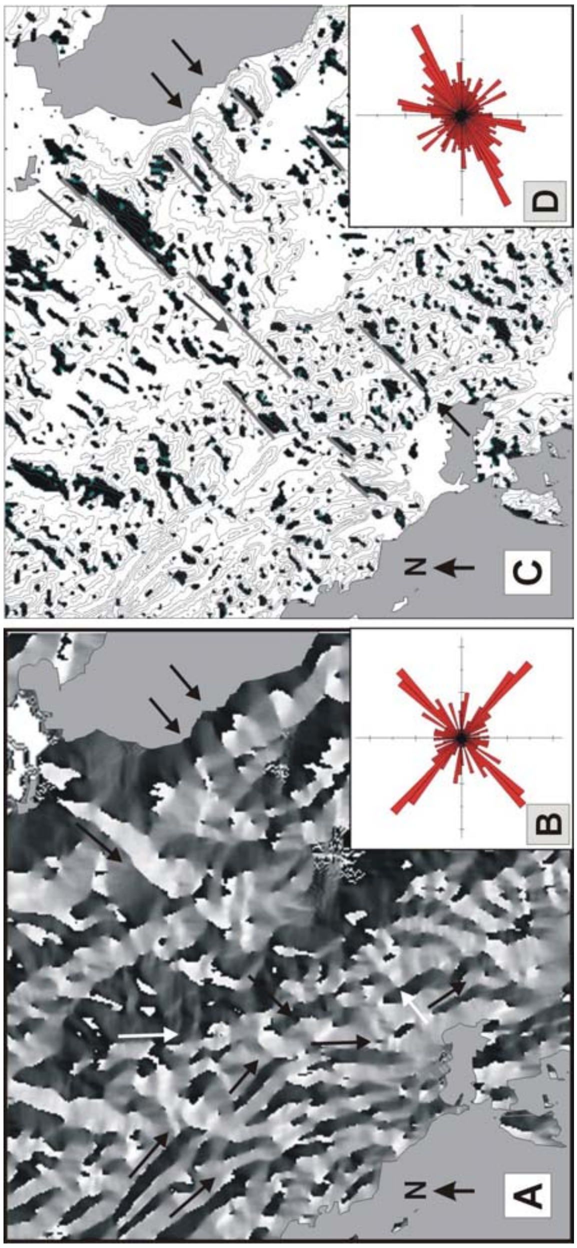

Figure 8. Grey-scale aspect image calculated from DEM smoothed with 7x7 moving average kernel. Arrows indicate main lineaments. B. Rose diagram of lineaments identified in the aspect model. C. Classified aspect image for angles between 280° and 350° after majority filtering. Dark and light tones show 3x3 and 5x5 majority filtering, respectively. Arrows and lines indicate main lineaments in the NE-SW direction. D. Rose diagram of lineaments identified in the satellite images.

Linear patterns in slope and curvature images, which could be interpreted as slope breaks, have been used as criteria to construct a lineament map. This construction involved two steps. Firstly, the slope map, smoothed with a 5x5 majority matrix, was classified at <4º, 4º-8º, 9º-11º and >12º angles, these values being based on slope breaks in the cumulative slope histogram. Next, the calculation of tangential curvature maps and profile curvature maps was performed on a DEM, smoothed twice with a 5x5 moving average filter.

The trend of the lineaments on the slope and curvature maps is, in general, NNW-SSE to NW-SE and with few numbers of lineaments in other directions. Most of the lineaments are located in Epirus and in the Olympos-Ossa mountain range to the east of Thessaly. The mixed second-order derivative map (Fig. 9.A) illustrates a series of significant slope-breaks, which align along a series of NW-SE trending lineaments in Epirus.

The frequency (Fig. 8.D) and length rose diagrams of the lineaments interpreted from satellite images illustrate a prominent NE-SW lineament orientation. Other but less prominent lineament orientations comprise NNE-SSW and NW to NNW lineament trends. There is also a fourth, less abundant set of lineaments in the E-W direction.

To test whether the results of the DTA provide information on the geologic structure of the investigated area, the lineaments were compared with the geology. Especially in Epirus, the high number of NW-SE striking folds and thrusts are easily recognised in the aspect map (Figs 8.B and 8.C), as well as on slope and curvature maps. The crosscutting fault systems of the Souli, Thesprotiko, Konitsa and Aliakmon faults and fault zones are recognised from the shaded relief and lineament maps of aspect models (Figs 2.B, 8.B and 8.C).

The morphological cross-sections (Figs 9.B and 9.C) and perspective views of the Kozani Basin and the Pindos Mountains illustrate the geology associated with the sudden topographical changes identified by the DTA: The Konitsa fault and the interference zone of the Thesprotiko and Kastaniotikos fault zones coincide with the slope breaks in the morphological cross-sections of Fig. 9.C and the jump in (tectono-) stratigraphic level along the faults gives the relative vertical motion direction.

The WNW-ESE striking Kastaniotikos fault zone, which is easily recognised on the geologic map (**Paper I**), is not well recognised by DTA. This probably results from the fact, that the NW-SE striking folds of the southern Pindos mountains are not cut off to form fault facets, but form more gentle drag folds along the WNW-ESE striking Kastaniotikos fault zone. Moreover, the elevation on both sides of the fault zone is rather comparable, although the lithology is different. Thus, no large topographic changes can be identified.

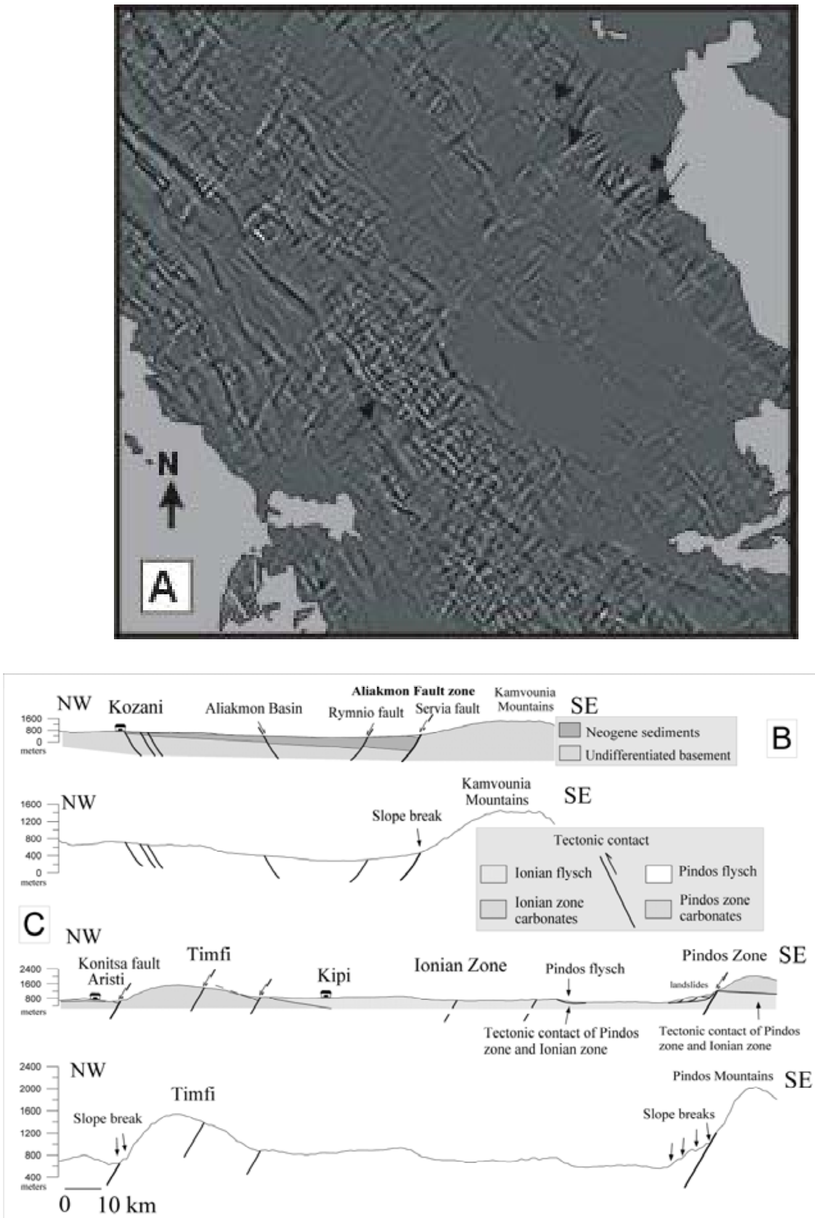

Figure 9. A. Grey-scale image of mixed second-order derivatives. Arrows and lines indicate main lineaments in the NE-SW direction. B. and C. Geological and morphological cross-sections through the Kozani region (based on Doutsos and Koukouvelas, 1998) and Pindos Mountains, respectively. For location of sections see Fig. 2.A.

6 Conclusions

- Basic geometry of faults and associated morphological features were studied, and topographic parameters necessary to recognise and characterise them were identified. Numerical methods to extract these parameters were developed and applied in two study sites. (**Paper I**)

- DTA in the described way (1) gives reproducible results and (2) it provides quantitative landform description. Reproducibility is an improvement to traditional morphological analysis and visual image interpretation. Quantitative geometric characterisation of landforms based on DEM analysis is an advantage if compared to digital processing of remotely sensed images or analysis of grey-scale terrain images. (**Paper I**)

- Evan's (1972, 1980) general geomorphometric method was further developed and adopted to digital tectonic geomorphology. The five basic geometric attributes (elevation, slope, aspect, profile and tangential curvatures) were complemented with the automatic extraction of surface specific points and ridge and valley lines in this study. Evan's univariate and bivariate methodology was extended with texture (spatial) analysis methods such as trend, autocorrelation, wavelet, variogram and spectral analysis and network analysis. (**Papers II, V and VI**)

- Digital image processing techniques of spatial operations and histogram manipulations were integrated in the GIS procedure and applied at almost all stages of digital tectonic geomorphology analysis in the case studies (**Papers I, II and III**).

- A method for the extraction of high-density drainage and ridgeline extraction was developed (**Paper VI**). It was used to create an artificial DEM to overcome problems of periodicity analyses using original topographic data (**Paper II**). The advantage of digital drainage extraction over traditional lineament extraction methods is that identified lineaments are directly related to the geometry and physics of the terrain and are independent of manipulations on grey scales of images. The extracted network is fully connected and it reflects the true nature of related valleys, their spatial distribution, density and intersections. For these reasons, digital drainage network extraction methods are found superior to lineament extraction methods using grey-scale images. Slope-breaks, however, cannot be identified with this method and profile curvatures together with slope maps were used for their spatial analysis (**Paper III**).

- A slope aspect generalisation method based on TIN interpolation over ridgelines was developed and applied to the Káli Basin DEM (**Paper IV**). Aspect analysis proved to be a powerful technique to identify slopes of uniform aspect with linear edges on both local and regional scales in this study (**Papers II, III and IV**).

- Wavelet analysis was used to identify periodicy in the terrain due to faulting (**Paper V**). Wavelet analysis proved superior to Fourier analysis because it is sensitive to sudden changes in a DEM. It gives not only the magnitude of the change but also its location. Wavelet analysis of N-S oriented lineaments in the Káli Basin confirmed the existence of periodicity that was also found by directional variograms.

- It was shown that geomophological setting of the Káli Basin is influenced by past tectonics, being most of the faults recognisable as regional morphological features in the regional scale DEM (**Papers II and III**).

- Comparison of the results of the DTA with the known geology from north-western Greece indicates that the major faults and fault systems correspond (in most cases) to clear lineaments. Many more lineaments are recognised, however, than faults have been identified in the field. The limited field check available was very successful, and it is likely that other lineaments that were not visited can be readily identified in the field. Thus, DTA of an area in the proposed way forms a useful and time-saving tool to identify major and minor structures covering large areas (**Paper I**).

References

Aubouin, J., 1957, Essai de corrélation stratigraphique de la Grèce occidentale. Bull. Soc. Géol. France, 7: 281-304.

Baas, J. H., 2000, EZ-ROSE: a computer program for equal-area circular histograms and statistical analysis of two-dimensional vectorial data, *Computers and Geosciences*, **26**, 153-166.

Bonneau, M., 1984. Correllation of the Hellenic Nappes in the south-east Aegean and their tectonic reconstruction. In: Dixon, J.E. and Robertson, A.H.F. (eds.) The geological evolution of the eastern Mediterranean. Geol. Soc. Lond. Spec. Pub. 17: 517-527.

Bornovas, I., Rontogianni-Tsiabaou, T. 1984. Geological map of Greece. 2nd edition, 1:500.000, Institute of Geology and Mining exploration, Athens.

Budai, T., Csaszar, G., Csillag, G., Dudko, A., Koloszar, L., and Majoros, G. 1999, Geology of the Balaton Highland. Geological Institute of Hungary, Budapest. (in Hungarian with English summary).

Csillag, G., 1989, Lineament map of the Balaton Highland. Research Report, Orszagos Foldtani es Geofizikai Adattar, Hungary.

Clark, C. D., and Wilson, C., 1994, Spatial analysis of lineaments. *Computers and Geosceinces*, **20**, 1237-1258.

Clews, J.E., 1989, Structural controls on basin evolution: Neogene to Quarternary of the Ionian zone, Western Greece. Journal of Geological Society London, 146 (3): 447-457.

Curran, P. J., 1988, The semivariogram in remote sensing: an introduction. *Remote Sensing of Environment*, **24**, 493-507.

Deffontaines, B., and Chorowicz, J., 1991, Principles of drainage basin analysis from multisource data: Application to the structural analysis of the Zaire Basin. *Tectonophysics*, **194**, 237-263.

Doornkamp, J., C., 1972. Trend-surface analysis of planation surfaces, with an east African case study. In: Chorley, R. J. (editor), 1972. Spatial Analysis in Geomorphology. Methuen, London, pp. 247-281.

Doutsos, T., Koukouvelas, I., 1998. Fractal Analysis of normal faults in northwestern Aegean area, Greece. Journal of Geodynamics, Vol. 26, No. 2-4, 197-216.

Drury, S. A., 1987, *Image Interpretation in Geology* (London: Allen and Unwin).

Dudko, A., 1999. Structural geology of the Balaton Highland. In: Budai T., Csaszar G., Csillag G., Dudko A., Kolosszar L. and Majoros G: Geology of the Balaton Highland. - Vol. 197 of the Occasional Papers of the Geological Institute of Hungary, Budapest, pp. 133-144, 225-235 (in Hungarian and English summary).

Evans, I. S., 1972, General geomorphometry, derivatives of altitude, and descriptive statistics. In: *Spatial Analysis in Geomorphology* edited by R. J. Chorley. (London: Methuen), pp. 17-90.

Evans, I. S., 1980, An integrated system for terrain analysis for slope mapping. *Zeitschrift für Geomorphologie*, **36**, 274-295.

Fabbri, A. G., 1984, *Image Processing of Geological Data*. (New York: Van Nostrand Reinhold).

Fraser, A., J., Huggins, P., Cleverley, P., and Rees, J., L., 1995. A satellite remote-sensing technique for geological horizon structure mapping. SEG Annual Meeting, Expanded Technical Program Abstracts with Biographies.65. pp. 134-137. Society of Exploration Geophysicists. Tulsa, OK, United States.

Frisch, W. (ed), 1997, Tectonic Geomorphology. In *Proceeding of the Fourth Int'l. Conf. on Geomorphology, Z. Geomorph. N. F., Suppl.-Bd.*, **118**.

Goldsworthy, M., Jackson, J., 2000. Active normal fault evolution in Greece revealed by geomorphology and drainage Patterns. Geological Society, London, Special Publication, 157: 967-981.

Gonzalez, R. C., and Woods, R. E., 1993, *Digital Image Processing* (New York: Addison-Wesley Publishing Company).

Guth, P., L., 1997. Tectonic geomorphology of the White Mountains, eastern California. In: Geological Society of America, 1997 annual meeting, Abstracts with Programs. 29, p. 235. Geological Society of America (GSA). Boulder, CO, United States.

Harrison, J., M. and Lo, C, 1996, PC-based two-dimensional discrete fourier transform programs for terrain analysis. Computers and Geosciences, 22: 419-424.

Hobbs, W. H., 1912, *Earth features and their meaning* (New York: Macmillian Co).

IGRS-IFP, 1966. Étude géologique de l'Épire (Grèce nord-occidentale). Editions Technip., Paris. 306 p.

Jordan, G. and Csillag, G., 2001. Digital terrain modelling for morphotectonic analysis: a GIS framework. In: H. Ohmori (ed), 2001. DEMS and Geomorphology. Special Publication of the Geographic Information Systems Association, **1**: 60-61. Nihon University, Tokyo.

Jordan, G. and Csillag, G., 2003. A GIS framework for morphotectonic analysis - a case study. Proceedings, 4th European Congress on Regional Geoscientific Cartography and Information Systems, 17-20 June, 2003, Bologna, Italy. Proceedings, **2**: 516-519. Regione Emilia-Romadna, Servizio Geologico, Bologna.

Keller, E., A. and Pinter, N., 1996, *Active Tectonics: Earthquakes, Uplift and Landforms* (New Jersey: Prentice Hall).

Koike, K., Nagano, S., and Kawaba, K., 1998, Contruction and analysis of interpreted fracture plnaes through combination of satellite-image derived lineaments and digital elevation model data. *Computers and Geosciences*, **24**, 573-583.

Lillesand, T. M., and Kiefer, R. W., 1994, *Remote Sensing and Image Interpretation* (New York: Wiley Co.).

Marsi, I., and Sikhegyi, F., 1985, Application of satellite images and aerial photographs for bauxite exploration. *Foldtani Kutatas*, **28**, 65-70 (in Hungarian).

Nemeth, K., and Martin, U., 1999, Small-volume volcanoclastic flow deposits related to phreatomagmatic explosive eruptive centers near Szentbekalla, Bakony-Balaton Highland Volcanic Field, Hungary: Pyroclastic flow or hydroclastic flaw? *Foldtani Kozlony*, **129**, 393-417.

Onorati, G., Poscolieri, M., Ventura, R., Chiarini, V., and Crucillá, U., 1992, The digital elevation model of Italy for geomorphology and structural geology. *Catena*, **19**, 147-178.

Prost, G. L., 1994, *Remote sensing for geologists. A guide to image interpretation* (Amsterdam: Gordon and Breach Science Publishers).

Ramsay, J., G. and Hubert, M., I. 1987, The techniques of modern structural geology. Vol. 2. Folds and Fractures. Academic Press, London.

Salvi, S., 1995, Analysis and interpretation of Landsat synthetic stereo pair for the detection of active fault zones in the Abruzzi Region (Central Italy). *Remote Sensing of. Environment*, **53**, 153-163.

Sauter, D., De-Frainpont, P., and Ruhland, M, 1989, Image processing applied to digital elevation models; a useful tool for structural studies. In: *Proceedings of the Thematic Conference on Geologic Remote*

Sensing, **7**, 1073-1080. (Ann Arbor: Environmental Research Institute of Michigan).

Siegal, B. S., and Gillespie, A. R., 1980, *Remote Sensing in Geology* (New York: John Wiley and Sons).

Simpson, D. W., and Anders, M. H., 1992, Tectonics and topography of the Western United States - an application of digital mapping. *GSA Today*, **2**, 118-121.

Skourlis, K. and Doutsos, T., 2003, The Pindos Fold-and-thrust belt (Greece): inversion kinematics of a possible continental margin. Int. J. Earth. Sc. (in press).

Sylvester, A., 1988, Strike-slip faults. *Bull. Geol. Soc. Am.*, **100**, 1666-1703.

Tirén, S. A., and Beckholmen, M., 1992, Rock block map analysis of southern Sweden. *GFF*, **114**, 253-269.

Trunko, L., 1995, *Geology of Hungary* (Berlin: Gebruder Borntraegen).

Vertessy, L., and Kiss, J. 1995, Report on the environmental investigations in 1993. Research Report, Eötvös L. Geophysical Institute, Budapest.

Wells, N. A., 1999, ASTRA.BAS: a program in QuickBasic 4.5 for exploiting rose diagrams, circular histograms and some alternatives. *Computers and Geosciences*, **25**, 641-654.

Way, D., S., 1973. Terrain Analysis. A Guide to Site Selection Using Aerial Photographic Interpretation. Dowden, Hutchinson & Ross, Inc., Pennsylvania.

Woldai, T., Schetselaar, E. M. and Haile Mariam, M., 2000, Structural analysis of the Asmara area, Erithrea: using remote sensing and GIS. In: 2000 Proceedings of the 28th International Symposium on Remote Sensing of the Environment: information for sustainable development, March 27-31 2000 Cape Town, South Africa. Cat. 5. pp. 2-7.

Woldai, T. and Bayasgalan, A., 1999, Strike-slip duplexes and neotectonics within the Gobi-Altay range, Mongolia. International Geological Symposium on east-Asia (IGSEA), October 13-15, 1999, Ulanbatar, Mongolia.

Abstract in Swedish

Tektoniska rörelser längs förkastningar uttrycks ofta genom karaktäristiska geomorfologiska former såsom långsträckta dalar, ryggar och sluttningskanter, likformig riktning och branta sluttningar, tektoniska sänkor och lutande terrängavsnitt. Digitala höjdmodeller (DEMs) som använder geomorfometriska metoder gör det möjligt att kvantifiera sprickor och karaktärisera morfotektoniken i landskapet.

Målet med avhandlingen är att utveckla numeriska metoder och en konsekvent GIS metodik för tektonisk geomorfologi och att testa dessa i provområden. Baserat på studier av landformer associerade med förkastningar, översätts geomorfologiska karaktärer till matematiska och numeriska algoritmer. Höjdelement i testområden, representerade av DEM, extraheras, beskrivs och tolkas strukturgeologiskt och geomorfologiskt. Metodiken är baserad på generell geomorfometri. I denna studie har de grundläggande geometriska egenskaperna (höjd, sluttning, riktning och kurvatur) kompletterats med automatisk extraktion (självextraktion) av dal- och höjdlineation samt ytspecifika punkter. Evans univariata och bivariata metodik av allmän geomorfometri är utökad med analyser av yt- och rumsstruktur såsom geografisk riktning (trend), autokorrelation, spektral, wavelet och nätverkanalyser (förgreningsanalyser). Digital terrängmodellering utförs genom att använda en kombination av (1) generell geomorfometri, (2) digital analys av dräneringsnät, (3) digital bild analys, (4) extraktion och analys av lineament, (5) rumsliga (spatial) och statistiska analyser, och (6) DEM specifika digitalmetoder som skuggad reliefmodell, digital genomskärning och tredimensionell ytmodellering.

En metod för extraktion av ett kontinueligt nätverk av dränerings och höjdlinjer med hög densitet och en pixels vidd från DEM är också beskriven i denna studie. I motsatts till existerande modeller som använder tröskelvärden för definition av dräneringslinjer använder den nu föreslagna metoden extraktion av hydrologiska system i kombination med metoder för matematisk morfologi för att identifiera dräneringsnätet.

Ett preliminärt högdensitetsnätverk innehållande fiktiva parallella kanaler formas till ett dräneringsnät med en pixels vidd som sedan bränns (burnt) in i DEMen. Vidden av de brännda dräneringslinjerna ökas med hjälp av ett

rörligt medelvärde som utjämnar linjerna i DEM. Den modifierade DEMen används sedan for att köra mot det hydrologiska dräneringsnätets extraktionsalgoritm for att erhålla det slutliga dräneringssystmet med topografiskt korrekt placerade höjd/krönlineation. En utjämningsmetod (smoothing method) är utvecklad för att eliminera dalar av olika Strahler-nivådräneringslinjer från DEMet och genom detta göra det möjligt att erhålla lokala och regionala trender/lutningar i terrängen. Utjämningsmetoden beräknar en DEM genom att använda TIN-interpolering baserad på höjder av digitalt extraherade höjdstråk. En fördel med metoden är att utjämningen är styrd av fysikaliska-hydrologiska egenskaper i terrängen istället för matematiska filter. Utjämningsmetodiken används i denna studie för generalisering av riktning/geografiskt läge (aspect) i morfotektoniska undersökningar i ett litet dräneringsområde. Förutom autokorrelation, variogram, lineamenttäthet och Fourier analys, används waveletanalysmetod för att fånga periodicitet och ytmönster i morfotektoniska lineament i undersökningsområdet. Geologiska data från olika källor och med varierande skalor såsom geofysiska mätningar, geologiska kartor och data fran borrkärnor och hydrologiska data är integrerade i en GISdatabas. Tolkning av information från flera källor bekräftar resultaten av den digitala morfotektoniska undersökningen. En enkel förskjutnings(shear)-model med huvudsaklig förkastningszon i NO-SV riktning och med återhållande och eftergivande kurvor kan förklara huvuddelen av de morfotektoniska elementen förknippade med strukturer identifierade genom geologiska och digitala morfoteltonisla undersökningar i Kali Basin. Jämförelser av DTA-resultaten med geologi fran nordvästra Grekland indikerar att de större förkastningarna och förkastningssystemen (i de flesta fall) koresponderar till tydliga lineament. DTA i ett område med hjäp av den föreslagna modellen ger en användbar metod för att identifiera större och mindre strukturer över stora områden. I den här avhandlingen har numeriska metoder för extraktion av dräneringsnät, riktnings och wavelet analys utvecklats och använts i tektoniska geomorfologi.

Acta Universitatis Upsaliensis

Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series *Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology*. (Prior to October, 1993, the series was published under the title "Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science".)

Distribution:
Uppsala University Library
Box 510, SE-751 20 Uppsala, Sweden
www.uu.se, acta@ub.uu.se

ISSN 1104-232X
ISBN 91-554-6072-0