Study of the Morphological Attributes of Crete through the Use of Remote Sensing Techniques

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Abstract: - Quantitative estimates of the morphological attributes of the island of Crete have been computed through the application of directional derivatives to the digital elevation model and the classification of loci with common landform characteristics. The specific study has also investigated the correlation of the resulting geomorphometric units with the geological properties of the island, including geological formations and faults. In the latter case, ground prospection methods and macroscopic geological surveys have been applied in order to verify the results of this correlation.

Key-Words: - Geomorphology, DEM, Remote sensing, geophysical prospection, faults.

1 Introduction

For a number of decades, the study of the geomorphometric properties of the terrain has been the subject of research for a number of researchers who were trying to explore the properties of the terrain and determine if there is a physical meaning in the quantitative analysis of them in terms of the land patterns. This kind of numerical estimates have been carried out manually in the period before 1970 (Horton, 1945, Coates, 1958) and gradually they started to be computed in a more automatic way, especially after the availability of digital products originating by digitization processes. The increasing accessibility of digital satellite images has made possible the automatic extraction of the basic terrain properties, especially those originating by the digital elevation model.

The digital elevation model and its products (aspect, slope, hillshade, etc) have undergone systematic processing in order to derive quantitative data regarding the terrain units (Onorati et al., 1992, Hutchinson & Gallant, 2000), the classification of slope steepness (Skidmore, 1990, Giles and Franklin , 1998), land use correlations, etc. Recently, a paper by Adediran, et al (2004) attempted a morphological units classification on north-central Crete by applying multivariate statistics to local relief gradients of the DEM. The specific study suggested a correlation among slope steepness, lithological structures and land cover typologies. The scale of the research was small enough to allow such kind of deductions. Still, the question remains in cases where we have to deal with a much larger scale of investigation.

Following a similar line of approach, the current research tried to cover the whole island of Crete and examined the possible correlation of the geomorphic units with the existence of faults. Furthermore, ground truthing techniques were also applied in order to verify the results of the computer processing. The final classification scheme was cross-correlated with the existence of faults and VLF prospection was carried out to verify the final conclusions of processing.

2 Geological and Geomorphological Attributes of the Study Area

Crete is a mountainous island, the largest of the Greek islands, located south of the Aegean Sea and consisting of a link between Asia, Africa and Europe. Its unique geographical position between the three continents determined its historical course both throughout antiquity and in modern times. It has an elongated shape having dimensions of 260 km along the W-E axis and 60 km maximum width along the N-S direction. Smaller widths are also noticed in specific parts of the island, such as in the region of Ierapetra where it is only 12 km. It has an area of 8261 sq. km and a coastline extending over 1046 km in length. To the south it is bordered by the Libyan Sea, to the west the Myrtoon Sea, to the east the Karpathion Sea and to the north the Sea of Crete. Its coastline, which consists of both sandy beaches and rocky shores, is framed by the small islets of Kouphonisi, Chrissi, Dia, Aghioi Pantes, Spinalonga, and Gavdos, in the Libyan Sea, the southernmost point of Europe. In the mainland, a number of tectonic basins and grabens separate the mountain range consisting of Lefka Ori, Idi and Talea Ori, which reach a maximum of 2456m above sea level.

The island of Crete is characterized by the presence of pre-alpine and alpine rocks that constitute a complex nappe pile, and of late alpine, neogene sediments that fill the basins occurring between the high mountains (Fytrolakis 1980, Bonneau 1984). A number of different, fault bounded units constitute the nappe pile of central Crete. According to their tectonostratigraphic position and their tectono-metamorphic history, these nappes are divided into two major groups; the upper nappes and the lower nappes, separated by a major normal detachment fault (Fassoulas 1995).

The alpine and pre-alpine rocks of Crete (the rocks which formed prior or during the alpine orogenessis) occur in the different nappes of the island. Three individual groups constitute the lower nappes: The lowermost *Plattenkalk* nappe (or Ida nappe, or Cretan-Mani sequence) is comprised of mainly carbonate rocks (Fytrolakis 1978). At the base level, Permian schists and clastic sediments occur. Neretic dolomites and limestones of Upper Permian age (Fodele beds) rest uncomfortably over these, lower rocks, while clastic dolomites and limestones (Sisses beds) continue till the Scythian. A characteristic dolomite containing stromatolites was deposited in Norian. Over these rocks the Gigilos beds crop out containing schists, clastic sediments and dolomites of unknown age (Creutzburg et al. 1977). Finally, since the Middle Jurassic, the typical platy limestones occur, covered in few areas by thin flysch sediments of Oligocene age (Fytrolakis, 1980). The sediments of the Plattenkalk nappe were deposited in a neretic platform, which gradually passed in to a pelagic environment.

Tectonically, in western Crete, the *Trypali* nappe lie just over the Plattenkalk series lies. This consists of carbonate, recrystallized conglomerates, limestones and dolomites of Triassic to Lower Jurassic age (Fytrolakis 1980). The phyllite-quartzite nappe is located at the uppermost position of the lower nappes and consists of two parts: the upper one with phyllites, schists, quartzites, limestones and meta-volcanic formations and the lower with dolomites quartzites and gypsum.

The upper nappes are comprised of several fault bounded units. Immediately above the main detachment fault which separates the lower and upper nappes, lie the alpine sediments of the Tripolis and Pindos nappes (Seidel et al., 1982). The base of the Tripolis nappe consists of Middle to Upper Triassic dolomites, schists and clastic sediments called Ravdoucha beds. A Mesozoic neretic carbonate series lies comfortably over the Ravdoucha beds ending with Upper Eocene flysch sediments. The Tripolis limestones are intensely karstified accommodating most of the aquifers of the island. The Pindos nappe consists of Triassic to Jurassic pelagic sediments, such as cherts, radiolarites, limestones and siltstones, an Upper Cretaceous first flysch, pelagic platy limestones of Palaeocene age and an Upper Paleocene/ Eocene flysch.

Above the Pindos nappe and below the crystalline rocks of the Asteroussia nappe, the Vatos, Arvi and Miamou units are comprised of sediments, whereas the Spili unit consists of crystalline, baroisite- bearing vand sheared serpendinites (Krahl et al. 1982), related to an old ophiolitic nappe. The Preveli unit consists of schists, marbles and rocks. These rocks expose relict tectonic structures related to subduction processes (Fassoulas, 1995). The top of the nappe pile comprises the Asteroussia and the Ophiolitic nappes. Late Cretaceous rocks (mainly amphibolites, quartzites, gneisses and schists) constitute the Asteroussia nappe.

The post-alpine rocks of Crete occur as Neogene and Quaternary sediments in the east-west and north-south trending basins, resting on the upper and lower nappes. The Neogene and Quaternary sediments of the central and eastern Crete can be classified into several groups.

The oldest, Neogene sediments consists of dark limestone breccias and conglomerates, sometimes well-cemented with a calcareous matrix. A good outcrop of these sediments occurs west of Tylissos in the Mylopotamos graben in central Crete, north of Ierapetra in eastern Crete and in the Topolia area west of Chania.

The terrigeneous - clastic rocks of the Tefeli groups were deposited on the basement rocks and comprises of conglomerates, sands and clays, reflecting deposition in fresh-water, brackish and marine environments. These sediments occur in central Crete and in Chania area.

In the Early Messinian period, marine sedimentation consisting of bioclastic, often reef algal-coral limestones with the associated alternations of laminated shallow marine marls that constitute the Vrysses group is increased. This group rests on the rocks of the Tefeli group and, in few places (such as in the area north of Tylissos and near Vrysses village east of Chania), on the basement rocks. In the same period, uplift processes and erosion resulted in the deposition of the Hellinikon groups. The group consists of coarse, non-marine, conglomerates, fluvial lacustrine and lagoonal sediments with gypsum.

During the early-middle Pliocene, the Finikia group was deposited on the Miocene sediments. The group consists of marl breccias at the base and open marine, white marls, clays and locally intercalations of brownish beds and diatomites. These beds are characteristically outcrops near Heraklion and west of Chania towns. During this period, a major uplift of the Heraklion area separated it from the southern, Messara basin, which, until that time had a common sedimentary history.

The erosion of the Heraklion basin's sediments supplied the Messara basin with coarse, generally reddish, non-marine conglomerates and sands, that constitute the Agia Galini group, witch appears to be the youngest Pliocene formation of Crete.

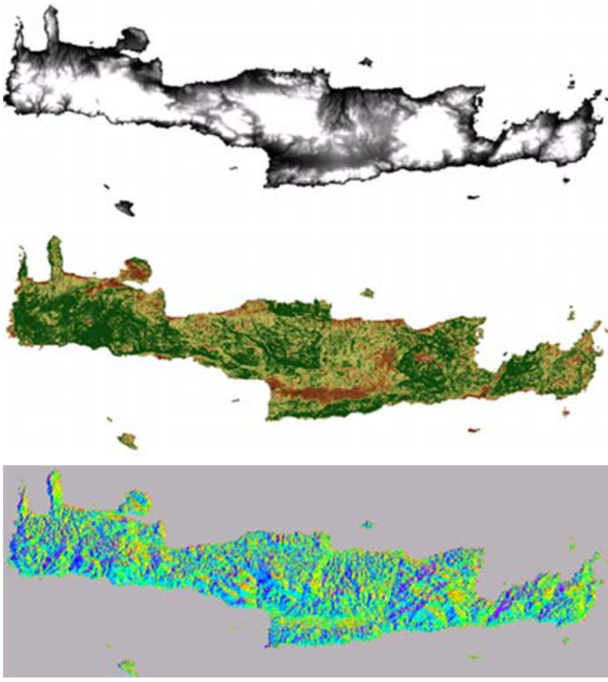
In the Pleistocene, sea level fluctuation caused the development of the Quaternary marine terraces and limestones and of terrestrial, generally reddish conglomerates and sands, which mainly occur near the southern and northern coasts of Crete.

Fig. 1 Geological map of Crete created through digitization and processing of the available 1:50,000 scale geological sheets of the Institute of Geological and Mineralogical Exploration.

3 Processing Methodology

Stereopair images of SPOT4 have been used to create a 50m pixel resolution DEM. The DEM was geometrically corrected using a 10m resolution orthorectified panchromatic image of SPOT4. Other geological and topographic data were also imported in the research scheme, including digital topographic maps of the Geographic Service of the Hellenic Army (1:50,000 scale), geological maps of the Institute of Geological and Mineralogical Exploration, land use and land capability maps of the Ministry of Agriculture and a number of multispectral satellite images (Landsat and SPOT) taken during the period of 1986 -2003.

The stereopair images of SPOT4 were stretched in order to construct the digital elevation model with the appropriate range of elevation values. The validity of the digital elevation model was tested for various altitudes. ERDAS 8.7 was employed to create secondary products of the DEM, such as slope, aspect and hillshade maps (Fig. 2). The specific maps emphasize the rate of change of the elevation values, the alignment of the sloping surfaces and the subtle differences of the terrain as seen from different lighting directions, respectively. All of the above products were used for the visual inspection of the morphological characteristics of the area of interest.



A

B

C

Fig. 2 Digital elevation model of Crete (A), slope map (B) and aspect map (C).

Idrisi Kilimanjaro software package was used for the application of the directional derivatives to the DEM. The directional filters, in the form of a moving window of dimensions 3x3, were formed in a similar way as it has been described in Adediran, et al (2004). Eight filters in total, describing the 8 main azimuth directions (N, NE, E, SE, S, SW, W, NW), were formed and applied to the DEM. The specific process has emphasized the morphometric attributes of the terrain in the specific directions (Fig. 3). The resulting maps were stacked and used as input for the classification scheme that followed.

ISODATA (Iterative Self-Organizing Data Analysis Techniques) algorithm was employed for the unsupervised classification of all the eight layers resulting by the filtering process. According to it, the resulting classes are assigned based to the common spectral or radiometric characteristics through an iterative process, namely through the repeating classification and calculation of statistics, until a threshold corresponding to the maximum percentage of unchanged pixels is achieved (Mather, 1999). In our case, 10 classes were chosen with 6 maximum iterations and a 0.950 convergence threshold.

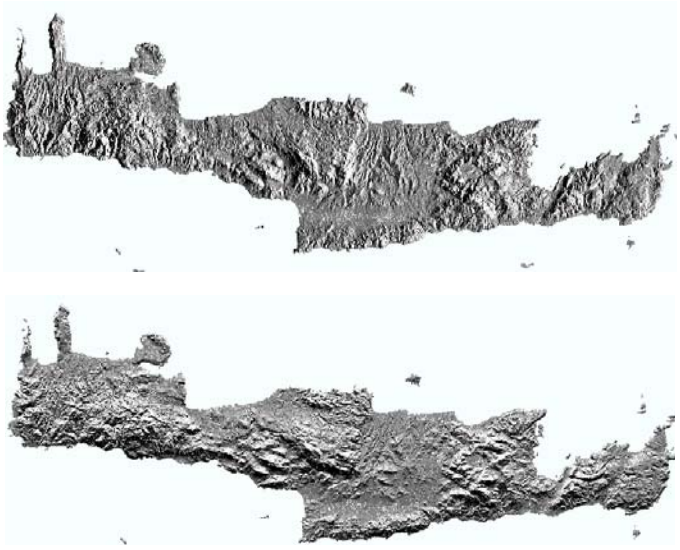


Fig. 3 Resulting maps after the application of the directional filters along the east (top) and north (bottom) directions.

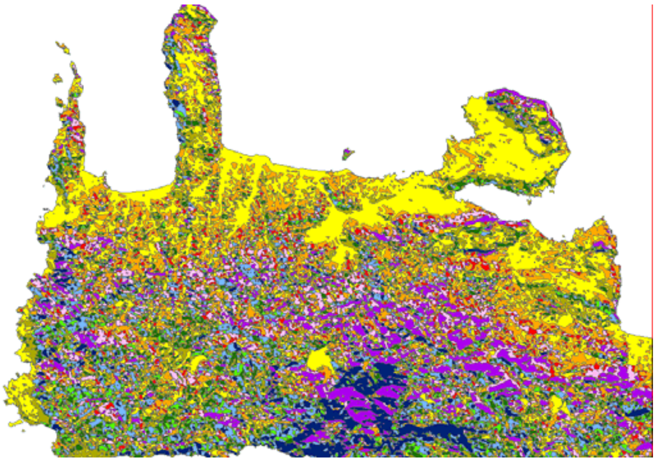


Fig. 4 Result of the generalized unsupervised classification process. Details from the west part of Crete (Chania region). The different colours are indicative, in order to emphasize the visual differentiation between the classes and help the interpretation of the geomorphic attributes in each area.

Due to the large scale of coverage, the result of the ISODATA classification consisted of a large number of fragmentary areas. In order to make it possible to compare the results of the analysis with the available geological data, it was considered necessary to generalize the regions extracted by the classification procedure, by joining the fragmentary classes into larger regions, based on the frequency of the classes' attributes in the surrounding region. Thus, a 5x5 majority filter, followed by a 3x3 majority filter was applied to the classification results. The final raster data were transformed to polygon features and then a clip process was applied in order to isolate the mainland from the sea (Fig. 4). Each polygon was also assigned the values of the directional derivatives and it was also linked to the database of the geological map. The mean value of the rate of the elevation differences of the central pixel and each neighbourhood along the 8 main directions for each one of the 10 classification categories is summarized in Table 1.

Class	**Mean value Elevation differences**			**Interpretation**
1	-13,3	-19,3	-23,7	**Steeply sloping areas facing S-SW**
	5,9		-5,7	
	21,1	15,9	9,6	
2	-7,9	-12,9	-17,0	**Steeply sloping areas facing SW**
	4,7		-4,8	
	14,1	10,1	5,4	
3	-7,3	-9,1	-10,4	**Average-Steeply sloping areas facing S-SW-SE**
	1,5		-1,7	
	8,2	7,2	5,5	
4	-5,9	-6,3	-6,6	**Average-Steeply sloping areas facing S-SW-SE**
	0,5		-0,6	
	5,3	5	4,2	
5	-2,3	-2,9	-3,6	**Average sloping areas facing SE**
	0,6		-0,9	
	2,9	2,4	1,4	
6	0,3	-0,0	-0,2	**Almost plain with low sloping**
	0,3		-0,3	
	0,3	-0,0	-0,2	
7	3,6	4,2	4,6	**Average sloping areas facing N-NE**
	-0,6		0,8	
	-3,5	-3,1	-2,2	
8	3,5	7,1	10,4	**Average-Steeply sloping areas facing N-NE**
	-3,5		3,8	
	-8,9	-5,7	-1,9	
9	7,8	11,4	14,8	**Steeply sloping areas facing N-NE**
	-3,6		4,3	
	-12,2	-8,9	-4,4	
10	14,6	17,9	21,4	**Steeply sloping areas facing N-NE**
	-3,4		5,1	
	-16,8	-13,6	-7,9	

Table 1. Mean value of the elevation differences within the neighbourhood of the central pixel for each of the 10 classification categories and interpretation of them regarding their slope and aspect.

A further verification of the exclusivity of the classes was achieved through the three-dimensional plotting of the classes with respect to their altitude, slope and aspect attributes (Fig. 5).

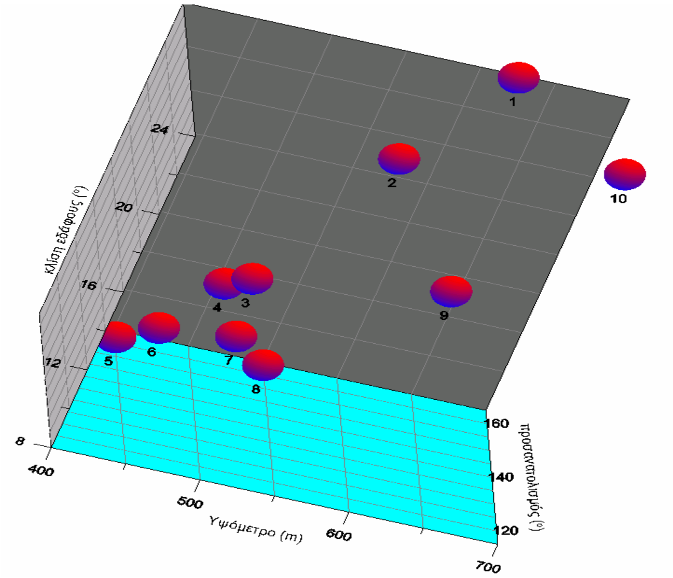


Fig. 5 3-D plotting of altitude, slope and aspect, indicating the distinction between the different classes.

4 Results & Interpretation

Different colors were assigned in each classification category in order to differentiate the classes and to distinguish larger regions with a more generalized degree of homogeneity of their morphometric features. Twenty one morphometric units were defined, based on the results of the classification, the visual interpretation of them and the statistical analysis of each class in terms of their slope, aspect and geological settings (Table 2, Fig. 6). Statistical analysis of the geological attributes of each unit was carried out aiming towards the geological interpretation of the morphometric units (Fig. 7).

GEOMORPHIC UNITS & CLASS DENSITY (%)										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
I	0	0	0	1	5	**89**	5	0	0	0
II	0	1	1	10	**37**	**42**	8	1	1	0
III	0	0	0	3	**60**	**35**	1	0	0	0
IV	0	1	1	5	11	**38**	**37**	5	2	0
V	0	1	1	6	18	**42**	**26**	3	2	1
VI	0	1	1	4	5	**20**	**56**	9	4	1
VII	**27**	**32**	14	11	4	4	3	1	2	2
VIII	**76**	13	2	2	1	2	1	1	1	2
IX	2	3	2	3	1	3	6	2	11	**67**
X	1	1	1	3	2	4	9	9	**25**	**44**
XI	3	4	3	5	3	8	17	11	**21**	**24**
XII	1	3	3	7	6	13	**28**	15	16	7
XIII	1	5	13	**42**	**24**	10	4	1	1	0
XIV	3	7	7	**19**	**16**	**18**	15	6	7	3
XV	2	13	15	**30**	16	11	7	2	3	1
XVI	0	3	2	**41**	**41**	8	2	0	1	0
XVII	2	9	6	12	8	14	**20**	10	**14**	6
XVIII	1	2	3	9	11	**27**	**31**	7	6	2
XIX	1	3	4	18	**21**	**28**	15	4	3	1
XX	0	2	2	5	5	13	**38**	17	17	2
XXI	**32**	7	3	4	3	5	5	1	7	**32**

Table 2. Statistical correlation between the morphometric units and the classification categories. The dominant percentages of the classes in each morphometric unit are also marked.

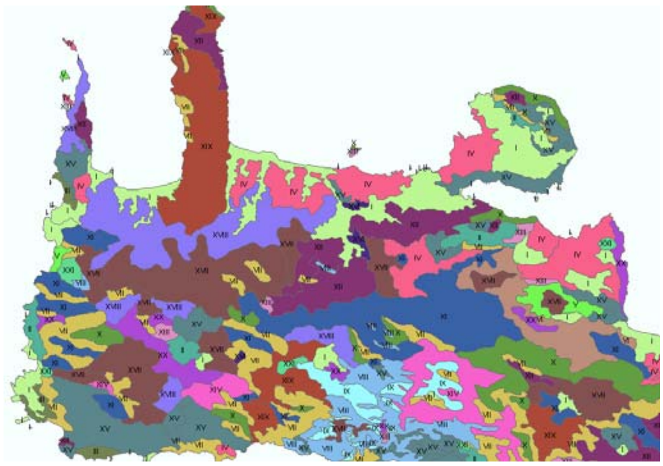


Fig. 6 The outline of the morphometric units was based on the statistical correlation with the individual classes. Details from the west part of Crete (Chania region).

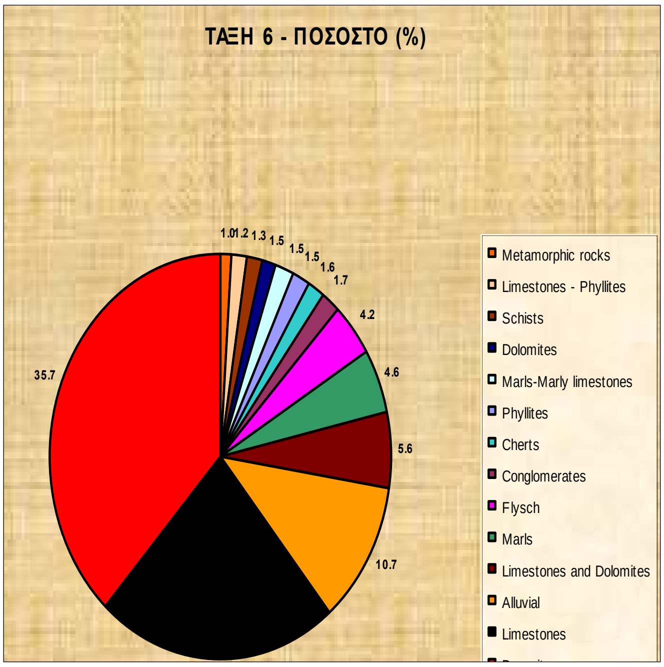


Fig. 7 Statistical results were computed for each morphometric unit in terms of their geological content, based on the geological categories outlined at the maps of the Institute for Geological and Mineralogical Exploration.

In order to examine any possible relationship between the morphometric units and the geological formations, the geology map of IGME has been classified into more general categories, namely sedimentary deposits and hard rocks. The cumulative percentage for each category has been estimated for each of the morphometric units (Table 3). Depending on the percentage presence of each category, three main characterizations have been assigned: S (Sedimentary deposits), R+S (Mixed - Sedimentary and rocks) and R (rocks). Based on the above classification scheme, it was observed that sedimentary deposits (S) are mainly included in units I, II, III and XVI, which are located along the coastal area of Chania, Rethymnon, Heraklion and Lasithi prefectures (tectonic basins) and which are dominated by almost plain (increased sedimenation) and low to average sloping areas (class 5 and 6). A more or less equal contribution of sedimentary deposits and rock formations (units IV, VI and XIII) is mainly observed in the central areas of Chania and Heraklion prefectures, dominated by average to steeply sloping areas (class 3 ,4 and 7) and occasionally, almost plains with low sloping areas (class 6). Finally, the rocky formations (units V, VII, VIII, IX, X, XI, XII, XIV, XV, XVII, XVIII, XIX, XX, XXI) cover the highlands of Lefka Ori and Idi Mountain and Lasithi plateau and are dominated by average to steeply sloping areas (class 1, 2, 3, 8, 9 and 10).

UNIT	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**
Sedimentary Deposits	70	71	87	41	33	52	14
Rocks	30	29	13	59	67	48	86
	S	S	S	R+S	R	R+S	R
UNIT	**VIII**	**IX**	**X**	**XI**	**XII**	**XIII**	**XIV**
Sedimentary Deposits	2	1	1	9	20	44	22
Rocks	98	99	99	91	80	56	78
	R	R	R	R	R	R+S	R
UNIT	**XV**	**XVI**	**XVII**	**XVIII**	**XIX**	**XX**	**XXI**
Sedimentary Deposits	33	78	13	30	31	23	6
Rocks	67	22	87	71	69	77	94
	R	S	R	R	R	R	R

Deposits, alluvial, flysch	S	I, II, III, XVI
50 % Sediments, 50% rocks	R+S	VI, IV, XIII
Limestones, Marls, Phyllites, Schists, Dolomites, Quartzites, Marble, Metamorphics	R	V, VII, VIII, IX, X, XI, XII, XIV, XV, XVII, XVIII, XIX, XX, XXI

Table 3. Statistical correlation between the morphometric units and the generalized geological formations. Numbers are given as percentages.

Except the geological interpretation of the extracted morphometric units, the relationship between them and the tectonic features, as they are defined by the geological map of IGME, has been also studied (Fig. 8). It has been noticed that the major tectonic lines (features with the largest size) exist at the interface between the unit pairs 1-4, 1-17, 1-15, 1-12, 1-21 and 17-18. Specifically, the tectonic basins of Herakleion, Chania and Ierapetra, were created by tectonic faults which were defined in the boundary between 1-21, 1-12 and 1-17 units, respectively. Although the above observations do not necessarily mean that the above mentioned units are directly related with a tectonic feature, it can be suggested that that tectonic features have a large probability to exist at the boundaries between deposits (geomorphic unit 1) and calcitic rocks (geomorphic unit 4, 12, 15, 17 & 18).

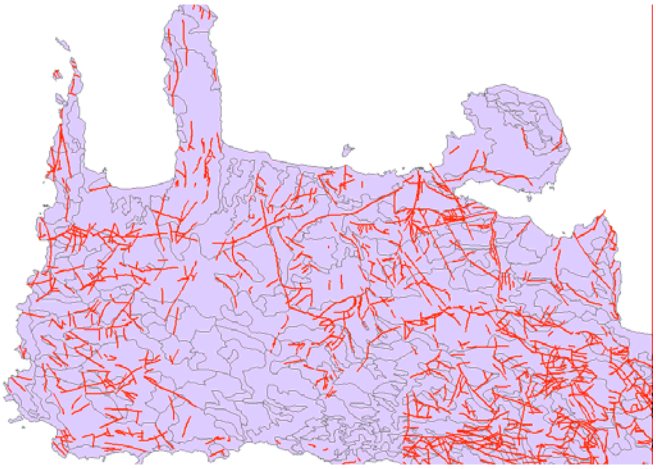


Fig. 8 Correlation of the morphometric units with the tectonic features of Crete was achieved through the overlay of the fault characteristics of the island of Crete on the resulting geomorphic map. Details from the area of Chania are given.

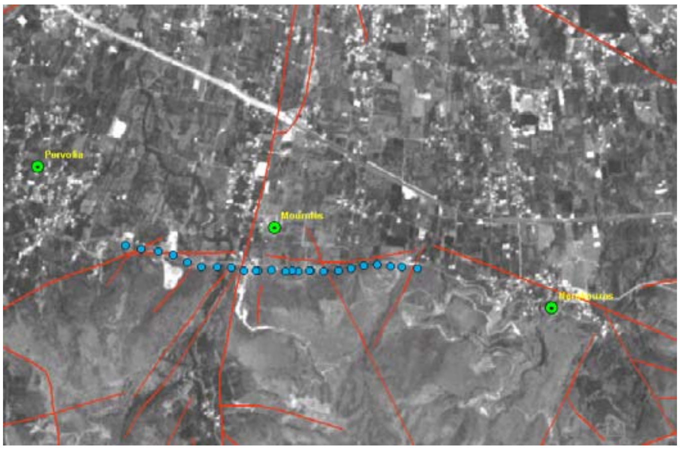


Fig. 9 SPOT4 satellite orthorectified image (PAN) of the area of Mournies, showing the path (blue dots), along which VLF measurements were obtained. The red lines indicate the location of the fault features represented at the IGME map.

In order to test the validity of the above observations in the field, shallow electromagnetic methods were employed at selected areas, where fractures are suggested to exist by both the resulted morphometric features and the geological map of the area. An area close to the village of Mournies, in the Municipality of Chania, was chosen in order to confirm the tectonic features suggested by the above maps with the geophysical measurements and modelling. The TVLF of IRIS was used for the acquisition of the VLF data. The measurements were carried out along one profile of total length of 2.100m. Readings were taken along the profile stepwise at 20 m intervals. The profile had an almost east-west orientation and was extended along the road to the north of the public hospital of Chania (Fig. 9). A Fraser filter (Fraser, 1969) was applied to the data in order to suppress the noise. More specifically, a modified 5-point Fraser filter was used to plot the output of the filtered data at the same locations as the tilt angle measurements. The tilt angle and ellipticity raw data as well as the Fraser filtered data are presented in Fig. 10.

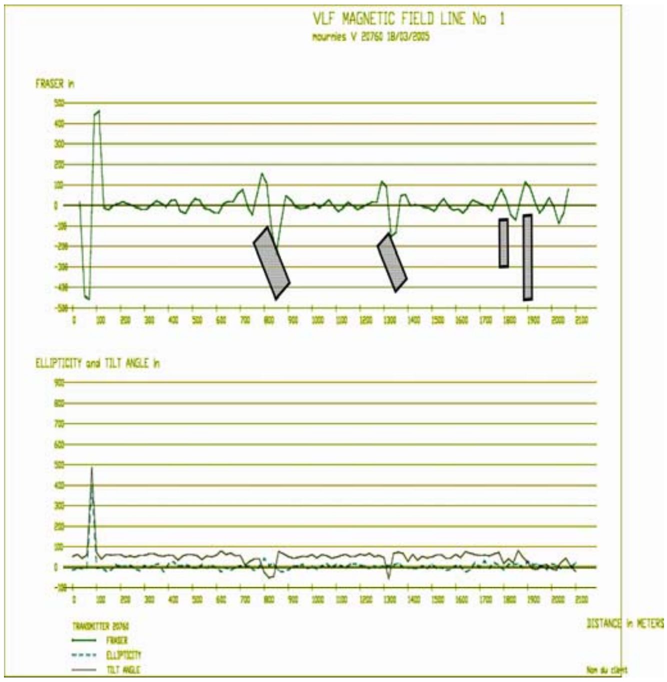


Fig. 10 Results of the VLF measurements conducted in the area of Mournies, close to the public hospital of Chania (bottom). Source frequency was equal to 20.7 kHz. X-axis represents the distance from the beginning of the profile. The Fraser filtered data, together with the measurements of ellipticity and tilt angle are given in the graph above (top).

Three fracture zones are clearly located between 700 to 900m, 1250 to 1400m and 1750 to 1950m from the origin of the profile, with a dip towards the West for the first two fractures and a vertical dip for the third fracture (Fig. 10 & Fig. 11). These zones are in agreement with the resulted morphometric features (interface between units I and XII) and geological maps.

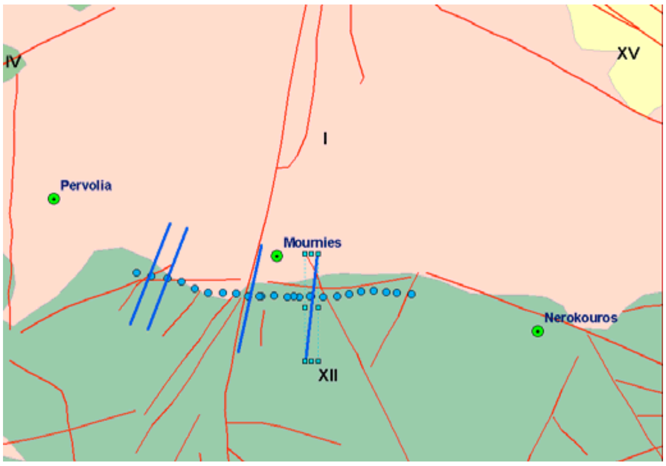


Fig. 11 Map of the morphometric units outlined in the area of Fig. 9. There is a clear relation between the tectonic features defined in the geological map (red lines) and the fractures located by the VLF measurements (blue lines). The direction of the fractures at the specific locations is shown on Fig. 10.

Fig. 12 Map of the morphometric units computed for the area of Akrotiri. Geological survey of the region verified the existence of the faults, according to the geological map of IGME and studied the macroscopic properties of them. Fieldwork concentrated close to the village of Sternes.

A similar confirmation of the fractural geomorphological features was carried out at the area near the village of Sternes (Akrotiri area) in Chania Municipality (Fig. 12). A systematic geological survey, aiming towards the recognition of possible tectonic faults, was conducted and focused in the area along the road connecting Sternes and Aroni villages. The purpose of the geological mapping was to investigate the correlation of tectonic features with the contact zone between specific morphometric units. The particular region is suggested to be located along the interface of geomorphic units I and XV. Natural exposed sections of the soil were studied macroscopically and the tectonic features between the two different geomorphic units were confirmed in a number of locations along the road, in agreement to the faults represented at the corresponding geological maps of IGME (Fig. 13).

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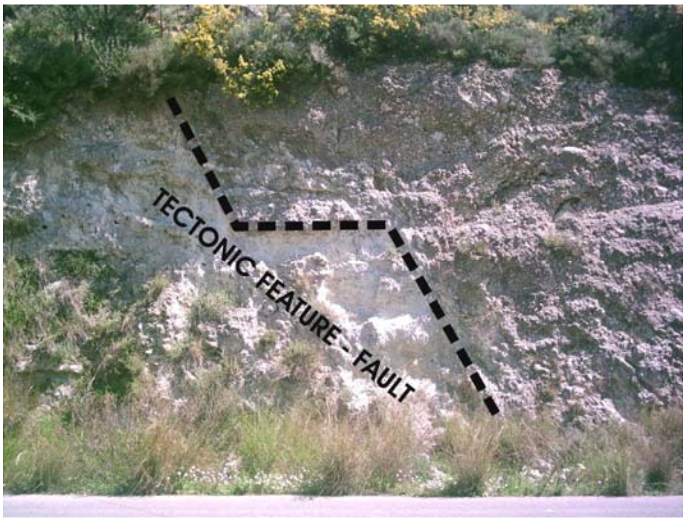

Fig. 13 Photo showing the tectonic contact between different geomorphic units is presented. The photo has been obtained along the road connecting Aroni and Sternes villages.

5 Conclusions

Mapping of the geomorphic attributes of Crete has been carried out (Fig. 14) and has provided encouraging results in terms of their relation to the geological and tectonic characteristics of the region. As such, the results of the particular study can be valuable in the mapping of the general geological formations of a region and the detection of possible tectonic features.

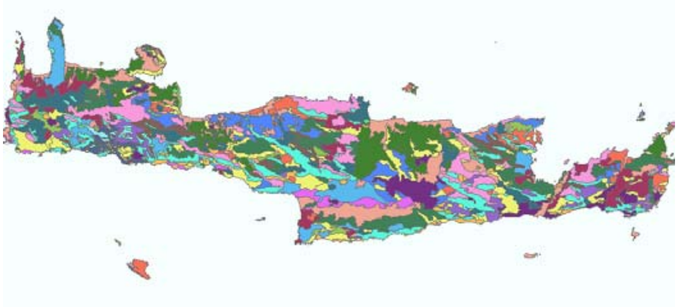

Fig. 14 Synthetic map of the geomorphic units of the island of Crete.

Future directions of the research will explore a) the sensitivity of the model to the DEM resolution, b) the correlation of the morphometric units with Landsat and ASTER spectral signatures, c) the relation of them with the land-use and vegetation classification originating by satellite classification techniques and d) the refinement of the definition of the morphometric units with the generalized geological map which will result through a more generalized classification of the geological maps of IGME.

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