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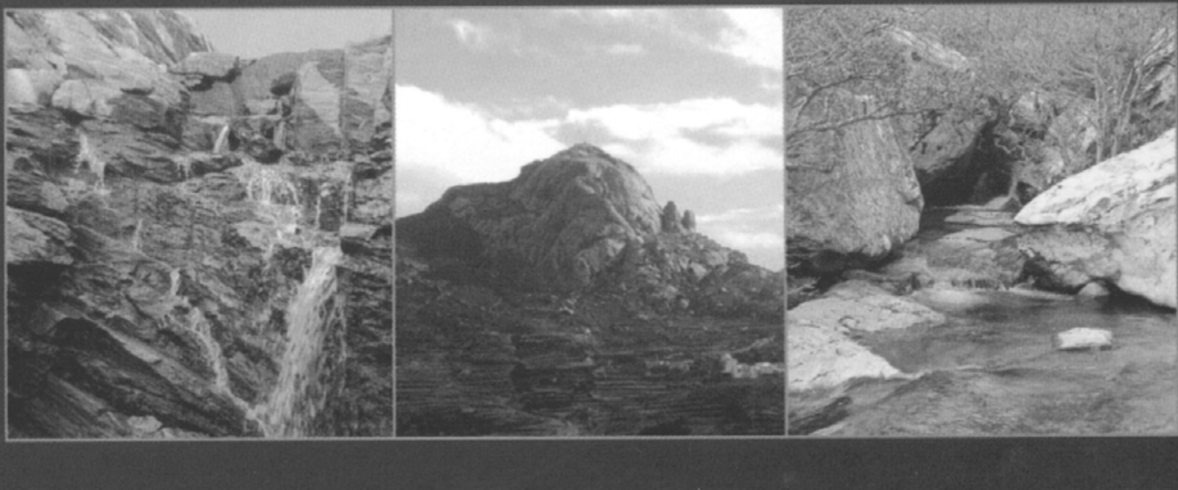

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FRACTURE PATTERN DESCRIPTION AND ANALYSIS OF THE HARD ROCK HYDROGEOLOGICAL ENVIRONMENT, IN A SELECTED STUDY AREA IN TINOS ISLAND, HELLAS

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Διερρηγμένα πετρώματα, σύστημα ασυνεχειών, υδρογεωλογία, Τήνος, τηλεπισκόπιση
Fractured Rocks, hydrogeology, fracture pattern, Tinos, remote sensing

ΠΕΡΙΛΗΨΗ
Η περιγραφή των κυριότερων παραμέτρων, οι οποίες ορίζουν το καθεστώς της υπόγειας ροής του νερού στο μέσο ασυνεχειών, είναι κριτικής σημασίας, κατά την διάρκεια μιας υδρογεωλογικής υδραυλικής ή γεωτεχνικής μελέτης. Στα πλαίσια της παρούσας δημοσίευσης επιχειρείται να γίνει περιγραφή και ανάλυση του συστήματος ασυνεχειών στο υδρογεωλογικό περιβάλλον των σκληρών διερρηγμένων πετρωμάτων, στην Νήσο Τήνο. Η μεθοδολογία που ακολουθήθηκε αφορά σε συνδυασμό τεχνικών ψηφιακής επεξεργασίας δεδομένων τηλεπισκόπισης και στατιστικής επεξεργασίας μέσω συστημάτων γεωγραφικών πληροφοριών, με στοιχεία από εργασίες υπαίθρου. Οι παράμετροι, που εξετάσθηκαν είναι α) η χωρική κατανομή, β) ο προσανατολισμός, γ) οι διαστάσεις, δ) η πυκνότητα, και ε) ο βαθμός διασύδενσης των ασυνεχειών, καθώς και η σχέση τους με γραμμικά στοιχεία τα οποία αναδεικνύονται μετά από επεξεργασία ψηφιακών δεδομένων τηλεπισκόπισης.

ABSTRACT
The description of the main parameters that control the groundwater flow regime, are of critical matter, in a hydrogeological/hydraulical or in a geotechnical study. This paper, aims to describe and analyze the fracture pattern in the hard rock hydrogeological environment in Tinos Island. Remote Sensing and GIS techniques were integrated along with results from field work. The parameters that were analyzed are: a) the frequency and spatial location of fractures, b) fractures orientation, c) fractures dimensions, d) fractures density and e) the degree of fractures intersection, along with their relation to lineament structure that was extracted after remote sensing image interpretation.

1. Introduction

The increasing need of groundwater for water supply during the last decades, led to a continuous interest for groundwater in hard rocks. This interest was focused on a better knowledge about the hydrogeological environment of hard rocks and the recharge, flow and composition of groundwater as well. The groundwater flow regime in hard rocks depends on several factors, including the climate (precipitation and evapotranspiration), geomorphology, tectonic regime and with no doubt on the dimensions, nature, density, orientation and interconnection of fractures. As a result the description of the fracture pattern is a crucial matter for a hydrogeological investigation in this type of environments.

The purposes of this study were the depiction and analysis of the fracture pattern of a selected study area in Tinos Island and its relationship with the major structures like faults and folds, by emphasizing on the following parameters:

a) Fracture frequency and distribution
b) Orientation of fractures
c) Fracture dimensions
d) Fracture density
e) Degree of intersection between fractures

Images collected by late generation satellites are characterized by improved spatial and spectral resolution. The spatial resolution could be improved more by using higher resolution images like air photographs, resulting images ready for lineament interpretation in larger scales. An image lineament, which is a linear object of a priori geological origin, is a structural expression detected by remote sensing (Scanvic 1997).

2. Geological Setting of Tinos Island.

From a geotectonic point of view, Tinos (Fig. 1) belongs to the unit of North Cyclades (Papanikolaou 1986). Metamorphic rocks are classified, by their mineral composition, metamorphic phase and the age of metamorphosis, into three tectonic units (Melidonis 1980, Para et al 2002): (1) the Upper Unit composed of serpentinites, metagabbros, metabassalts, phylittes and stratified amfibolites. Its thickness is 500m approximately; (2) the unit of Cycladic Blueschists, which thickness is more than 2.000 meters and covers the greatest part of the island. Meta-volcanic, clastic rocks and marbles are being met into that unit; (3) the Lower unit, derived from Mesozoic Limestones, marls, shales, cherts, tuffs, basaltic volcanites and acidic rocks of probable volcanic origin. Magmatic rocks of the island are being classified into two main categories: (1) a complex of granite and granodiorite intrusion, which took place at early Miocene (Melidonis 1980, Soukis 1999); (2) small outcrops of rocks of volcanic origin, with rhyolitic and andesitic composition. (Melidonis 1980).

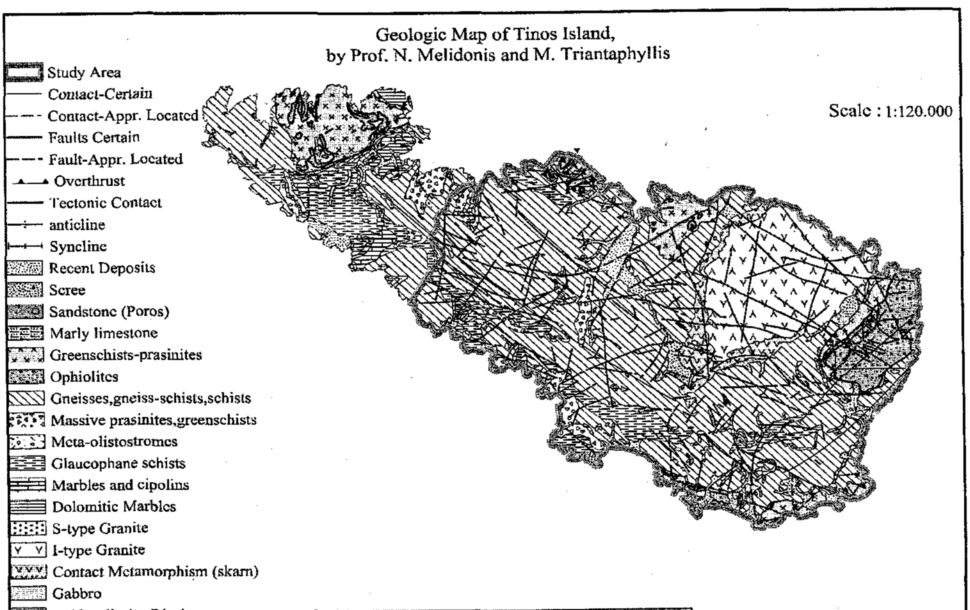

Figure 1: Geological Map of Tinos Island

The Neogene and Tertiary deposits are lying into small basins. The small outcrop of those sediments is the result of the steep slopes of the island (Stournaras et al 2002). Three systems of folds are being recognized. The first one is directly related with the metamorphic phases and has a general strike of NE-SW. The other two systems are of NW-SE and N-S strike, and are characterised as post metamorphic (Melidonis 1980). As far as fault systems concern, two categories of faults are being recognized. The two main categories have a general strike of NE-SW and NW-SE.

3. Fracture pattern extraction

To obtain a complete description of the fracture systems of the study area, it has been necessary to map the area at many different scales. For this purpose an integration of remote sensing techniques and field work was made. For the purposes of this paper, the term *fractures* (Berkowitz 2002) refers to all cracks, fissures, joints, faults, lineaments, that may be present in a formation.

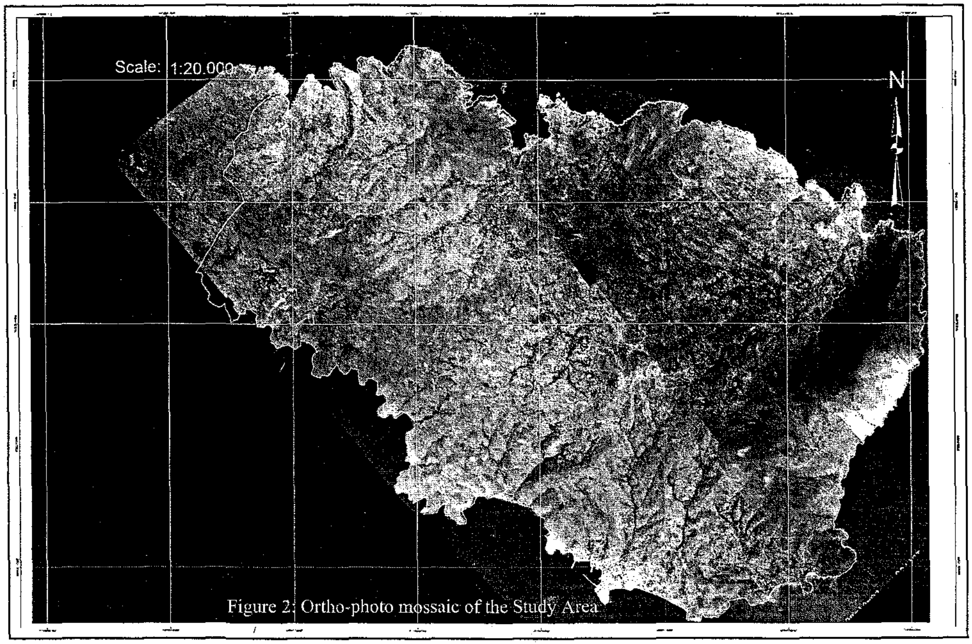

Figure 2: Ortho-photo mossaic of the Study Area

One dataset of Landsat 7 – ETM+ was subset and a combined satellite image of Tinos Island was produced with a resolution of 15m per pixel and 8 available spectral bands to combine. In order to reach the best possible accuracy, the georeferenced images were orthorectified using a digital elevation model with a cell size of 10m and finally projected on the Hellenic Geodetic Reference System (HGRS'87). The orthorectified image was used in order to identify lineaments that could correspond to tectonic structures which might be supplementary to previous researchers' mapping work (Melidonis and Triantaphyllis, 1980).
Consequently a set of air photographs (1/30.000 scale) was also orthorectified at the same projection and an orthophoto mosaic was produced reaching a high resolution of 5 meters per pixel. Following, the high and relatively low resolution images were merged using the principal component method, in order to produce a higher resolution digital set of 8 bands. This image has the same spectral characteristics of Landsat 7, but also better resolution. The new image was used for lineament interpretation as these could be related to zones of deformation and fracturing, which implies zones of higher secondary porosity (Gupta 1991).
Field observation was then conducted in order to confirm which of the lineaments that were extracted from the interpreted remote sensing images are faults, fissures or cracks and which of them are man made structures or topographical discontinuities. The orthophoto mosaic and the lineament map are shown in figures 2 and 3 respectively.

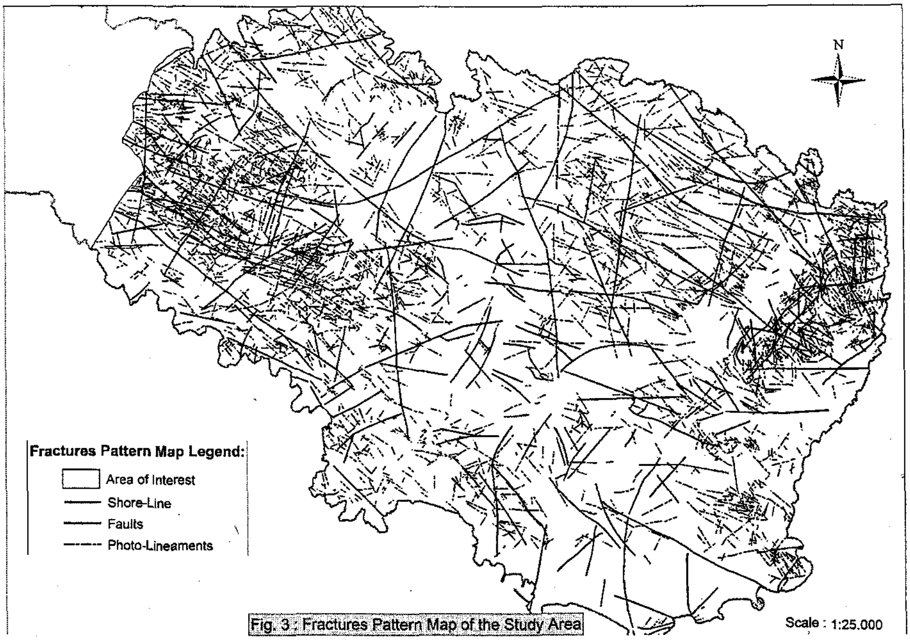

Fig. 3 : Fractures Pattern Map of the Study Area

4. Fractures Pattern Depiction and Analysis

The fracture map (fig.3) demonstrates 3178 features which correspond to map-scale faults and lineaments from aerial photographs and satellite images. Most of these lineaments are easily identified in the field as steeply dipping to vertical large scale fractures, and as meso-scale faults. The criteria of interpreting image lineaments and identify them as indicators of fractured zones of hydrogeological interest are (Scanvic 1997): i) their length, ii) their directional distribution, iii) the detection of anomalous directions, iv) their intersection, v) the existence of a constant distance between lineaments of a directional group and vi) relation between fracture density and the density of lineament intersections.

4.1 Fractures Frequency and Distribution

Fracture map shows that the fracture distribution is hardly homogeneous. The fracture frequency varies from very high in the west and northeast of the study area to moderate/low in the southeast and in northwest. The majority of the fractures are located on lithologies that correspond to the term "hard rocks" (Krasny 1996b, Krasny 2002). These are the greenschists and prasinites (ab), gneisses, gneiss-schists and schists (gn, sch and sch-gc) and granites (γs and γi) as well. The minority of the fractures is located on quaternary sediments and they are representing neotectonic faults. Fracture frequency also depends on the weathered mantle thickness, suggesting that the fractures frequency increase with decreasing the weathered mantle thickness. In the southeast and in northwest where the topographical slope angle is relatively low, the mantle thickness increases, and resulting low fractures frequency.

Nevertheless the fracture pattern is strongly depended on the relative position to major structures like faults. In order to show this relation, a buffer zone of 1500m, was created around each fault. This buffer zone was divided into 30 sub zones of 50 meters each and the total number of lineaments in each zone was computed.

Figure 4 shows the buffer zone around faults and fig. 5 the distribution, of lineaments in each sub zone. The distribution of lineaments shows that 51.93% of the lineaments are located in a distance of 150m from the faults. After this distance the lineaments frequency, follows roughly a lognormal curve, as is common in many geological populations (Krumbein and Graybill 1965).

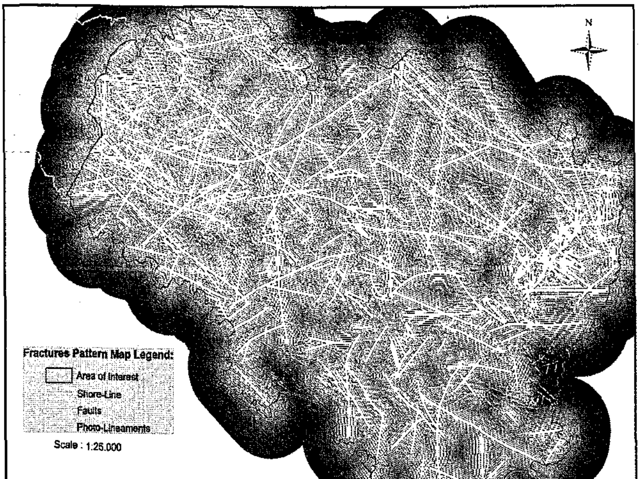

Fig. 4 : Buffer Zones around Faults

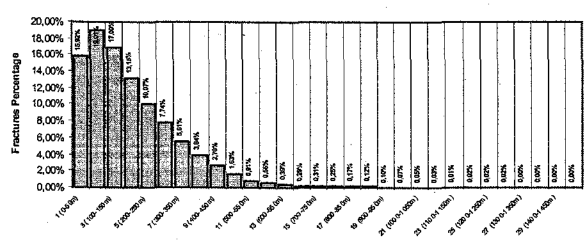

Fig. 5: Fractures Distribution, in each buffer zone

4.2 Orientation of Fractures

The study of the fracture orientation is fundamental, for the study of ground water flow. In most of the cases, the orientation of fractures is identical with the orientation of the preferential flow path. In fig. 6 the fractures rose plot shows that there are two sets of orientation classes. The main one has a NW-SE strike while the secondary one has NE-SW strike. The faults rose plot (fig.7) reveals four orientation classes. The two main classes have NW-SE and NE-SW strike, while the secondary ones are of N-S and E-W strike. On the other hand the lineaments rose plot, indicates that two main orientation classes exist (NW-SE and NE-SW). In order to describe the relationship, between faults and lineaments, rose plots of each of those features for each lithological unit were created (fig.9 to fig.16). It can be seen from these plots, that the dominant orientations are the NW-SE and the NE-SW strike on both faults and lineaments, suggesting the link between them. Exception occurs in the case of the Upper Unit of Greenschists and Prasinites. Faults in the Upper Unit are classified in two main orientation sets (N-S and NE-SW respectively) and in two secondary ones (NW-SE and E-W), while the majority of the lineaments seem to be oriented along NW-SE. This fact is due to the effect of the ductile tectonics, as two parallel fold axes, of NW-SE trend (a syncline and an anticline) are located in the area of the Upper Unit.

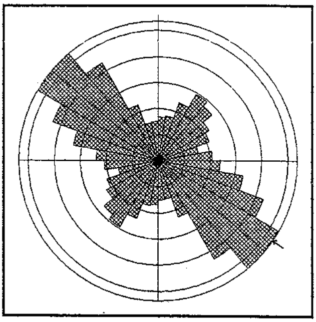

Fig. 6: Fractures Rose Plot

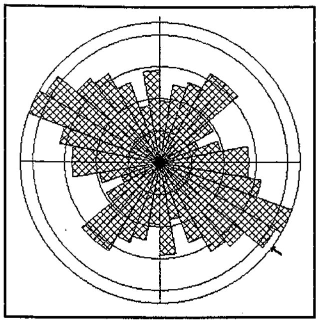

Fig. 7: Faults Rose Plot

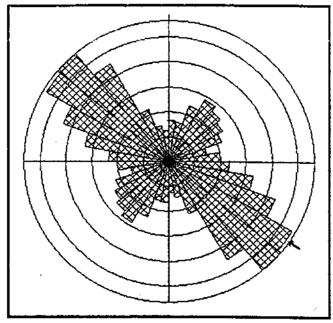

Fig. 8: Lineaments Rose Plot

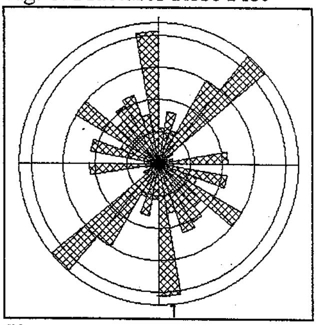

Fig.9: Faults Rose Plot in Upper Unit

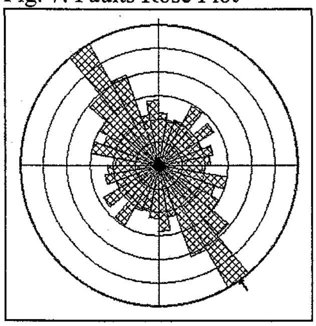

Fig.10: Lineaments Rose Plots in Upper Unit

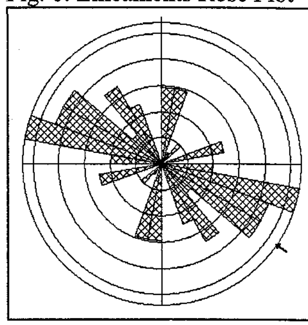

Fig 11: Faults Rose Plot in Granites

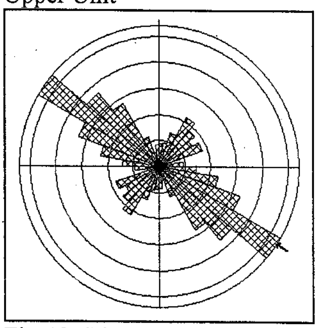

Fig 12: Lineaments Rose Plot in Granites

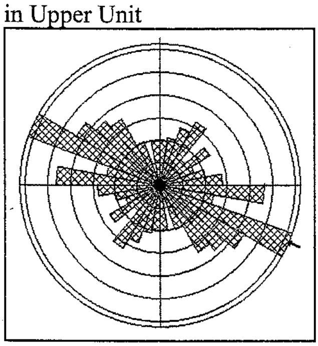

Fig. 13: Faults Rose Plot in Lower Unit

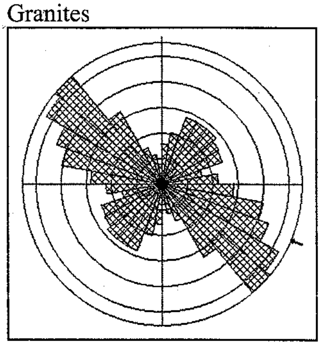

Fig14: Lineaments Rose Plot Lower Unit

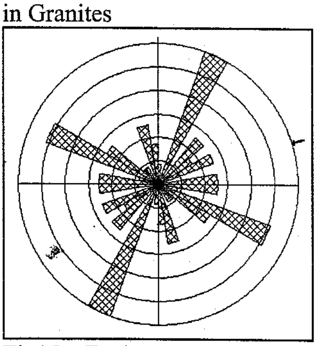

Fig15: Faults Rose Plot in Quat. Sediments

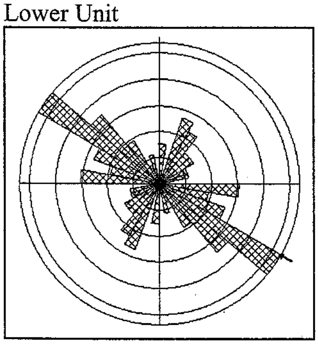

Fig.16: Lineaments Rose Plot in Quat. Sediments

ł.3 Fractures Dimensions

ʳractures dimensions such as aperture and apparent aperture, are very difficult to be defined in erms of spatial analysis. Additionally, the effect of depth on the aperture makes its neasurement even more complicated. On the other hand, length measurement is relatively easy vhile it shows the effect of a fracture on the groundwater flow. Usually, fractures of greater ength affect the groundwater flow in a more dominant way, than those of smaller length.

[he fracture map reveals lengths of surface traces of fractures varying between 40m and 7761m. ʳig.17 shows the length size distribution of these fractures.

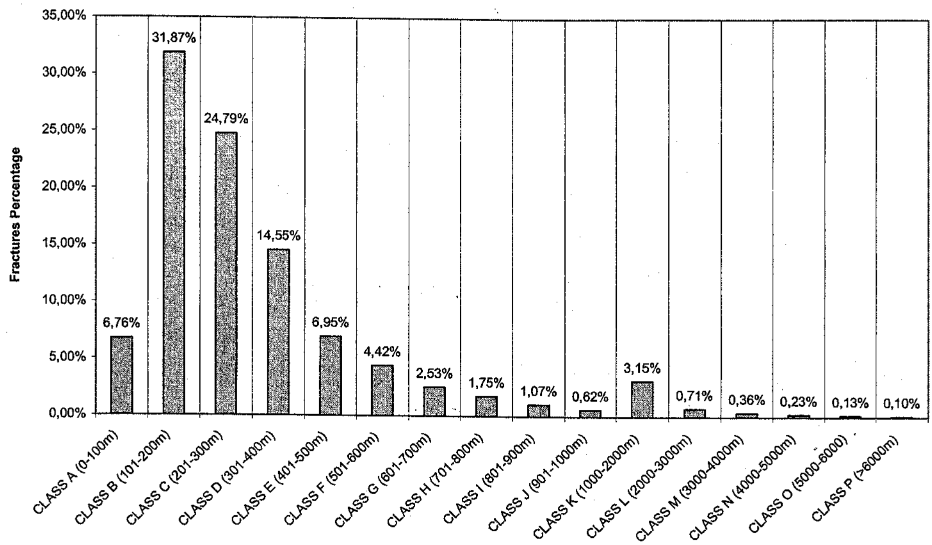

Fig.17: Length Size Distribution of Fractures

ł.4 Fracture Density

ʳracture density is an important parameter for the delineation of the groundwater flow in hard ocks. Fracture density maps were constructed in order to confirm the observations made above, ıbout the frequency and distribution of fractures. Density maps represent the total length (in cm) of lineaments per square kilometer of area. Fig. 18 represents the density map of faults and n fig. 19 the density map of the interpreted lineaments is presented. The comparison of these wo maps reveals that the density pattern of faults and lineaments in granite is almost identical Sub Area 1). In the Sub Area 2 where the Upper Unit of prasinites and greenschists is located, he lineament density varies from moderate to high, and their distribution is relatively ıomogeneous. On the other hand the fault density distribution is not so homogeneous relatively o the lineaments one. The same phenomenons takes place in greater extend in Sub Area 3 vhere the Cyclades Blueschists unit is present. In these two sub areas the three main fold axes ıre located, striking from NW to SE and from NNE to SSW respectively.

[his antithesis in the density patterns suggests that the development of fractures is linked not ɔnly with the brittle deformation, but also with the ductile one. In the southeast part of the study ırea (Sub Area 4) the anomaly that is depicted between the faults and lineaments patterns occurs lue to the increased thickness of the weathered mantle of the Cyclades Blueschists. Finally the noderate to high faults density of Sub Area 5 corresponds to very low lineaments density. This ıntithesis occurs due to the development of faults on unconsolidated Quaternary sediments.

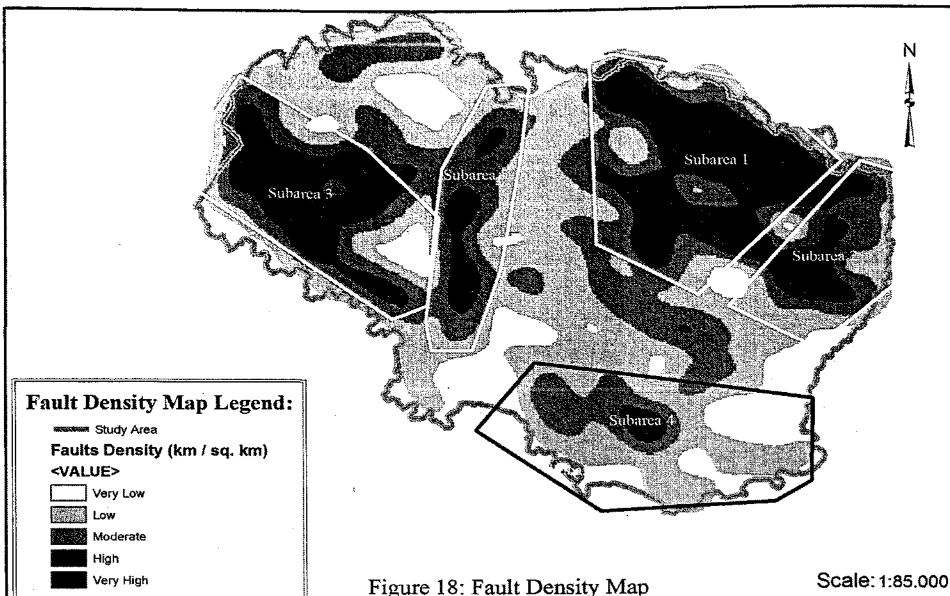

Figure 18: Fault Density Map

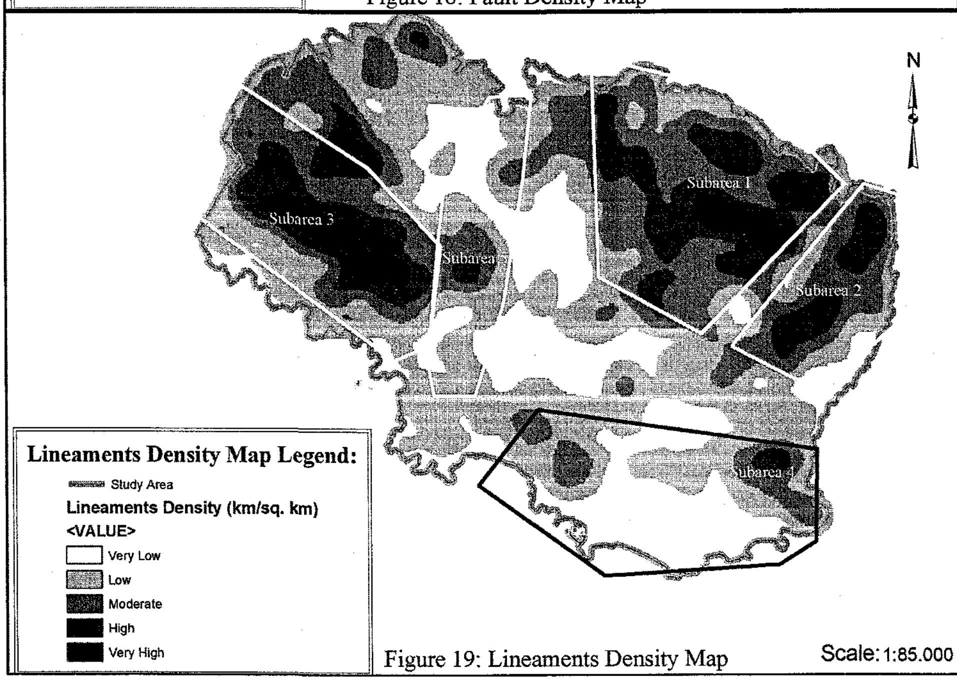

Figure 19: Lineaments Density Map

4.5 Degree of fracture intersection

The degree of fracture intersection along with fracture density, depict completely the fracture network in terms of spatial analysis. These two parameters determine the degree of anisotropy of the groundwater flow in the fracture network. It is unquestionable the fact, that in environments with high degree of interconnection, the groundwater flow is smoother and more uniformly (Stournaras 2005).

In order to depict the degree of fractures interconnection, the intersection points between two or more fractures, were digitized. Consequently the density map of intersection points was produced, in which the frequency of intersection points per square kilometer, is illustrated. The higher the density the higher the degree of interconnection is.

The interconnection density map (fig. 20) shows moderate to very high density in Tsiknias Mountain where the Upper Unit of prasinites and greenschists is located and in Mesovouni Mountain, where the Cyclades Blueschists unit is present. Granites, show very low degree of interconnection, as the majority of the lineaments are trending to ESE.

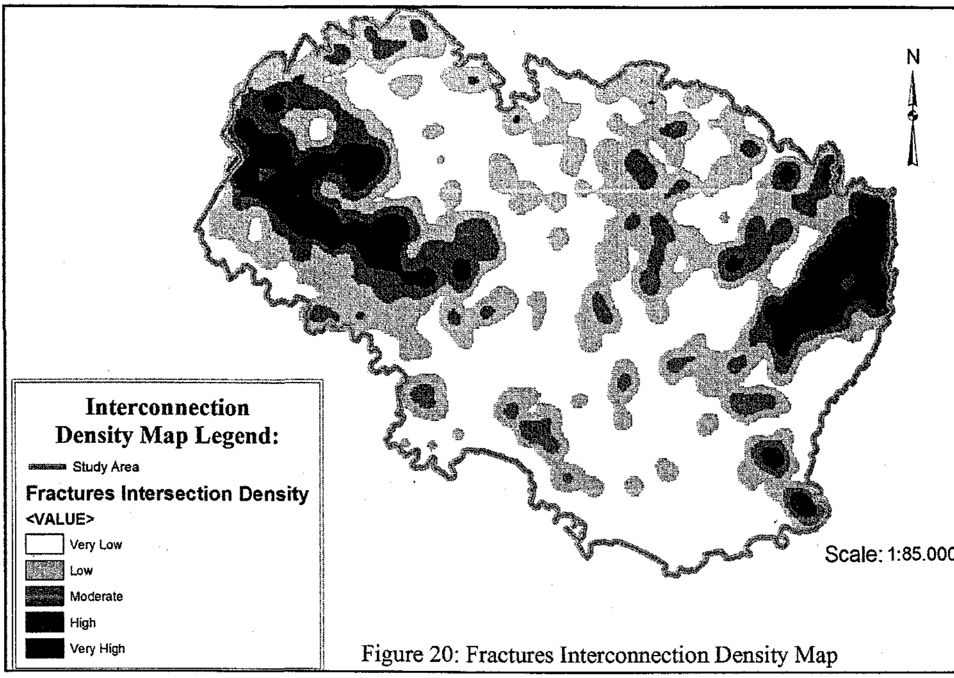

Figure 20: Fractures Interconnection Density Map

5. Conclusions

The general idea of increasing the spatial resolution of multispectral satellite images with other remote sensing data seems to be the key of using them at a variety of scales, depending on the aim of the work to be done.

The study of the fractures pattern reveals that:

a) Four orientation classes of faults are located in the study area. The two main classes have NW-SE and NE-SW strike, while the secondary ones are of N-S and E-W strike.
b) Lineaments are trending at the same strike with the main fault systems (NW-SE and NE-SW). Exceptions occur, where ductile tectonics affect the development of fractures.
c) The occurrence of fractures is strongly linked with the proximity to the map scale faults. The majority of lineaments/fractures is located in the distance of 250m to faults.
d) The fractures density and degree of interconnection is depended on the combination of brittle and ductile tectonics, on the thickness of the weathered mantle, and on the lithology.
e) The combination of Remote Sensing, GIS, and field work, leads to an accurate and reliable description of the fractures pattern, in hard rocks hydrogeological environments.

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