Technological Educational Institute of Crete
School of Applied Sciences
Department of Environmental & Natural Resources Engineering

M.Sc. Program *Geoenvironmental Resources & Risks"*

GEOMORPHOLOGICAL AND GEOLOGICAL ANALYSES FOR THE WIDE AREA OF TINOS ISLAND

M.Sc. THESIS

Toulia Efstathia

Supervisor: Associate Professor Dr. Kokinou Eleni

2017

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2017

ACKNOWLEDGEMENTS

Through this note I would like to thank my supervisor Associate Professor Eleni Kokinou for her excellent guidance, caring and patience during the implementation of my thesis and the prompt to deal with such an interesting area as the island of Tinos in Aegean, Greece. I also thank her for providing me with an excellent atmosphere for doing this research and the memorable experiences that will stay forever in my heart.

I acknowledge my gratitude to the members of the Department of Environmental & Natural Resources Engineering and the scientific committee of this work.

My sincere thanks to my family and to him, the extraordinary person, who is always next to me, cheering me up and stand by me through the good and bad times.

ABSTRACT

Scope of the present work is to apply modern state of the art methods of pattern recognition concerning the automatic detection of geomorphologic features, with emphasis in geological faults and to compare the results of the automatic detection with data collected from field work in a selected area of study. The contribution of this work in the geosciences is multi disciplinary because a) it proposes to geoscientists a new tool of geomorphologic analysis prior the field work and especially at the stage where published work and already available data are collected, evaluated and reprocessed, b) it increases the detection accuracy of the geological features both prior and after the field work and (c) it decreases the time of field work and consequently the cost of the entire geological research.

The above methodology has been applied to geologically study the southern part of Tinos island and it proved successful concerning both the performance of the applied pattern recognition algorithms and the identification of the normal faults in the study area. The evaluation of the results confirms that the proposed technique can be used to rapidly and accurately map areas of any spatial size.

Elevation data, previously published geological data and field measurements-observations are analyzed and further combined in the present work using Matlab and ArcGIS platforms. The processing of the tectonic data has been done using the FP Tectonics.

This work has been already presented in the EARSEL2016 conference in Bonn, Germany.

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CHAPTER 1. GEOLOGICAL SETTING OF TINOS ISLAND

1.1 Introduction

Tinos [Figure 1.1] is a Greek island situated in the Aegean Sea. It is located in the Cyclades archipelago, southeast of Andros and northwest of Mykonos. Tinos Island is the fourth largest island of the Cyclades (area of 194,59 km^2.) after Naxos, Andros and Paros and it has 8,574 inhabitants (2001 census). The distance from Andros, called Andros - Tinos strait, is 1/2 mile, while the closest distance from the coast of Mykonos is about 5 miles and 9 miles from port to port. Southwest of the island at a distance of 12 miles is Syros, where Ermoupoli, the capital city of the prefecture of Cyclades is located. The shape of Tinos is triangular and the large side the island is oriented NW-SE. The highest mountain is the Tsiknias which is located in the southeastern part of the island having a height of 726 meters. In the central part of the island is located of Exombourgo (height of 641 meters). The total length of the coastline, which presents rich horizontal and vertical dismemberment, with numerous coves and headlands, is estimated at 114 km.

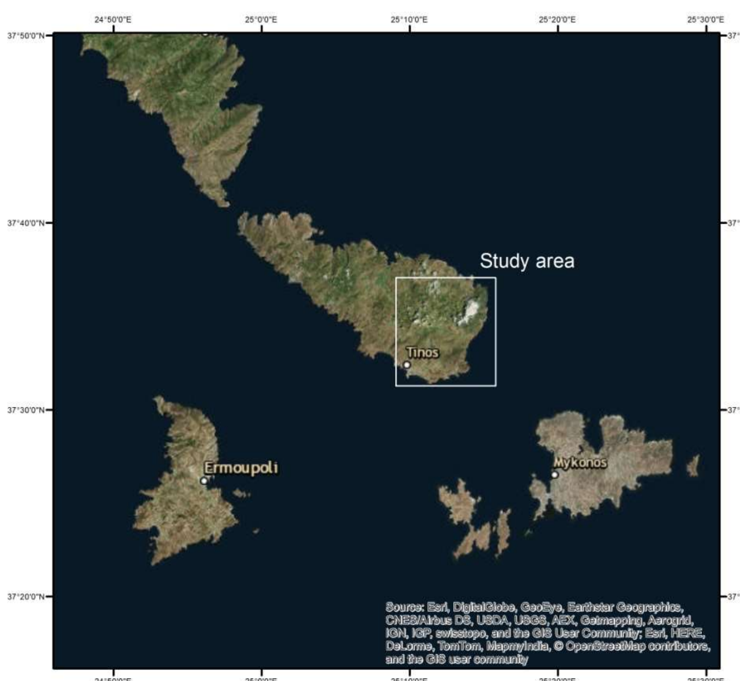

Figure 1.1: Location map showing the wide area of Tinos island (Cyclades, Aegean, Greece). The data concerning the basemap are from the ArcGIS 10 online database.

The automatic extraction of geomorphologic features (Panagiotakis and Kokinou, 2014; 2015; 2017) using high resolution digital elevation models (DEMs) belongs to the remote sensing techniques used to improve our understanding of regional geomorphology and geology prior the field work. This approach highly contributes towards a rapid, objective and lower cost geological mapping. Furthermore, remotely sensed data are widely used for geological mapping (Massironi et al., 2008; Rowan and Mars, 2003) and a variety of machine learning algorithms are applied in photo interpretation, automating the feature classification concerning these datasets. For example Harvey and Fotopoulos (2016) compared four supervised machine learning algorithms (naïve Bayes, k-nearest neighbour, random forest, and support vector machines) in order to evaluate their performance for correctly identifying geological rock types in a well previously surveyed area, showing that random forest is the best approach. The application of the pre-mentioned techniques prior to a field visit, helps the geologist to recover all known geological information about a site and it greatly facilitates the field work. It is well known that the onshore geological structures are easier detected and analysed in relation to the geological structures in the marine environment. This is because the access to land is easier. On the contrary, the investigation of the marine environment is more complex, time consuming and more expensive.

In the context of the present work, recent developed algorithms (Panagiotakis and Kokinou, 2014; 2015; 2017; Kokinou, 2015a) to automatically detect geomorphologic features, with emphasis in geological faults, are applied in high (4m) and medium resolution DEM onshore and offshore Tinos island. Furthermore, the results of the automatic detection are verified with data collected from field work in the southeastern part of Tinos in order to study the geomorphologic and geological features of this area [Figure 1a]. Specifically, this works aims to:

(1) Check the efficiency of new developed pattern recognition methods on DEMs to automatically detect the geomorphologic features with emphasis in normal faults.

(2) Compare the results of the automatic detection with the geological data provided from field work on Tinos Island in relation with previous researches.

(3) Evaluate the proposed methodology.

1.2 Geomorphology of Tinos island

The geomorphology of both the offshore and onshore environment is strongly related to the past and modern geodynamics-tectonics. Additionally, the onshore environment of Tinos is affected by the climate and the expansion of the lithological formations of Tinos. The mean air temperature of Tinos is in the range 10 – 11 C and in summer at 26 C. The air humidity is between 65 to 70%. In the cold period prevail northern and northeastern winds and in the hot period prevailing winds are the annual with great frequency and intensity.

The climate of the study area is characterized by strong winds, intense sunlight and high relative air humidity, factors which enhance the chemical and aeolic erosion, creating Alveoles and Tafoni formations [Figures 1.2]. People have constructed terraces to retain the products of weathering and territories.

Penck (1984) defined Tafoni formations referring to the honeycomb weathering bigger than 0.5 m of granite in Corsica. Formations smaller than 0.5 m are defined as Alveoles; the latter are sometimes developed (as in Tinos Island, Evelpidou et al., 2010) on schist surfaces (Theodoropoulos, 1974). Tafoni and Alveoles formations are often characterised as "aeolian erosion formations". In fact, their development is partly due to wind action, but is mainly due to chemical weathering (Soukis et al., 1998). Tafoni formations are developed especially in granites and granodiorites, as well as in gneisses and sandstones, that is in typical medium to coarse-grained silicate rocks with granular fabric (Wilhelmy, 1981; Mellor et al., 1997; Matsukura and Tanaka, 2000).

Figure 1.2: Formation of Tafoni near Kardiani.

1.3 Geological structure of Tinos Island

Geological mapping (Marjoribanks, 2010) aims at providing the graphical presentation of geological observations and interpretations for a selected area on a horizontal plane and it is usually implemented in three phases. At the first stage, previous information, concerning already published topographic and geological maps, air photos and satellite images, small or large scale geophysical data such as aeromagnetic data, borehole data and any other useful contribution, is collected and evaluated in order to design the most efficient plan of the geological field works (selected traverses across strike, detect horizons or contacts, faults and other geological structures). At the second stage ground truth data (field observations and measurements excluding noise) are collected. The geologist must be open to all possible ideas, hypotheses and observations (Marjoribanks, 2010). In case the observations do not fit the hypotheses, new models have to be constructed and tested using the field measurements in a repeatable process. At the last stage a database is constructed including all previous and collected in the field measurements and observations in order to construct the geological map at the proper scale.

According to Bröcker & Franz (2000) the geological units in Tinos from top to bottom are (1) the Akrotiri unit, (2) the Upper unit, (3) the Cycladic blueschist unit (Kumerics, 2004) and (4) the Basal unit. The Akrotiri unit is present in the southern part of Tinos consisting of amphibolites, paragneisses and minor silicate marbles (Patzak et al., 1994). Previous published work (Avigad and Garfunkel, 1989; Ring et al., 2003) supports that the Akrotiri unit is separated from the underlying Upper unit by the low angle top to the NE Vari detachment. Brichau et al. (2007) reported the presence of several detachments in Tinos that were active at different periods. Later Jolivet et al. (2010) presented a synthesis of the northern Cyclades detachments and supported that all these structures are part of a single crustal-scale detachment, called the North Cycladic Detachment System (NCDS), that partly reactivated the Vardar oceanic suture zone. The Upper Unit in Tinos is characterized by greenschist-facies metamorphism, consisting of serpentinites, meta-gabbros, ophicalcites and phyllitic rocks (Melidonis, 1980). The Cycladic blueschist unit consists of marbles, calcschists, siliciclastic metasediments, cherts, basic and acid metavolcanic rocks (Melidonis, 1980) mainly characterized by greenschist-facies corresponding to mineral P-T metamorphism of ~450-500°C and ~4-7 kbar. Bröcker et al. (1993) found evidences of the earlier high-pressure event corresponding to ~450-500°C and 15 ± 3 kbar. The lower Basal unit is present in the northeastern part of the island, consisting of various metamorphic carbonate rocks (Avigad and Garfunkel, 1989). During the low to medium

P-T metamorphism in the Miocene I- and S-type granites intruded into the units and caused intensive contact metamorphism (Altherr et al., 1982).

According to the IGME map (1:50,000) of Tinos island [Figures 1.3, Figure 1.4a, b], the geological formations in the southern part (study area) correspond to a wide range of geological ages, from very recent (Holocene) to very old (Permian), i.e:

- The section of Metamorfites
- The section of Magmatites
- The section of Quaternary sediments

In specifics, recent deposits are present near the coastline. Gneisses, gneiss-schists and schists cover the majority of the study area. Tsiknias mountain is located to the north east, composed of ophiolites, while around this mountain are present greenschists-prasinites. Additionally, small areas are covered by marbles, sipolines and gabbrodiorite-diorite.

The section of metamorfites is represented by metamorphic Mesozoic age rocks which cover the greater part (153.7 Km^2 namely 79%) of the island. The main lithological unit of the first section is the schist in various forms. The group of metamorfites is divided by Melidonis (1980) from top to bottom into two individual series, i.e the upper series or series of green schists with ophiolites and the lower series or series of schists-gneiss-marbles. More specifically, the upper series correspond to green schists, phyllites, quartzites, pyritic marbles and talkite or chlorite schists. In the lower series dominate gneiss, marble, gneiss and mica schists and other metamorphic forms.

Magmatic rock formations are divided into syntektonic formations, such as serpentines, green Tinian marble, gabbros, and granodiorites and hysterotektonic formations such as granite (granite in Volax). The granite in village Volax constitutes a monument attracting the international scientific interest for two reasons: a) the spherical weathering and b) the formations of tafoni and alveoles, cavities shaped mostly by the wind and the chemical weathering.

The section of Quaternary sediments corresponds to lacustrine, marine and terrestrial deposits, covering an area of 8.4 Km^2 (1/24 of the island's surface). These deposits are the contemporary geological sediments corresponding to products of the erosion and weathering of the geological formations.

Detailed geological structure of the study area

The geological structure in the study area corresponds to:

- Recent deposits of Holocene (al) are present along and near to the coastline.
- The majority of the study area is covered by gneisses, gneiss-schists, schists of Permian (gn.sch).
- The Tsiknias mountain is covered by ophiolites (σ), while around the mountain are present Permian greenschists-prasinites (ab).
- Finally marbles and sipolines (mr.sp) and less gabbrodiorite-diorite (g) are presentin the coastline near to Tsiknias mountain.

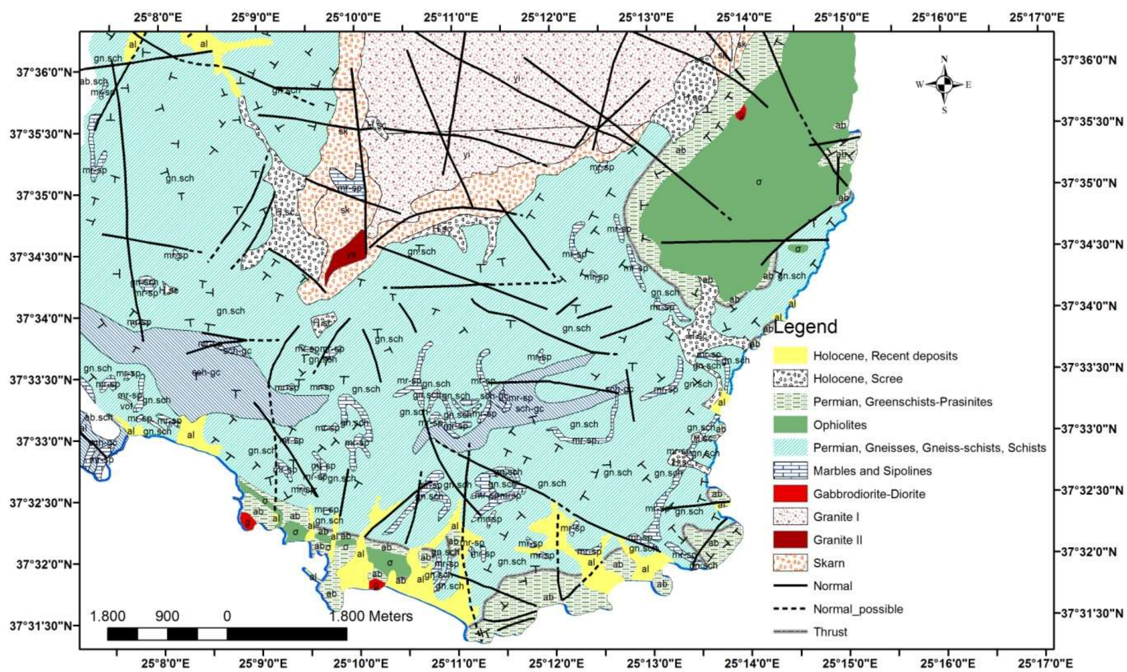

Figure 1.3: Geological map of the southern part in Tinos island, according to the IGME map (1:50,000) and field observations.

(a)

(b)

Figure 1.4: (a) Granite in Volax, (b) Quaternary sediments.

1.4 Tectonic structure of the study area in Tinos

Recent studies concluded that the Attic-Cyclades cluster constitutes an Alpine tectonic cover which was formed by overthrust and normal faults. During the Oligocene-Miocene decompression of the blueschistolithic unity took part, accompanied by metamorphosis of low pressure-medium temperatures and the rise of granite. Abundant normal faults were the result of this tectonic phase.

Concerning the distribution of the normal faults in the southern part of Tinos, which are being studied in the context of the present work, four (4) main categories of normal geological faults are indicated [Figures 1.5a-c, 1.6], corresponding to E-W, N-S, NW-SE and NE-SW trending faults, mainly with slopes greater than 60º. The tectonic data were collected in selected sites, based on the results of the automatic detection and according to the stratigraphic units (Kamberis et al. 2012; Kokinou et al., 2015). In case, two generations of normal faults were present in the same site they were divided prior the numerical analysis., based on (a) the criterion of relative overprinting between two generations of striations (e.g. Mercier et al. 1989) and (b) geometric and morphotectonic elements such as the strike, dip and plane of the faults, the presence of recent screes, facets and fault scarps. Fault groups were estimated using the directional histogram for planes [Figure 1.6], with angle of deviation less than 15o.

(a)

(b)

(c)

Figure 1.5: Normal faults in the study area. (a) N-S trending normal faults, (b) NW-SE trending normal faults, (c) NE-SW trending normal faults.

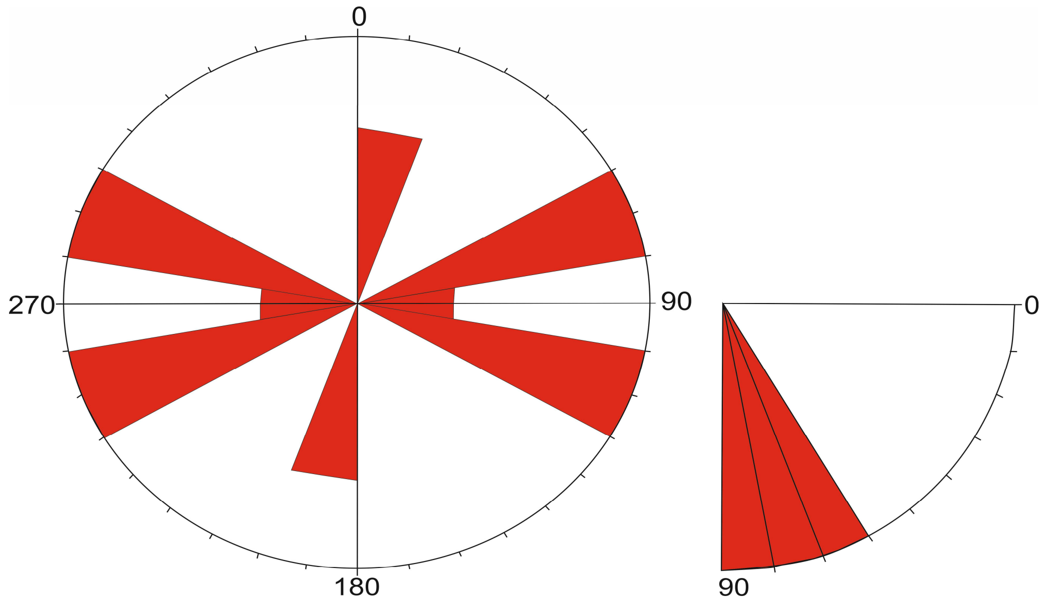

Figure 1.6: Rosediagram showing the strike and the dip of the normal faults measured during the field trip in Tinos island.

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CHAPTER 2. METHODOLOGY

2.1 Techniques applied in this work

Digital elevation data, previously published geological data and field measurements-observations are analyzed and further combined in the present work using Matlab and ArcGIS platforms.

2.1.2 Techniques of pattern recognition

The elevation data were digitized [Figures 2.1, 2.2] from the topographic maps of scale 1:5,000, published by the Hellenic Army Geographical Service (H.A.G.S.). The Digital Elevation Model (DEM) was created by digitizing the contours with 4m interval.

The methodology, concerning the processing of the DEM, has been developed by Panagiotakis and Kokinou (2014, 2015, 2017) and it has been successfully applied in previous studies (Kokinou, 2015a; Kokinou and Kopp, 2016). The main steps of this method are:

Input data are bathymetric/elevation data (.shp format), in the present case elevation data. The first two columns of the input file correspond to the x, y coordinates. The third column corresponds to the ground elevation.

Calculation of the F(p) = $F(p) = (S^2(p) * SS(p) * SA(p))^{1/4}$ (1)

where,

$$S(p) = tan^{-1}(|v(p)|) \quad (2)$$

, corresponds to the slope at point p of the topographic surface Z. v(p) denotes the plane tangent vector defined as: $v(p) = \left[\frac{\partial Z(p)}{\partial x}, \frac{\partial Z(p)}{\partial y}\right]^T$ (3)

Slope is measured in degrees with $S(p) \in [0, 90^o]$.

$$A(p) = atan2\left(\frac{\partial Z(p)}{\partial y}, -\frac{\partial Z(p)}{\partial x}\right) \quad (4)$$

corresponds to the aspect at point p of the topographic surface Z. Aspect is measured in degrees with

$A(p) \in [0, 360^o]$.

SS(p) is the first derivative of the Slope image.

SA(p) is the first derivative of the Aspect image (Slope of Aspect).

Estimation of the absolute value-image of the convolution of F with a zero mean filter G(a, w) [Figure 2.3] of orientation angle a and width w (Panagiotakis et al., 2012), as follows:

$$Ig(a,w) = |F * G(a,w)| \quad (5)$$

The resulting image Im is provided by getting the maximum of the corresponding pixel values of images

$$Ig(a, w): Im = \max_{a,w} Ig(a, w). \quad (6)$$

Im corresponds to an image showing the automatic detections of the geomorphologic features in the study area, with emphasis in geological faults.

Furthermore, the local maxima (topographic tops) of the DTM are computed based on the isocontour approach (Panagiotakis and Kokinou, 2017), in order to automatically detect the most important topographic highs in the study area. An important parameter, included in the computations, is the MinA, used to define the minimum possible expanded area of a high and to sample the topographic tops that are very close together, in order to reduce the computational cost. A topographic top is selected if and only if it is the highest top in its neighborhood. Next, the sequence of isocontours for different decreasing levels r are computed. During this process, the isocontours are gradually merged providing a topological hierarchy of highs in an inclusion tree structure. A novel formulation of a topographic high is given, taking into account the volume evolution of an isocontour that starts from the top of a high and grows, as decreasing the altitude level of the isocontour, until a high of higher altitude is reached. This formulation yields to a robust unsupervised algorithm that can be sequentially applied to automatically recognize the topographic highs of a region.

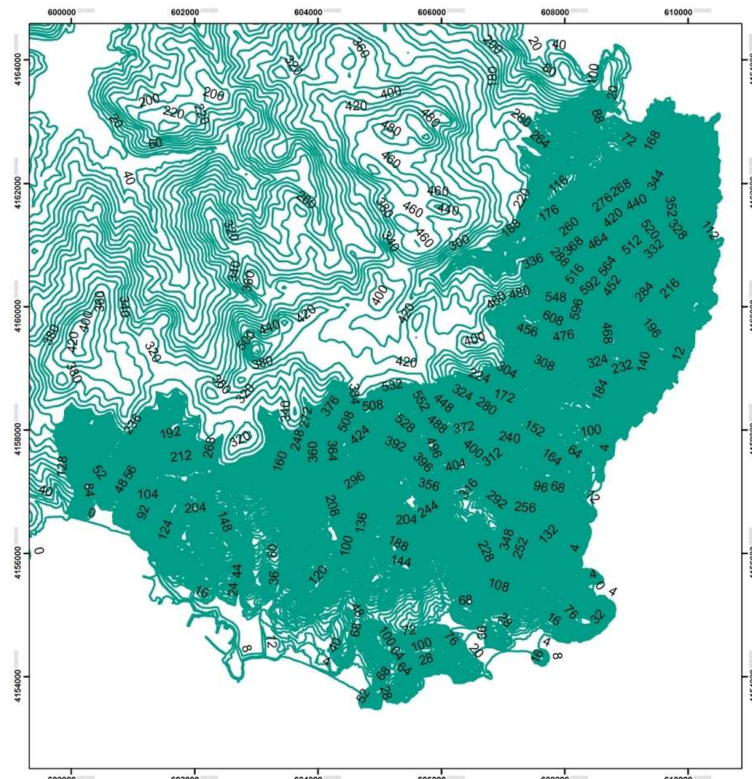

Figure 2.1: Isocontour map of the study area.

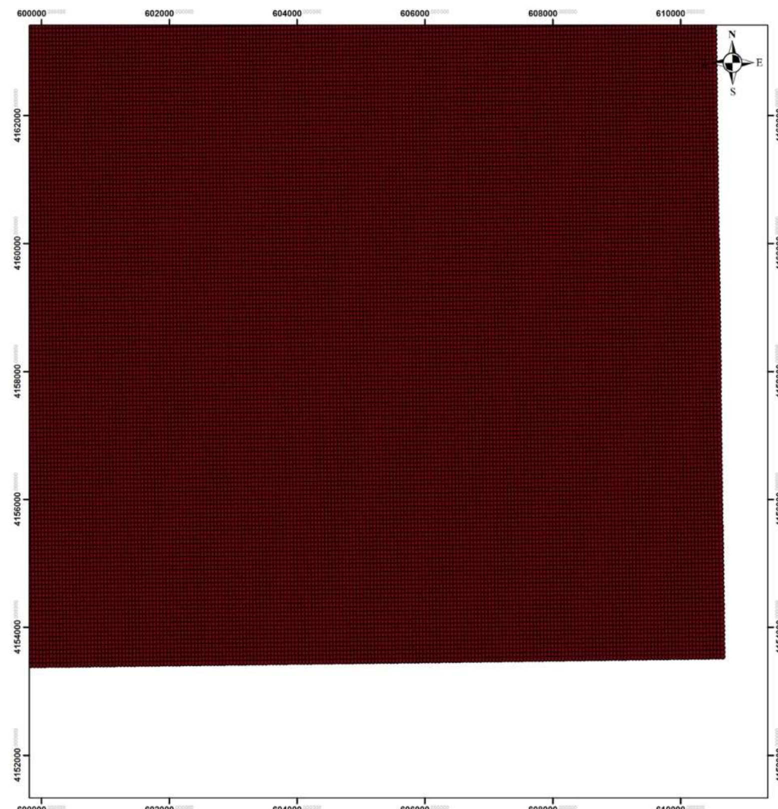

Figure 2.2: Elevation grid used as input in the alogirthms used in the context of this work.

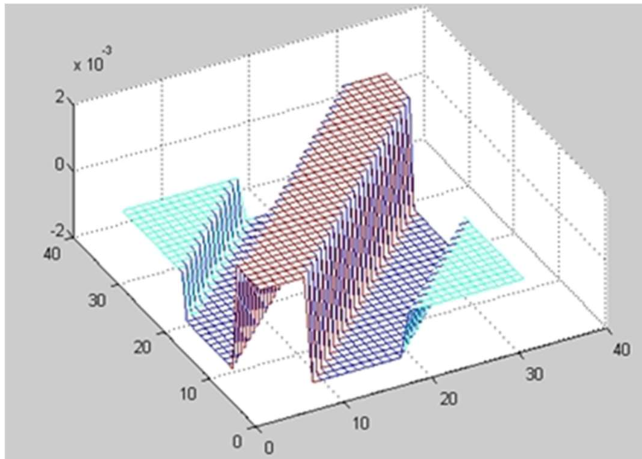

Figure 2.3: The step filter (Panagiotakis et al., 2012).

2.1.2 Geological mapping

The field trip in Tinos took part in the beginning of 2016. The collected geological data (Toulia et al., 2016) have been processed using commercial software ArcGis and FPTectonics. In general, the time and the financial cost of the geological mapping have been significantly reduced (approximately 50%). This is because we selected specific sites for geological research, based on the results of the pattern recognition methods.

The tectonic data were collected in selected sites, based on the results of the automatic detection and according to the stratigraphic units (Kamberis et al. 2012; Kokinou et al., 2015). In case, two generations of normal faults were present in the same site they were divided prior the numerical analysis., based on (a) the criterion of relative overprinting between two generations of striations (e.g. Mercier et al., 1989) and (b) geometric and morphotectonic elements such as the strike, dip and plane of the faults, the presence of recent screes, facets and fault scarps. Fault groups were estimated using the directional histogram for planes, with angle of deviation less than 15^{o}.

2.2 Tectonics FP software

Tectonics *FP* software (http://www.tectonicsfp.com/) is a very comprehensive and powerful tool to generate plots for structural geology. The TectonicsFP trying to support both brittle tectonic calculations and conventional statistics fabrics while maintaining or improving the scientific level. One of the main objectives was to improve application stability, speed and handling.

Processing structural data with TeconicsFP takes three steps:

1. Entering data into datafiles.

2. Manipulating data, proceeding calculations, visualizing data. As results you might get text or graphics.

3. Export of the results (text or graphics) to a word processing, spreadsheet, database, graphics, GIS or CAD application.

2.2.1 Numerical input

All field data and calculated data are stored in text-based tables. The list separator (default: comma (,)) can be changed in the options-window. This should only be done by advanced users for special purposes. Non-table format data are preceded by a semicolon.

Characterset accepted: ANSI (=Windows) - standard.

File extensions: helpful to distinguish different types of data (see below).

Caution: Use the period (”.”) generally only to separate an extension from a filename.

Number of datasets per file: principally not limited, depending on available resources.

Exception: With manual sorting (<File> <Sort...>) max. No. of datasets is limited to 999.

TectonicsFP accepts the following external file formats:

- ✓ *.hf....fault plane data used by H. Peresson’s program.
- ✓ *.hk...corrected fault plane data used by H. Peresson’s program.
- ✓ *.hoe...fault plane data used by Sperner-Software.
- ✓ *.stf...a more recent data format used by Sperner-Software.

TectonicsFP will convert these third-party file formats while reading them. You can save changed data only in an appropriate TectonicsFP-fileformat. For numerical input, we accepted angle scale 360 degrees, azimuth-angles clockwise from north. The values for dip/plunge is between 0.01 to 89.99 degrees downplunge from horizontal.

2.2.2 Processing Tectonic data

For enter tectonic data first generate a new datafile. We select <File> <New datafile> to call the new file dialog box. After of this process we select the type of tectonic data but it is important to know the TectonicsFP accept four classes of field data.

The first class are the fault planes. These files record the following data about the fault: the dip direction and the dip of fault plane, the azimuth and the plunge of slickenside lineation and the relative sense of movement.

The second class are the planes this dataset consists of dip direction and dip angle of the plane.The third class are the lineations this files have the same structure as plane files but record azimuth and plunge of lineations.

The forth class is the azimuthal data and this files contain only azimuths.

2.2.3 Display fault plane data - Rose-diagram

Initially for the processing of tectonic data we have the visualization of tectonic data that contains the plot and the result of this is output, the great circle plot and the result of this is planes in the lower hemisphere, the small circle plot and the result of this is small circle in the lower hemisphere, the pi plot and the result of this is poles to planes in the lower hemisphere and the lineations with lineations in the lower hemisphere. About computations we have a lot of methods. The rotation, the mean vector (fisher statistics), the mean vector (R% and center), the eigenvectors, the rose-diagram, the contour plot, the plane from lineations, the lineation from planes, the fault slip from main and Riedel planes, the Dihedral angle and the apparent dip but for the present work we use the rose-diagram and the result of this method is directional histogram for planes or lineations.

Especially the rose-diagram accept datafiles of planes (*.pln), lineations (*.lin), fault planes (*.fpl, *.cor), pt-axes (*.t??). The next step of the rose-diagram is the selection of rose parameters. We compute dip angle but dip or plunge angles are displayed in a second rose diagram. Azimuth interval in degrees counting interval for azimuth angles, dip interval in degrees counting interval for dip angles but not for azimuthal data files and center to center if checked class centers will be drawn otherwise class boundaries.

Additionally, for fault plane data the strike direction and the dip angle of fault planes are processed and displayed. In fault lineations the azimuth and plunge of lineations are processed and displayed. In use of p-axes, t-axes and b-axes the azimuth and plunge of all axes are processed and displayed.

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CHAPTER 3. RESULTS AND INTEPRETATION

3.1 Introduction

The purpose of this chapter is to present the results and the interpretation for the southern part of Tinos island. Futhermore, we discuss the evaluation of the automatic detected geomorphologic elements on land in relation to the field collected data.

3.2 Results and discussion of the processed data

3.2.1 Onshore data in the southern part of Tinos - Pattern recognition and geological analysis

[Figure 3.1] depicts the results of the automatic detection of the topographic highs in the study area. Generally, the area presents a rough topography, with altitudes ranging between 0 - 697.73 m. Five (5) topographic highs, namely Tsiknias (max. altitude 697.73 m), Kerovouni (max. altitude 599.02 m), Ktenados (max. altitude 507.39 m), Monastiria (max. altitude 481.39 m) and Plagia (max. altitude 499.19 m) are automatically detected in the wide area of study. The main orientations [Figure 3.2] of the topographic highs in the study area are (1) NE-SW (25^o-35^o) corresponding to Tsiknias, (2) N-S (160^o-170^o) corresponding to Kerovouni and (3) NW-SE (135^o-145^o) corresponding to Monastiria.

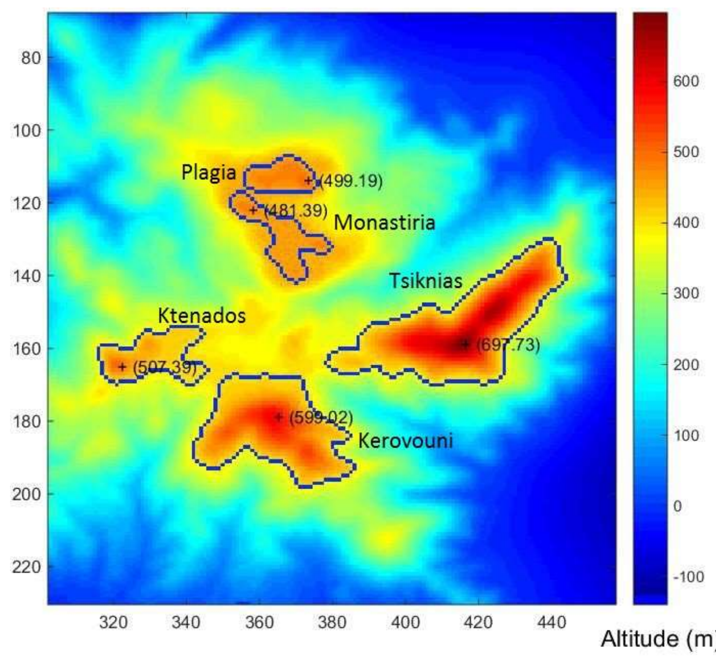


Figure 3.1: Automatic detection of the topographic highs in the study area according to the scheme proposed by Panagiotakis and Kokinou (2017).

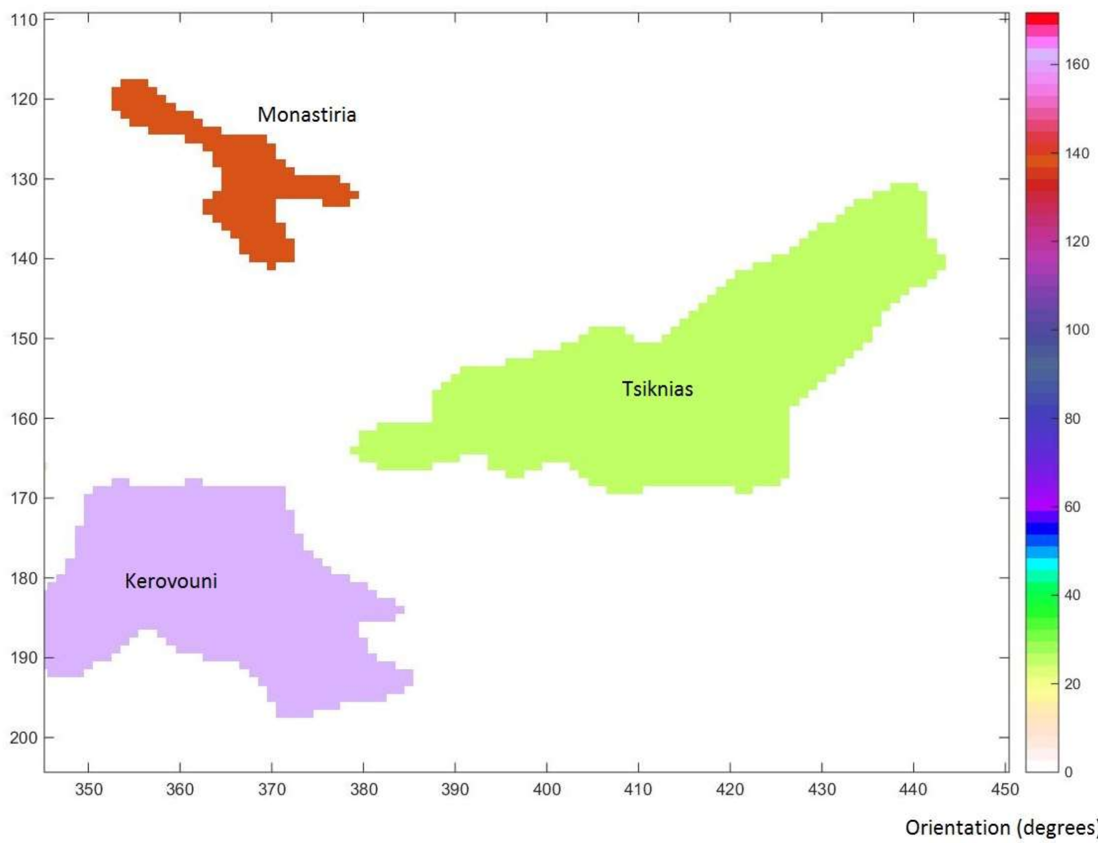


Figure 3.2: The main orientation (in degrees) of the detected topographic highs.

[Figure 3.3] shows the result of the interpolated elevation data (in 15 classes) using kriging method. Kriging method is generally based on statistical models including autocorrelation. Specifically, it is a multistep process that includes statistical analysis of the data, variogram modeling and creation of the surface.

The slope map (9 classes) of the study area is presented in [Figure 3.4]. The lower slopes (near to the coastline) are shown by dark green color, corresponding to the range 0^o to 10^o. In the central part of the study area slopes are ranging between 21^o to 30^o (light green color), 31^o to 40^o (light yellow color), 41^o to 50^o (yellow color), 51^o to 60^o (light orange color) and 61^o to 70^o (orange color). The eastern part of the study area presents a rough relief with slopes greater than 41^o. In the rest of the study area, slopes are generally gentle.

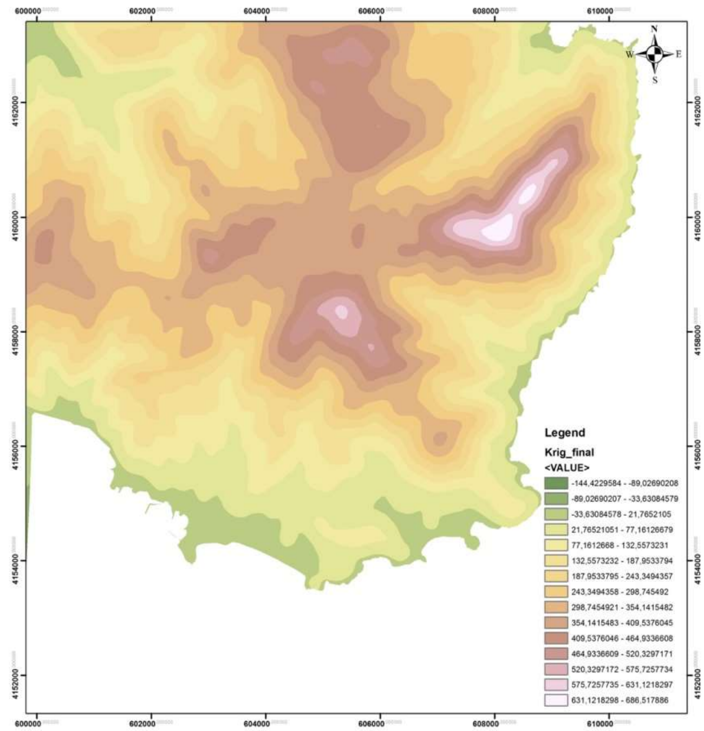


Figure 3.3: Elevation data (in 15 classes) using kriging method. The maximum altitude (697.73 m) in the study area corresponds to Tsiknias. See [Figure 3.2] concerning the location of Tsiknias.

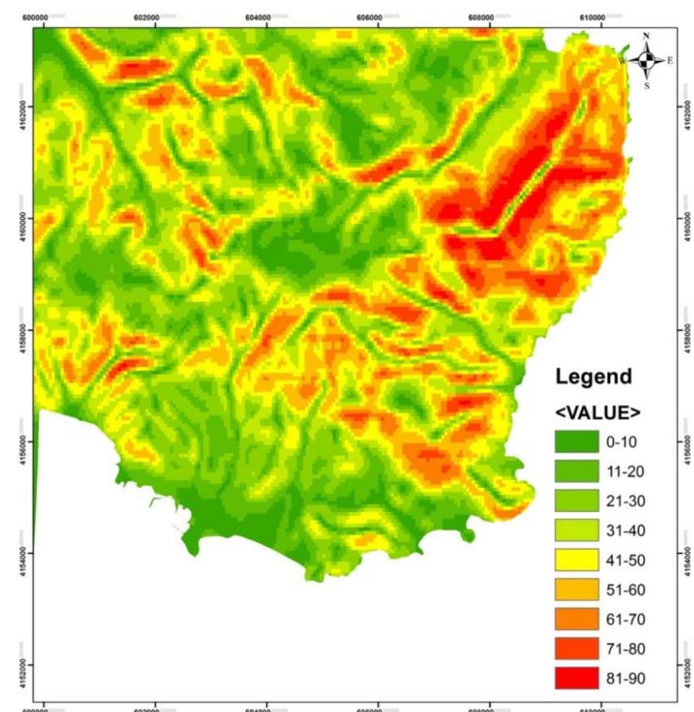
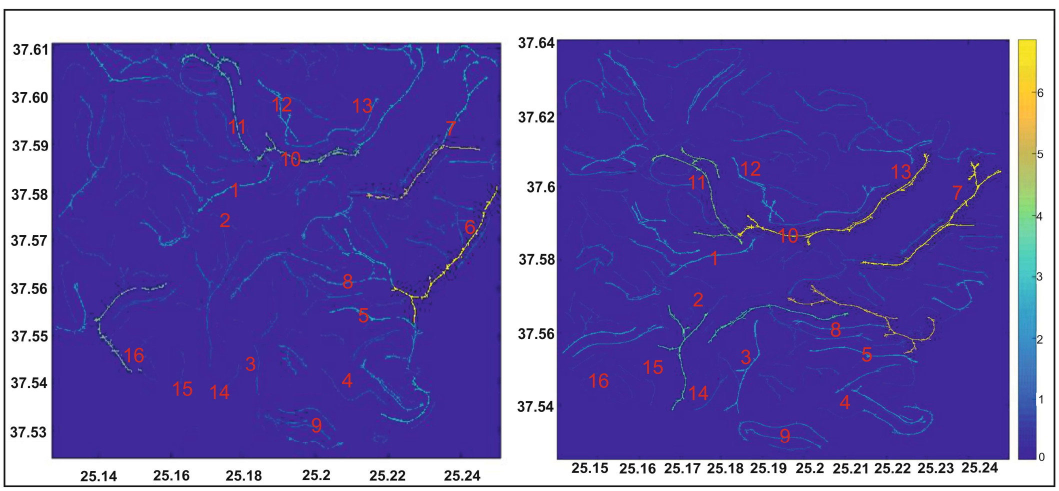


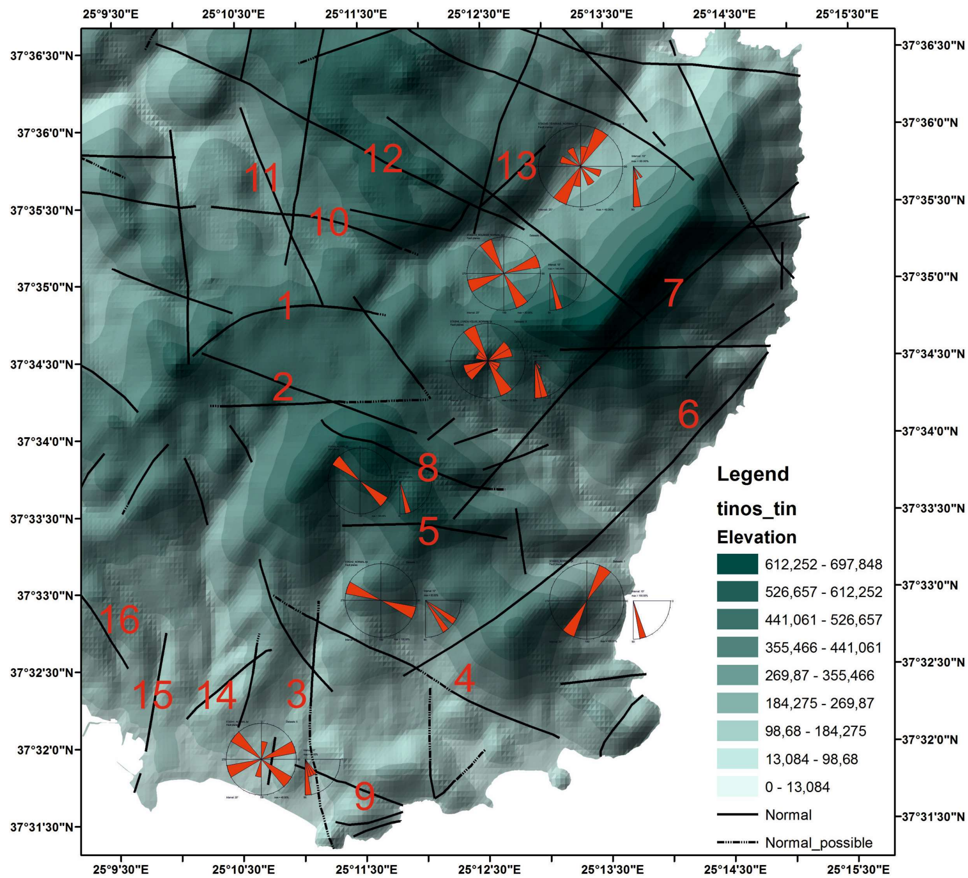
Figure 3.4: The slope map of the study area.

[Figure 3.5] presents the results of the automatically detected linear-curvilinear geological elements, mainly corresponding to the normal geological faults present in the study area. In our experiments concerning the automatic detection, we used two datasets of DEMs, corresponding to contour interval 100m [Figure 3.5a left] and 4m [Figure 3.5a right], respectively aiming to demonstrate the accuracy and the strength of the automatic detection in both medium and high resolution DEMs.

Furthermore, the normal faults on Tinos island are presented in [Figure 3.5b], according to the IGME map in scale 1:50,000 overlain by the rose diagrams resulted from the processing of the tectonic field measurements (Kamberis et al., 2012; Kokinou et al., 2015; Kokinou, 2015b). NE-SW to ENE-WSW and NW-SE trending normal geological faults characterized by steep slopes (>60^{o}) prevail in the northern sector of the study area. Concerning the southern sector of the same area the previously mentioned trending fault groups and some N-S trending faults are present. The shape and the orientation of the pre-mentioned topographic highs (Tsiknias, Kerovouni, Monastiria) seem to be controlled by the tectonic regime in the wide area of study corresponding to the NE-SW, N-S and NW-SE trending normal geological faults.



(a)



(b)

Figure 3.5: Comparison of the automatic detected features with the ground truth data. The reference system is WGS84. Figure 3.5 (a) automatic detected features using DEMs of contour interval 100m (left) and 4m (right), in order to check the accuracy of the automatic detection. Comparing the left image, that corresponds to the DEM of contour interval 100m and the right image, that presents the DEM of contour interval 4m, we conclude that the accuracy of the detection increases rapidly using data of contour interval 4m. The vertical color bar corresponds to the intensity of detection. Figure 3.5 (b) the normal faults on Tinos island according to the IGME map in scale 1:50,000 overlain by the rose diagrams resulted from the processing of the field measurements. Red numbers in both figures correspond to the similar linear and curvilinear geological elements, i.e normal faults.

3.2.2 Offshore data in area between Tinos and Mykonos

Bathymetric data were also used in the context of the present work. Data are from the EMODNet, European Marine Observatory and Data Network (Berthou, 2008).

[Figure 3.6] presents the slope map of the offshore area between Tinos and Mykonos. Steep slopes prevail in the northern offshore area between Tinos and Mykonos island, ranging between 65^o to 90^o and shown by yellow color. Slopes lower than 50^o prevail in the rest of the study area. Concerning the bathymetric aspects [Figure 3.7], NNE (0-50^o), SSW (180-230^o) and NNW (300-359^o) prevail in the study area.

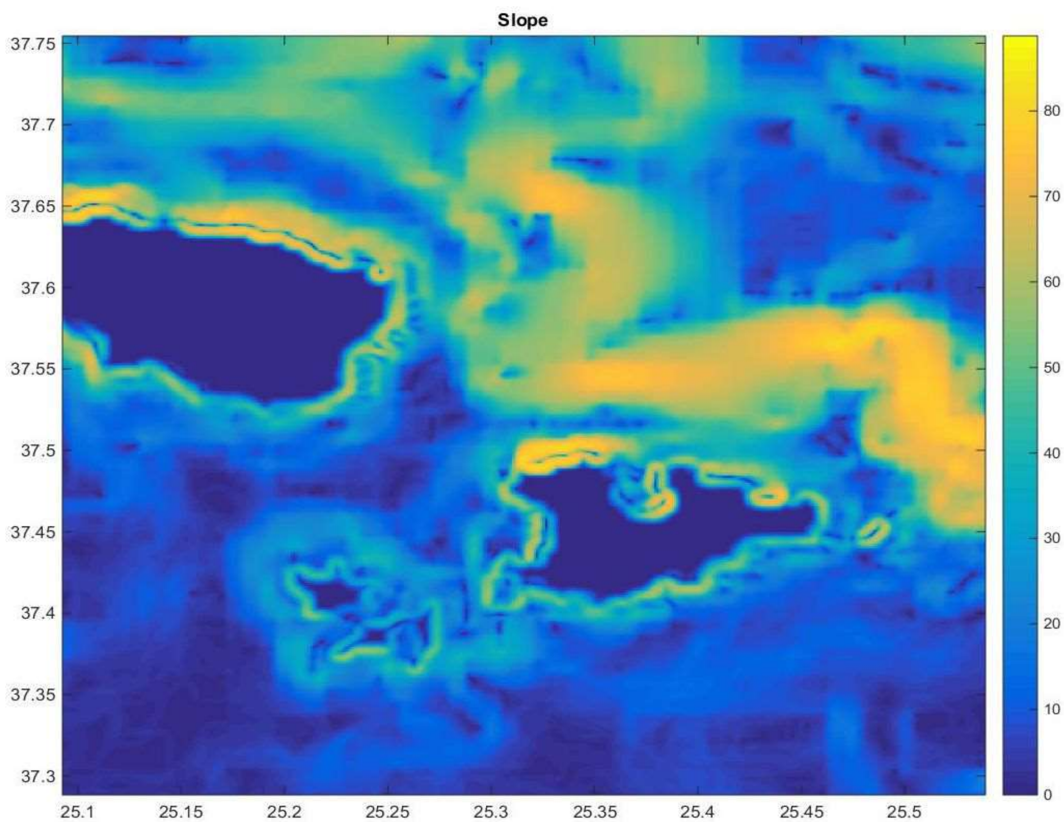


Figure 3.6: Bathymetric slopes in the study area. Note that steep slopes (>65o) prevail in the northern offshore area of Tinos and Milos islands.

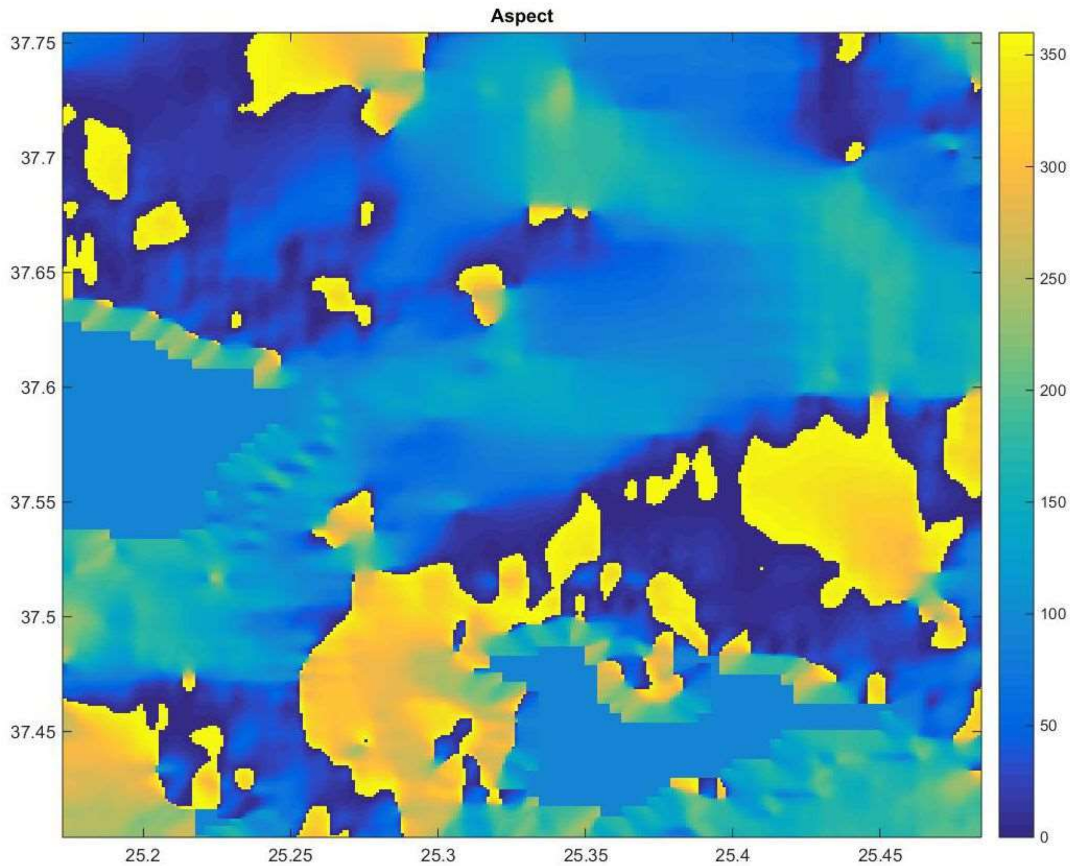


Figure 3.7: Bathymetric aspects in the study area.

[Figure 3.8] presents the automatic detected elements in the study area based on the methodology of Panagiotakis and Kokinou (2015), while in [Figure 3.9] the possible offshore normal geological faults are indicated in red color. Finally in [Figure 3.10], four fault groups of geological faults are indicated both on land and in the sea according to their general orientation. The first category of faults corresponds to N-S trending normal faults in green color. The second category of faults corresponds to E-W trending normal faults in yellow color. The third category of faults corresponds to NE-SW trending normal faults in blue color and the forth category of faults corresponds to NW-SE trending normal faults in red color. Especially, NW-SE trending faults prevail offshore north of Tinos Island while NE-SW to N-S trending faults prevail to the east of this island.

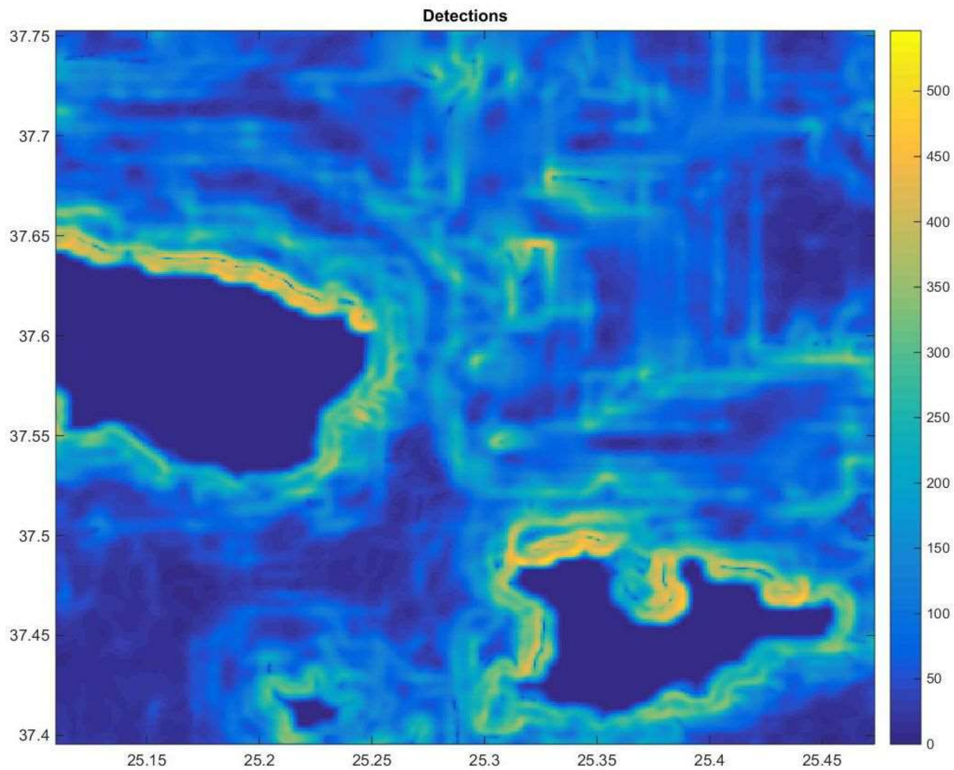


Figure 3.8: Automatic detected elements in the study area.

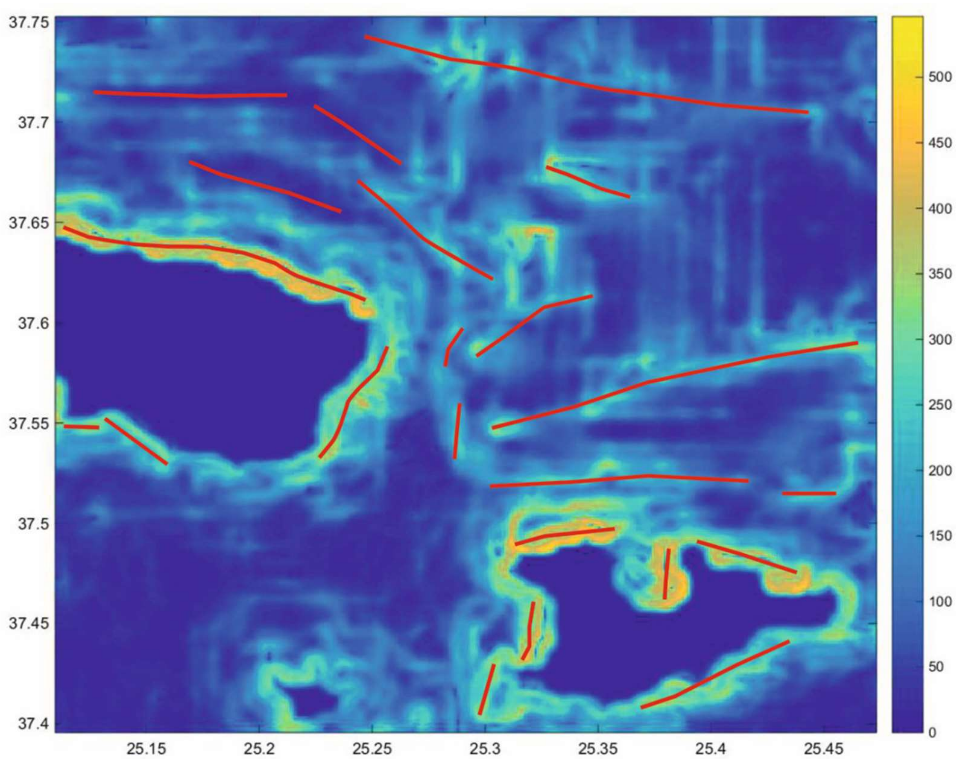


Figure 3.9: Possible offshore normal geological faults in red color based on the automatic detection.

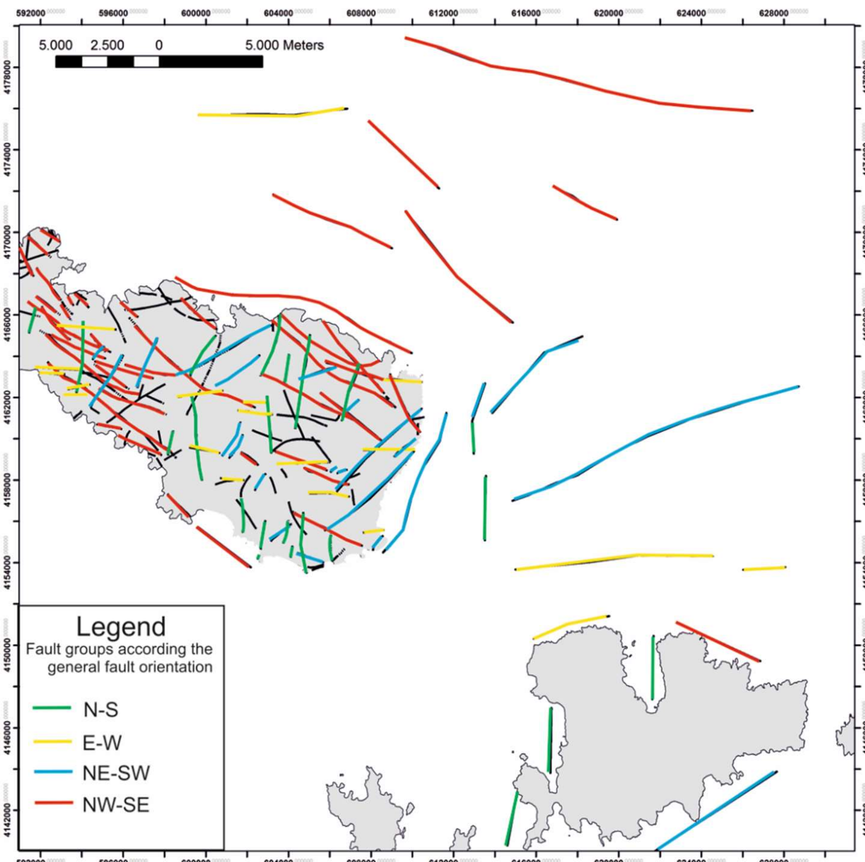


Figure 3.10: Both on land and in the sea are indicated four fault groups of geological faults, according to their general orientation.

3.3 Evaluation of the automatic detected geomorphologic elements on land in relation to the field collected data

The evaluation of the results in the present study is qualitative and not quantitative. This is because the ground truth data for the study area are from the Geological map of I.G.M.E. (Tinos–Yaros sheet, 1:50000), published more than 20 years ago. So we considered, a quantitative assessment of the results of the present study, based on so old ground truth data, would not be objective.

In order to qualitatively assess the results of the applied methodology, we selected some of the most important normal geological faults, which initially have been detected using the pattern recognition methods and then identified during the field work in Tinos. The selection criteria of the geological faults, used for the evaluation, are their location in the study area as well as their orientation, slope, and length. These normal faults are indicated with red numbers in [Figure 3.11 left, middle and right], corresponding to the ground truth data. Then we detected these faults in [Figure 3.11 middle and right], corresponding to the automatically detected linear and curvilinear geological formations. At this point we have to refer that during the comparison of the automatically detected linear and curvilinear elements with the ground truth data, some differences emerged, mainly concerning the shape of the automatically detected geological elements. This is because the scale of the ground truth data is 1:50,000 [Figure 3.11 left] while the scale of the DEMs used for the pattern recognition is 1:5,000 [Figure 3.11 right], which means that the linear and curvilinear geological elements are detected with higher accuracy using topographic data 1:5,000. The location and the orientation of the automatically detected geological elements agree in the majority of the cases examined as shown in [Figure 3.11].

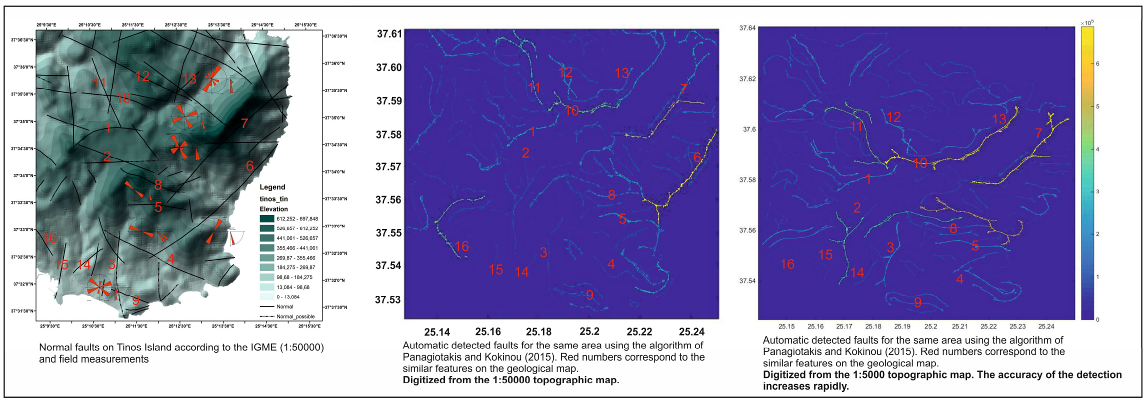


Figure 3.11: Comparison of the automatic detection results (middle and right) with the real data collected (left).

Finally, in [Figure 3.12] the results (right) of the automatic detection in the wide area of Tsiknias are compared with the lineaments detected in an aerial photo (302639_2013_15000_359_BW) provided by the Hellenic Army Geographical Service) as well as published data by Jolivet et al. (2010). All major geological faults, delimiting Tsiknias high, are estimated with high precision concerning their location and shape.

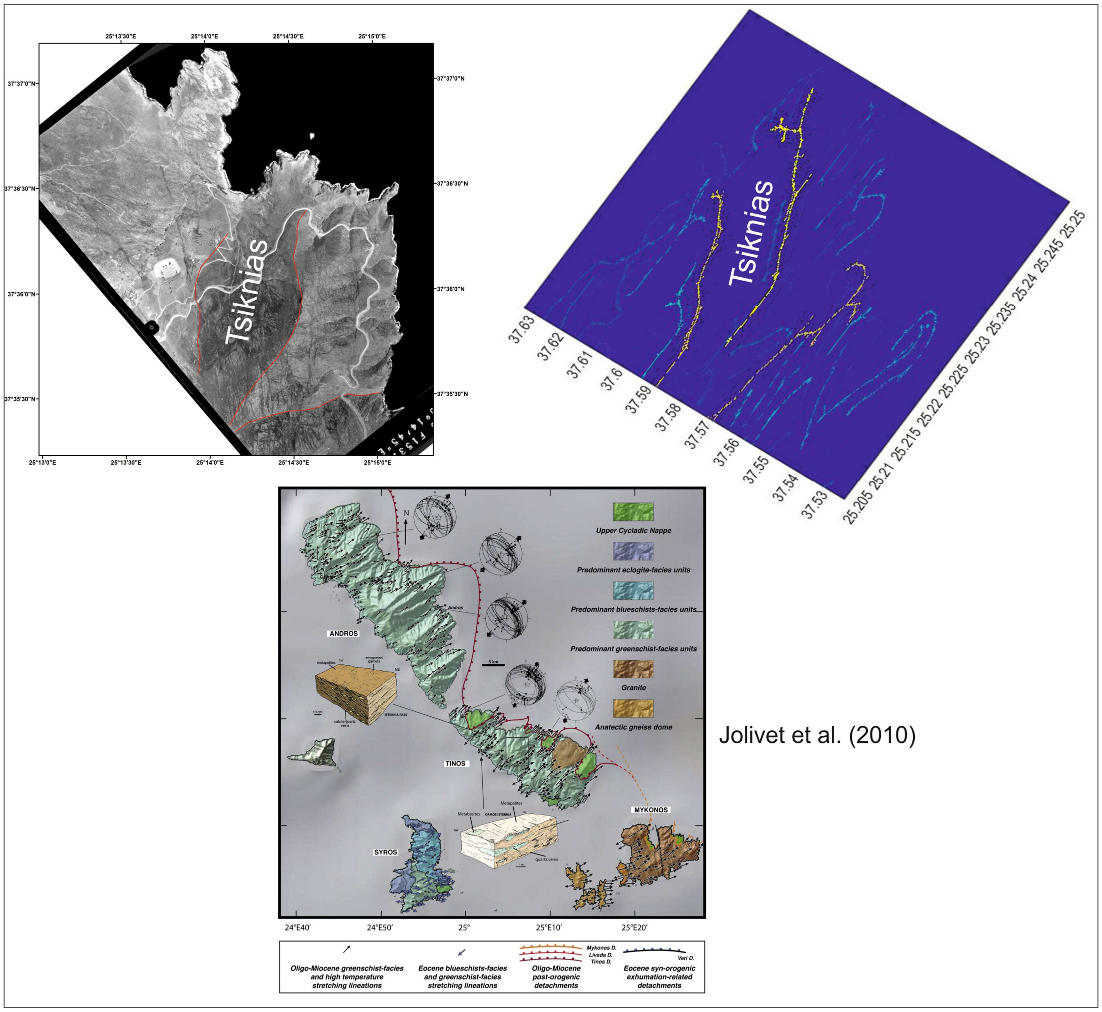


Figure 3.12: Comparison of the automatic detection results (right) with aerial photo (302639_2013_15000_359_BW, Hellenic Army Geographical Service) and published data (Jolivet et al., 2010, down).

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CHAPTER 4. CONCLUSIONS

4.1 Conclusions

In the context of this work the geomorphological features in the southern part of Tinos island and the related structures are identified using a modern processing methodology. Furthermore, the automatically geomorphologic parameters are compared with field data collected in the beginning of 2016 during the field trip in Tinos. More specifically:

- Major and accompanying morphological structures on land are estimated with high precision concerning their location and shape.
- NE-SW to ENE-WSW and NW-SE trending normal geological faults characterized by steep slopes (>60^o) prevail in the northern sector of the study area. Concerning the southern sector of the same area the previously mentioned trending fault groups and some N-S trending faults are present. The shape and the orientation of the pre-mentioned topographic highs (Tsiknias, Kerovouni, Monastiria) seem to be controlled by the tectonic regime in the wide area of study corresponding to the NE-SW, N-S and NW-SE trending normal geological faults.
- NW-SE trending faults prevail offshore north of Tinos Island while NE-SW to N-S trending faults prevail to the east of this island.
- The automatic detected features were further compared and confirmed using ground truth data digitized from the IGME map in scale 1:50,000, an aerial photo provided by the Hellenic Army Geographical Service and data collected during a field trip in 2016.
- The experimental results indicate the reliable performance of the proposed methodology. Further this method has a low computational cost.
- The contribution of this work in the geosciences is multi disciplinary because a) it proposes to geoscientists a new tool of geomorphologic analysis prior the field work and especially at the stage where published work and already available data are collected, evaluated and reprocessed, b) it increases the detection accuracy of the geological features both prior and after the field work and (c) it decreases the time of field work and consequently the cost of the entire geological research.

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APPENDIX I - FIELD WORK PHOTOS

Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

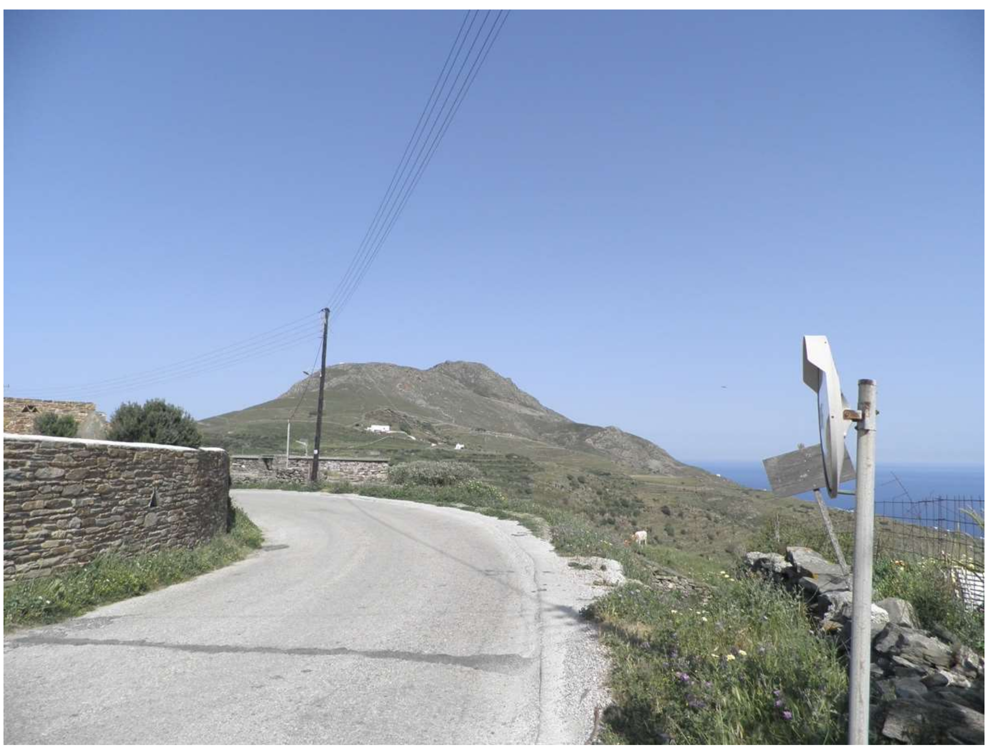
Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

Geological structure - Gneisses, gneiss-schists, schists (gn.sch)

Normal geological fault in gneisses, gneiss-schists, schists (gn.sch)

Geological structure - Greenschists- prasinites (ab)

Geological structure - Greenschists- prasinites (ab)



Tsiknias mountain - ophiolites (σ)

Tsiknias mountain, geological structure - ophiolites (σ)

Geological structure - Ophiolites (σ)

Geological structure - Resent deposits (al)

Geological structure - Granite (gr)

Geological structure- Granite (gr)

Normal geological fault trending NW-SE

Normal geological fault

Normal geological fault

Normal geological fault trending N-S

Normal geological fault trending E-W

APPENDIX II - PUBLISHED WORK

36th EARSeL Symposium 2016
Frontiers in Earth Observation
20-24 June 2016, Bonn, Germany

Morphological Analysis Using Modern Techniques (Tinos Island, Aegean, Greece)

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PRESENTATION OUTLINE

- *Scope of the present work*
- *Methodology*
- *Results - Discussion*
- *Conclusions*
- *References*

SCOPE OF THE PRESENT WORK

- *Geomorphologic study of the southern part in Tinos island (Greece) in order to:*

1. *Check the efficiency of a new developed in Matlab algorithm to automatically detect the geomorphologic features using topographic data*
2. *Compare the results of the automatic detection with the data provided from field work on Tinos Island*
3. *Detect possible new geomorphologic structures, not mapped up to now*

METHODOLOGY

- *Topographic data in the present work are analyzed using the methodology developed by Panagiotakis and Kokinou (2014, 2015), concerning the automatic enhancement and detection of geomorphologic features*
- *Elevation data, used in Matlab to check the algorithm, were digitized from the topographic maps of a scale 1:5,000 (contour interval 4 m) published by the Hellenic Army Geographical Service (H.A.G.S.).*
- *The field trip in Tinos took part in the beginning of 2016. The geological data collected have been processed using commercial software ArcGis and FPTectonics*

The algorithm

•***Input data*** *are bathymetric/elevation data (in .txt or .shp format. The first two columns of the input file correspond to the x, y coordinates. The third column corresponds to the depth of the sea floor or the ground elevation (in case onshore data are to be processed).*

•*Calculation of the* $F(p) = (S^2(p) \cdot SS(p) \cdot SA(p))^{1/4}$ *where,*

1. $S(p) = tan^{-1}(|v(p)|)$, *corresponding to the slope at point p(S(p)) of the topographic surface Z.* $v(p)$ *denotes the plane tangent vector. Slope is measured in degrees with* $S(p) \in [0, \quad 90]$

2. $A(p) = atan2\left(\frac{\partial Z(p)}{\partial y}, -\frac{\partial Z(p)}{\partial x}\right)$ *corresponding to the aspect at point p(S(p)) of the topographic surface Z. Aspect is measured in degrees with* $A(p) \in [0, \ 360]$.

3. *SS (p): the first derivative of the Slope image.*

4. *SA(p): the first derivative of the Aspect image (Slope of Aspect).*

•*Estimation of the absolute value image convolution of the F with a zero mean filter G(a,w) of orientation angle a and width w (Fig. 1), as follows:* $Ig(a, w) = F * G(a, w)$

•*The output corresponds to an image showing the automatic detections of the geomorphologic features in the study area. The resulting image Im is provided by getting the maximum of the corresponding pixel values of images Ig(a,w):* $Im = max_{a,w} Ig(a,w)$.

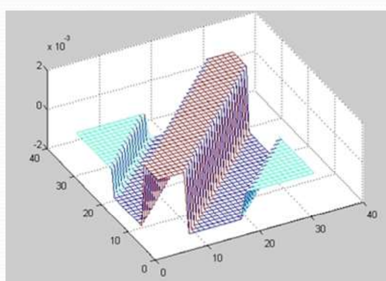


Figure 1. The step filter (Panagiotakis et al., 2012)

The topographic data digitized

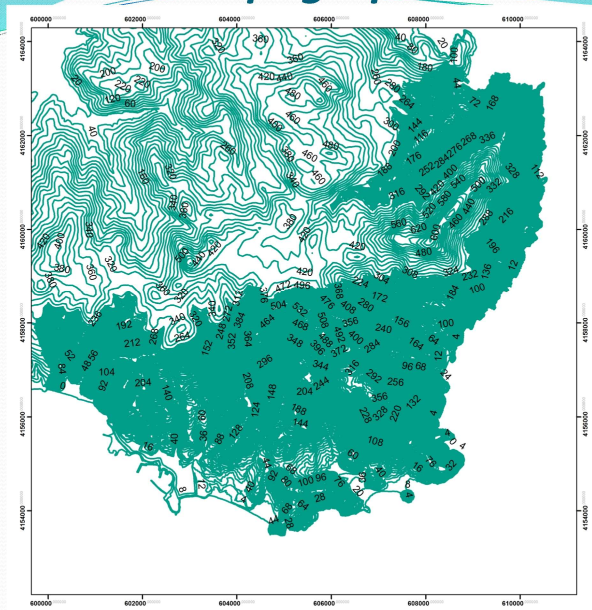


Figure 2. Topographic contours of the southern part in Tinos island (Greece) , digitized from the topographic maps of a scale 1:5,000 (contour interval 4 m) published by the Hellenic Army Geographical Service (H.A.G.S.).

Field work in Tinos island

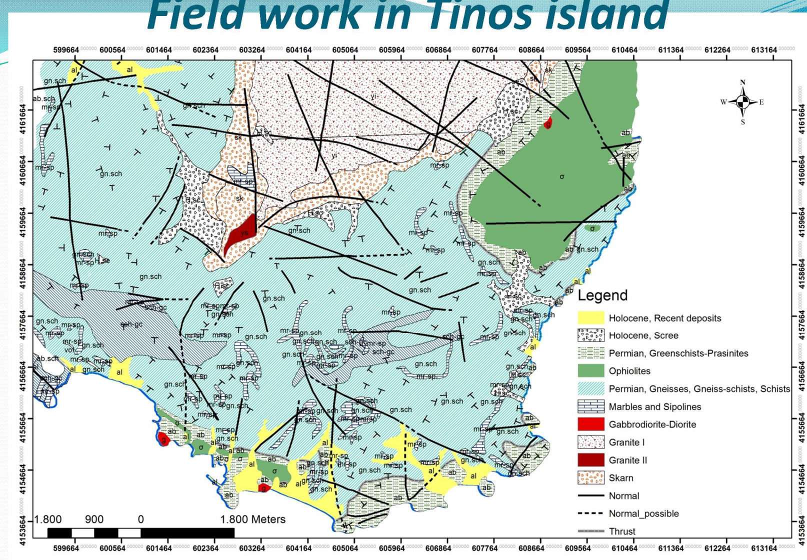


Figure 3. Geological map of the southern part in Tinos island (Greece, Aegean), digitized from the geological map of IGME (1:50000)

Field work in Tinos island

(a) gn.sch

(b) ab

(c) σ

(d) al

Figure 4 (a-d). The geological formations

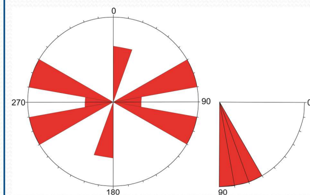
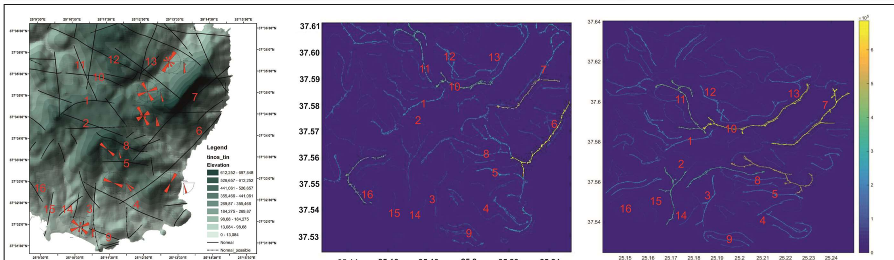


Figure 5. Rosediagram showing the strike and the dip of the normal faults measured

Comparison of the automatic detection results (right) with the real data collected (left)



Normal faults on Tinos Island according to the IGME (1:50000) and field measurements

Automatic detected faults for the same area using the algorithm of Panagiotakis and Kokinou (2015). Red numbers correspond to the similar features on the geological map.
Digitized from the 1:50000 topographic map.

Automatic detected faults for the same area using the algorithm of Panagiotakis and Kokinou (2015). Red numbers correspond to the similar features on the geological map.
Digitized from the 1:5000 topographic map. The accuracy of the detection increases rapidly.

CONCLUSIONS

- *In the context of this work, the geomorphological features in the southern part of Tinos island and the related structures are identified, using a modern processing methodology.*
- *Furthermore the automatically geomorphologic parameters are compared with field data collected in the beginning of 2016 during the field trip in Tinos.*
- *Major and accompanying morphological structures are estimated with high precision concerning their location and shape.*
- *The pre-mentioned methodology has been proved successful, yielding high-performance results concerning the study area. More specifically, the geomorphologic structures and especially the normal faults seem to be detected with sufficient accuracy concerning their location and orientation.*
- *The experimental results indicate the reliable performance of the proposed methodology. Further this method has a low computational cost.*

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CORRELATION OF ONSHORE AND OFFSHORE TOPOGRAPHY TO DETECT SIMILAR GEOMORPHOLOGIC FEATURES IN THE PROXIMITY OF THE LAND AND THE SEA

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36th EARSeL Symposium 2016
Frontiers in Earth Observation
20-24 June 2016, Bonn, Germany

ABSTRACT

The geomorphology of both the offshore and onshore environment is strongly related to the past and modern geodynamics-tectonics. It is well known that onshore geological structures are easier detected and analyzed in relation to the geological structures in the marine environment. This is because the access to land is easier. On the contrary, the investigation of the marine environment is more complex, time consuming and more expensive.

Scope of this study is to analyze digital elevation data and bathymetric data from the onshore and offshore region of Tinos island in Aegean, based on modern processing techniques in order to qualitatively estimate the similar geomorphologic features (geological faults) in both the land and the marine environment. Digital elevation and bathymetric data have been processed by applying a new algorithm for the automatic enhancement and the identification of the linear patterns, relating to important geomorphologic features. According to this method (Panagiotakis and Kokinou, 2014, 2015; Kokinou 2015) the slope and aspect images, as well as their derivatives are initially computed. Rotation and scale-invariant filter and pixel-labeling methods are then applied to enhance the detection of the geomorphologic features.

Concerning the evaluation and interpretation of the detected land and seabed geomorphologic features, previous geological studies have been used.

METHODOLOGY

Data were processed and combined in the present work using commercial and free software such as Matlab and ArcGIS.

Elevation and bathymetric data in the present work were analyzed using the methodology developed by Panagiotakis and Kokinou (2014, 2015). Part of the algorithm was already available by previous work of the same authors (Panagiotakis et al., 2012). Elevation data were digitized from the topographic maps of a scale 1:5,000, published by the Hellenic Army Geographical Service (H.A.G.S.), while bathymetric data are from the EMODNet, European Marine Observatory and Data Network. The main steps of this method are:

A. Input data are bathymetric/elevation data (in .txt or .shp format), in the present case. The first two columns of the input file correspond to the x, y coordinates. The third column corresponds to the depth of the sea floor or the ground elevation (in case onshore data are to be processed).

B. Calculation of the $F(p) = (S^2(p) \cdot SS(p) \cdot SA(p))^{\frac{1}{4}}$ where,

1. $S(p) = tan^{-1}(|v(p)|_2)$ corresponds to the slope at point p(S(p)) of the topographic surface Z. u(p) denotes the plane tangent vector defined as: $v(p) = [\frac{\partial Z(p)}{\partial x}, \frac{\partial Z(p)}{\partial y}]^T$ Slope is measured in degrees [0, 90].

2. $A(p) = atan2(\frac{\partial Z(p)}{\partial y}, -\frac{\partial Z(p)}{\partial x})$ corresponds to the aspect at point p(S(p)) of the topographic surface Z. Aspect is measured in degrees [0, 360].

3. SS (p): the first derivative of the Slope image. 4. SA(p): the first derivative of the Aspect image (Slope of Aspect).

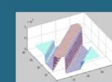

Figure 1. Step Filter

C. Estimation of the absolute value image convolution of the F with a zero mean filter G(a,w) of orientation angle a and width w (Fig. 1), as follows: Ig (a, w) = F * G (a, w).

D. The output corresponds to an image showing the automatic detections of the geomorphologic features in the study area. The resulting image Im is provided by getting the maximum of the corresponding pixel values of images Ig(a,w): Im = maxa,w Ig(a, w).

RESULTS (A) and INTERPRETATION (B)

(A)

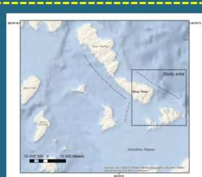

Figure 2. Location map of the study area. Basemap is from the ArcGIS 10 online database . Geological faults are from the seismotectonic map of Greece ,1:500000 (1989).

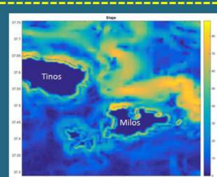

Figure 3. Bathymetric slopes in the study area. Note that steep slopes (>65°) prevail in the northern offshore area of Tinos and Milos islands.

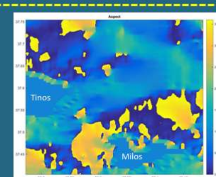

Figure 4. Bathymetric aspects in the study area. Note that NNE (0-50°), SSW(180-230°) and NNW (300-359°) prevail in the study area.

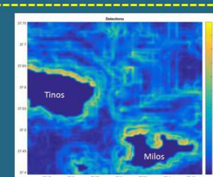

Figure 5 Automatic detected elements in the study area based on the methodology of Panagiotakis and Kokinou (2015).

(B)

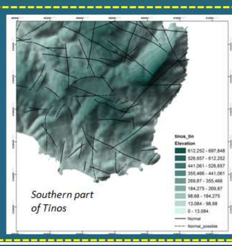

Figure 6. First step- digitization of topographic data and normal faults (Geological map of Tinos , 1:50000).

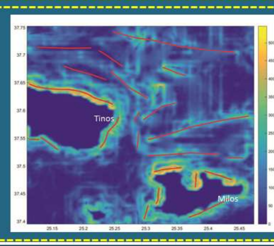

Figure 7. Second step Possible offshore normal geological faults in red color based on the automatic detection.

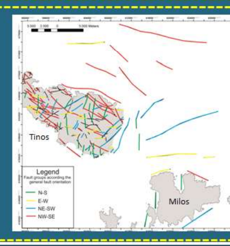

Figure 8. Third step Both on land and in the sea are indicated four fault groups of geological faults, according to their general orientation. NW-SE trending faults prevail offshore north of Tinos, while NE-SW to N-S prevail to the east of this island.

CONCLUSIONS: In this work, bathymetric and elevation data are combined using modern processing techniques to trace the continuity of land geological faults towards the sea environment of Tinos island. NW-SE trending faults seem to prevail offshore north of Tinos, while NE-SW to N-S prevail to the east of this island.

References:

1. Panagiotakis C. and Kokinou E., 2015, Linear Pattern Detection of Geological Faults via a Topology and Shape Optimization Method, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(1), 3-11.
2. Panagiotakis C. and Kokinou E. , 2014, Automatic enhancement and detection of active sea faults from bathymetry. In: Proceedings of the 22nd International Conference on Pattern Recognition (ICPR), pp. 855-860, 24–28 August, Stockholm, Sweden. Publisher: IEEE, DOI: 10.1109/ICPR.2014.157
3. Kokinou E.,2015, Geomorphologic features of the marine environment in Eastern Mediterranean using a modern processing approach, In: Helmut Schaeben, Raimon Tolosana Delgado, K. Gerald van den Boogaart, Regina van den Boogaart (Eds.) (2015) Proceedings of IAMG 2015 Freiberg, September 5-13, 2015 The 17th Annual Conference of the International Association for Mathematical Geosciences, 436-445, ISBN 978-3-00-050337-5.

EARSeL: Poster Session Time: Tuesday, 21/Jun/2016: 4:00pm - 5:30pm, Location: S 29/31