Groundwater in fractured rocks

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CHAPTER 8

The fractured rocks in Hellas

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ABSTRACT: The contribution deals with geotectonic position and hydrogeological behaviour of hard-fractured rocks (mainly igneous, metamorphic, but not karstified carbonate rocks, as defined by the I.A.H Commission on Hardrock Hydrogeology). In particular geotectonic zones within the Hellenic territory their lithological and structural conditions are characterised. The main aquifers are defined with general features of groundwater flow related to the formation of the rock mass fractures. Five typical hardrock areas were selected for a detailed hydrogeological analysis.

1 INTRODUCTION

In Hellas, hard-fractured rocks are extended in many areas (Figure 1). From a geotectonic point of view the territory corresponds to the Aegean or Hellenic Arc, in which the African plate converges to the European. The alpine orogenetic system of Hellas, the so-called Hellenides, is composed by a set of geotectonic zones, extended primarily in N-S direction, changing southwards, in an E-W direction. Hellenides are subdivided to the following zones (Figure 2): (a) *Internal (eastern) Hellenides*: Rhodope Massif, Servo-Macedonian Massif (or zone), Axios Zone, Pelagonian Zone, Sub-Pelagonian Zone or Eastern Hellas Zone; (b) *External (western) Hellenides*: Parnassos Zone, Pindos Zone (or Pindos-Olonos zone), Gavrovo – Tripolis Zone, Ionian Zone and Paxi Zone.

At this point it should be mentioned that, in the frame of the Alpine orogenetic phase, some tectonometamorphic – tectonic units, have been created subparallel and transverse to Hellenides structures. The most significant of them is the Atticocycladic unit and the Olympos – Ossa and Almyropotamos tectonic windows, which geotectonically correspond to the external Hellenides. We find that the fractured rocks occur mainly in the Internal Hellenides related to metamorphic rocks and ophiolites (Mountrakis 1985, Ferriere 1982, Katsikatsos et al. 1986, Krásný 2002, Meyer & Pilger 1963).

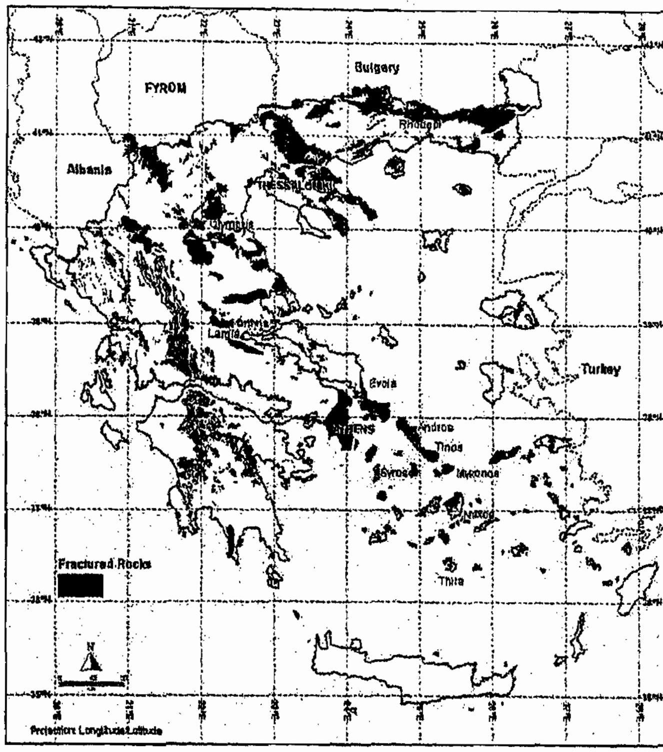

Figure 1. The fractured rock outcrops in Hellas.

2 THE CHARACTERISTICS OF THE GEOTECTONIC ZONES

(1) **Rhodope Massif** is characterized by the occurrence of gneiss (mainly orthogneiss), schists (mica-schist) and amphibolites, in alterations with marble horizons. The magmatic rocks are composed of Carboniferous to Cretaceous plutonic masses (granites, granodiorites, monzonites and diorites) and Eocene to Oligocene volcanic rocks (rhyolites, dacides, andesites and dolerites). The main aquifers of the Rhodope massif are related mainly with the metamorphic rocks, which are the typical fractured media included within the considered fractured rocks environment. Even in the case of the marble sequence, where karstification occurs, the horizons of schist and amphibolites into the sequence as intercalations could be included in the fissured rock sequence, and both plutonic and eruptive rocks are included within the considered fissured rocks.

(2) **Servo-Macedonian Massif (or zone)** is composed by a thick metamorphic formation of marbles, schists and gneisses, with intercalation of amphibolites, which is crosscut by Paleozoic to Oligocene granites. In the upper part of the sequence metagabbros, metadiabases, amphibolites and bodies of serpentinites are tectonically emplaced. The composition of the Servo–Macedonian corresponds to the typical hydrogeological environment of the fractured rock aquifers.

(3) **Axios Zone** is characterized by the intense tectonic events, where folding and thrusting occur and is subdivided (from E to W) in the sub-zones of: (a) Paeonia, (b) Paiko and (c) Almopia. The formations that occur are: (a) sedimentary and volcanosedimentary

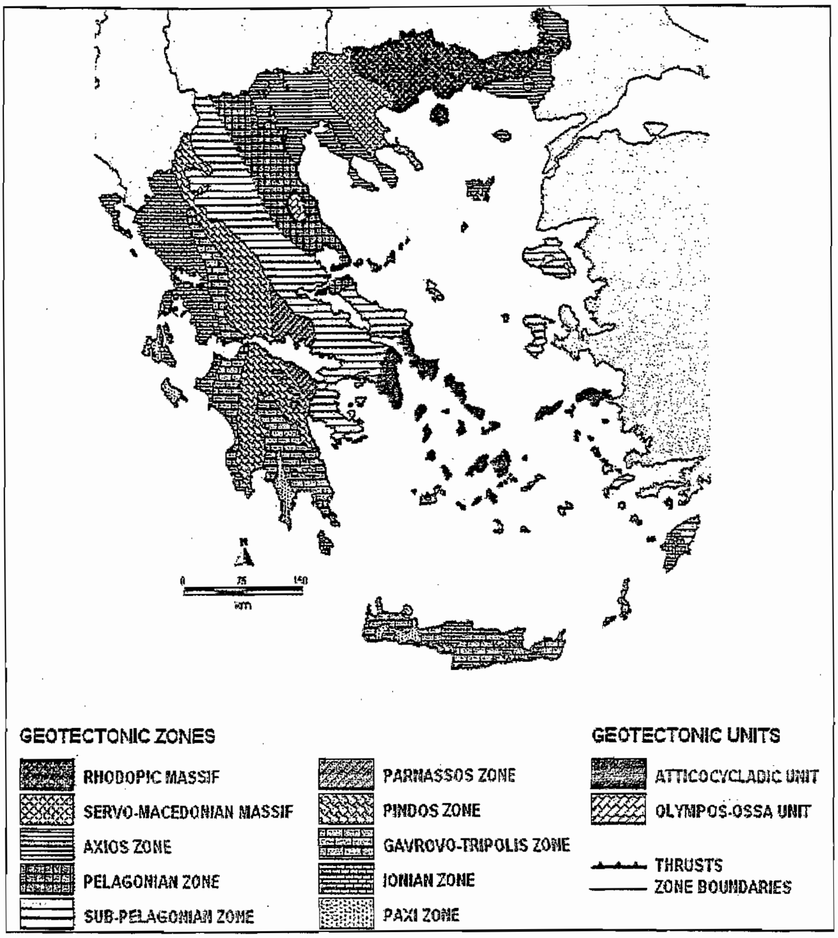

Figure 2. Geotectonic sketch map of Hellenides.

formations of Mesozoic age. These formations are composed of cherts, limestones, volcanic beds and intrusions, tuffs, and pyroclastics. (b) ophiolitic formations, which are mainly ultrabasic rocks, gabbros, pyroxenites, and basaltic lavas with intercalations of pelagic sediments and (c) formations of altered schists, sandstones, conglomerates, and limestones that are of Upper Jurassic-Cretaceous age. Due to the intense tectonics and to the nature of the formations, Axios zone is a classic example of the fractured rocks hydrogeological environment.

(4) **Pelagonian Zone** is composed by the following formations, from base to top: (a) crystalline basement consists of gneisses, granites/migmatites, schists and amphibolites; (b) Permian-Triassic meta-clastic sequence with volcanic rocks and tuffs; (c) Triassic-Jurassic carbonate sequences (marbles and dolomites) that correspond to the platform sedimentation of Alpine system. (d) ophiolitic formations that constitute an extent tectonic nappe; (e) Cretaceous formations composed of crystalline limestones and metaflysch. Gneisses, schists, granites, and ophiolites are typical example of discontinuous media included within this zone.

(5) **Sub-Pelagonian Zone** is characterized by the intense lithological transformations over its whole extent. The stratigraphy of the zone, from base to top, is: (a) Neo-Paleozoic formations that are composed of sandstones, phylittes and schists; (b) Lower-Middle Triassic formations that are composed of sandstones, basic volcanic rocks and intercalations of limestones; (c) Middle Triassic-Upper Jurassic neritic limestones that include radiolarites, pellites, clay schists, etc; (d) Upper Jurassic-Lower Cretaceous clastic formations that are composed of radiolites, conglomerates, sandstones, and shales with olistostromes of ophiolites; (e) Pre-upper Cretaceous tectonic nappe, of volcano-sedimentary formations and ophiolites; (f) Upper Cretaceous limestone and flysch formations. The Neo-Paleozoic formations and the pre-upper Cretaceous formations of the tectonic nappe constitute the principal fracture rocks environment in this zone.

(6) **Parnassos Zone** is characterized by continuous Mesozoic neritic carbonate formations, typical karst configuration, and intense paleogeographic evolution, which fortmed three characteristic bauxite horizons. The carbonates pass upwards to flysch of Upper Cretaceous Lower Paleocene age. Pre-alpine basement is not recognized in this zone, and eruptive rocks are totally absent. The absence of crystalline or igneous rocks and the simultaneous presence of karst configuration in the neritic formations, excludes this zone from the typical hydrogeological environment of the fractured rock aquifers.

(7) **Pindos-Olonos Zone** is the "backbone" of the Hellenides Mountains and is characterized by deep sea sedimentary formations. Lithologically, the older deposits are dolomites and limestones of Middle-Triassic age, which in some cases also overlie clastic rocks (sandstones) of Middle-Triassic age. Upper-Triassic limestones of pelagic phase are present with intercalations of cherts and shales. During the Jurassic, alteration of cherts, clay schists, pelagic limestones, and sandstones occurred. Lower Cretaceous altered breccias, conglomerates, sandstones,and shales are the dominant rocks with characteristics similar to those of the flysch. A second sequence of thin-bedded pelagic limestones overlies the first flysch until the start of Paleocene, where the typical flysch (alterations of sandstones, shales, with intercalation of conglomerates) occurs. Despite the absence of crystalline and igneous rocks in Pindos zone, thin bedded limestones, radiolarites, and some horizons of flysch (sandstone), due to the intense folding and thrusting, cause quick drainage of the groundwater. The aquifers in those formations present very similar properties with the typical hard rock aquifer, especially because these limestones are not significantly karstified.

(8) **Gavrovo-Tripolis Zone** is composed by continuous neritic carbonates from the early stages to the end of Mesozoic. Limestones are thick-bedded to massive and are karstified. The carbonate rocks pass upward to the flysch formations of sand-stones, conglomerates, and shales. Groundwater flow in this zone is mainly controlled by large karstic conduits. Equivalent with this zone is the tectonic window of Olympos-Ossa.

(9) **Ionian Zone** is characterized evaporates above which there is a thick Triassic carbonate sequence. The overlying Jurassic consists of altered cherts with marly limestones and shales overlain by red pelagic limestones with intercalations of cherts. The flysch (Upper Eocene-Lower Miocene) of Ionian zone is composed of altered marls and sandstones in its lower parts. The upper parts are composed of altered marls, marly limestones, and conglomerates. Despite the fact that this zone is characterized by the absence of crystalline or igneous rocks, some sequences present typical characteristics of hard rock aquifers due to the intercalation of cherts and of marly limestones.

(10) **Attico-Cycladic Unit (Complex)** consists of concatenations of tectonic covers and windows, of ophiolites and metamorphic rocks (schists, gneiss-schists, amphibolites, greenschists, and glaucophane schists). Plutonic intrusions of granitic composition are Miocene age. The Attico-Cycladic Unit corresponds to the typical hydrogeological environment of the fractured rocks. This is very important for the Cyclades Islands, where the fractured rocks are the principal aquifer in an environment of limited precipitation, strong evaporative conditions, and limited island surface.

3 CASE STUDIES

(a) Xanthi area. The study area of the Xanthi region geotectonically is part of the Rhodope Massif and is characterized by marbles, gneisses, and schists (Figure 3) (Kronberg & Raith 1977, Meyer & Pilger 1963). The Rhodope Massif is subdivided into two tectonic units: (a) Sidironero with orthogneiss, micaschists, amphibolites, and intercalations of marbles and (b) Paggaeo, which consists of three sequences: (i) the lowest of orthogneiss, micaschists, schists and amphibolites (ii) the middle of marbles with intercalations of mica-schist and amphibolite, and (iii) the upper of schists and marbles. Plutonic rocks are granites, granodiorites, monzonites, and diorites. Their age ranges from Carboniferous to Cretaceous to Oligocene. The volcanic rocks of Rhodope are rhyolites, dacites, andesites, and dolerites,of Eocene-Oligocene age.

The orientation analysis of the tectonic and microtectonic regime Rhodope Massif is shown on Figure 3(a).

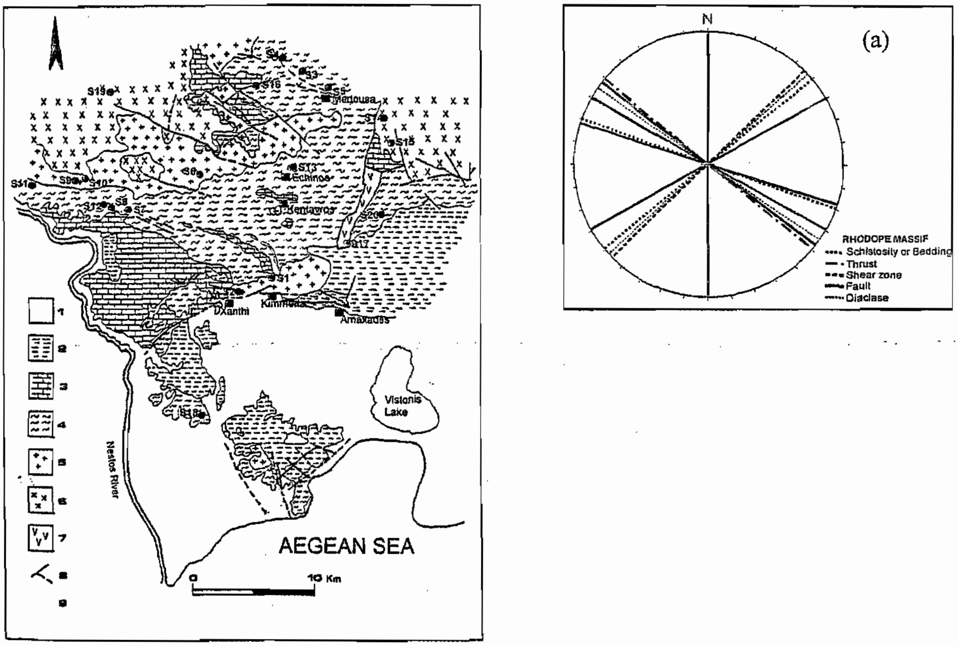

Figure 3. Geological map of Xanthi area (western Rhodope): 1. Quaternary formations; 2. Neogene formations; 3. marbles; 4. schists and gneisses; 5. granites; 6. volcanic rocks (andesites and cacites); 7. ophilites (mainly ultra basic masses); 8. faults; 9. springs (S). (a) Rose Diagram of tectonic elements.

The fractured rocks encountered in the massif of Rhodope are: (a) metamorphic rocks: gneiss, schist, amphibolites, migmatites, and marbles; (b) plutonic rocks: granites, granodiorite, monzonites, and diorites); and (c) volcanic rocks: rhyolites, andesites, dacites, and dolerites.

In the Xanthi study area springs emerge from marbles, volcanic rocks, granites, and schists. Thermal springs emerging from schists are also located (Table. 1, Figure 3).

Springs emerging from marbles. At the northeastern part of Xanthi, schists are characterized by lenticular intercalations of marbles from which springs issue. Their chemical characteristics are shown in Table 1. Geochemically these springs are classified as normal geo-alkaline, (mainly bicarbonate) and belong to the hydrochemical type Ca—Mg—HCO_3. The hardness ranges from 5.4 to 10.4°dH (German degrees), characterizing the water from soft to hard. TDS ranges between 179.6 and 350.0 mg/L with an average value of 250.0 mg/L. The dominant cations are the calcium and the magnesium the dominant anions are the bicarbonate and the sulfate. Generally, the waters are of good quality.

Springs emerging from volcanic rocks. Volcanic rocks springs are characterized by low values of dissolved solids, low hardness, and their alkaline character. These waters contain few metals and are classified as geo-alkaline, corresponding to the hydrochemical type Ca—Na—Cl—HCO_3.

Springs emerging from granites. The main characteristics of these springs are low dissolved solids, low hardness, and their alkaline character. They contain few metals and are classified as geo-alkaline, corresponding to the hydrochemical type Ca—Na—HCO_3.

Springs emerging from schists. The main characteristics of these springs are low dissolved solids, low hardness, and their alkaline character. The water is classified as normal geo-alkaline, corresponding to the hydrochemical type Ca—Na—Cl—HCO_3. The hydrogeological environment of these springs corresponds to the typical one of fractured rocks. Some of the springs emerge directly from fractures. In some other cases, groundwater percolates through the weathered mantle to the fractured zone and emerges through the intersection of the topographical surface and the fractured zone/bedrock contact.

Thermal spring of Thermes. The thermal spring of Thermes (Figure 3, spring S5) is located in Xeropotamos basin and issues from schists. Its occurrence is strongly related to fracture pattern of the surrounding area. The water temperature ranges between 33°C and 43°C. The "Thermes" spring has the hydrochemical type Na—Ca—HCO3 (Table 1). The amount of the dissolved solids reaches 1200 mg/l. The spring has alkaline characteristics and, according to the temperature, is classified in the category of mesothermal springs.

(b) Olympos–Ossa area. The geological composition of Olympos and Ossa mountains (Figure 4) is complicated. It is composed of several tectonic units, which are (Ferriere et al. 1998, Godfriaux 1962, Katsikatsos et al. 1982, Stamatis 1999, Stamatis & Migiros 2004):

Olympos-Ossa Unit, which is a series of crystalline limestones and dolomites equivalent to the Gavrovo Zone, from Triassic up to Eocene. This series ends in slightly metamorphic flysch.

Ampelakia Unit, which is mainly composed of schists, gneiss-schists, gneisses and prasinites, with some intercalations of marbles, meta-basalts, meta-greywacke and metapelites. The unit is characterized by blueschist phase metamorphism. From hydrogeological point of view, the formations of this unit present variable permeability connected to the presence of the gneisses or prasinites.

Pelagonian Unit, which is a complex, entirely metamorphosed unit of gneisses, granites/migmatites, amphibolites, schists, intercalations of marbles, and thrusts of metamorphosed

Table 1. Hydrochemical characters of the springs the Xanthi area.

	Marble			Schists			Granites			Volcanic rocks			Thermal water
	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	
T °C	14,7	17,3	15,6										33–43
pH	7,8	8,7	8,3	8,0	8,1	8,0	8,8	9,1	9,0	7,5	8,1	8,2	7,3
EC (μS/cm)	235	484	332	126	185	156	11,5	19,5	15,5	61	130	96	1369
Ca^{2+}(mg/l)	24,1	54,5	43,1	22,8	27,6	25,2	8,8	13,6	11,2	6,0	15,1	10,7	136,4
Mg^{2+}(mg/l)	6,8	11,9	7,7	2,2	2,4	2,3	1,5	2,4	2,0	1,0	2,2	1,7	10,0
Na^{+}(mg/l)	4,7	12,0	10,5	3,1	4,0	3,6	9,2	18,0	13,6	5,2	6,7	5,8	171,8
K^{+}(mg/l)	1,0	2,2	1,4	0,7	1,3	1,0	4,1	4,3	4,2	0,9	1,4	1,1	19,6
HCO_3^-(mg/l)	79,3	201,3	140,5	67,1	88,4	77,8	32,9	34,2	33,5	12,2	54,9	35,1	652,7
Cl^-(mg/l)	7,8	26,5	13,6	10,6	12,4	11,5	5,3	7,1	6,2	5,7	10,6	7,5	64,5
SO_4^{2-}(mg/l)				0	0	0	2,5	13,2	7,8	38,4	0,0	19,7	144,5
NO_3^-(mg/l)	0,5	32,0	4,7	0,2	17,0	8,6	0	0	0	0,0	17,0	4,3	1,0
TDS (mg/l)	179,6	350,0	250,0	125,0	135,0	130,0	81,5	93,6	87,6	37,9	103,8	75,4	1200
Tot. Hard.*	5,4	10,4	8,2	3,7	4,4	4,0	2,8	4,4	3,6	1,1	2,6	2,1	21,4
Temp. Hard.*	3,6	9,2	7,1	3,1	4,1	3,5	2,8	4,4	3,6	0,1	0,8	0,4	16,7
Perm. Hard*	1,8	1,2	1,1	0,6	0,3	0,5	0	0	0	1,0	1,8	1,7	4,1

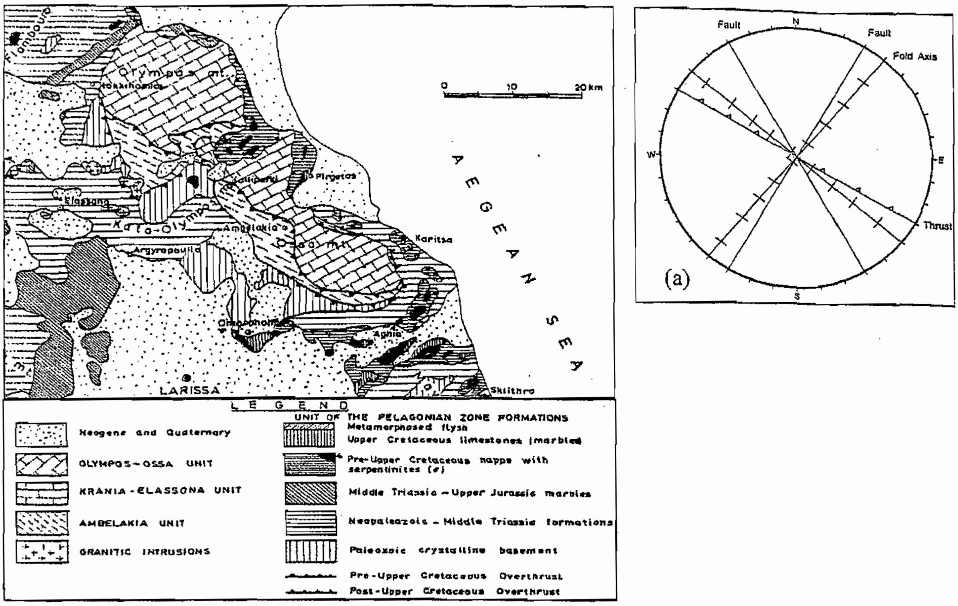

Figure 4. Olympos-Ossa geological map. (a) Rose diagram of major fault, thrust and diaclase orientations of Olympos-Ossa region.

ophiolites (basic and ultra-basic rock formations). The gneisss are connected with improvement of the hydrogeological behavior.

The main tectonic direction is N30°–60°W, which is combined with axes of structures, thrusts and faults. The direction N30°–70°E is a second major tectonic direction combined with axes of structures and faults. Related to the structural geology conditions that control groundwater flow within the fractured (hard) rocks of the given area, the rose diagram on Figure 4(a) shows that the orientation relation between folds and faults present a remarkable constancy.

Some hydrogeological and hydrochemical characters of the discussed groundwater manifestations are given in Table 2.

(c) Othrys area. Othrys is a mountain of Central Hellas consisting of Alpine formations that geotectonically belongs to the Sub Pelagonian zone. The fractured rocks are represented by the intercalations of basaltic lavas within a schist-chert sequence. Ophiolites and limestones are also present. The following sequences are encountered (Figure 5) (Ferriere 1982, Migiros 1990):

- *Chert-schist sequence*. This is a thin-bedded formation of chert, clayey schist, siltstone, that is intensively tectonised and folded.
- *Basaltic rock sequence*. These are volcanic rocks, fractured and alternated with chert and siltstone intercalations.
- *Ultrabasic rock sequence*. Peridotites with variable serpentinization that are intensively fractured. In the base of the system gabbros, basaltys, and amphibolites are encountered.

The area's faults and rupture surfaces are induced by the tensional post-orogenetic stresses.These are depicted in Table 4 and on Figure 5(a). Hydrogeologically, two groups of formations are distinguished at the base of their permeability. The first, mainly including

Table 2. Hydrochemical characters of the Olympos – Ossa area.

	Marble			Gneisses			Ultrabasic			Metaflysch			Schists			Serpentinites			Thermal water
	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver	
T°C	11,7	14,9	13,63	11,5	17,6	13,83	6,5	12,3	9,8	9,6	13,6	11,98	11,4	14,6	13,2	7	7,2	7,1	14,5
pH	7,1	7,4	7,2	7,3	7,5	7,43	7,1	7,9	7,48	6,8	8,2	7,3	6,7	7,6	7,3	7,1	7,5	7,3	5,3
EC (µS/cm)	277	465	375	250	375	317	65	436	259	203	582	314	162	505	334	234	348	291	2447,0
Ca^{2+}(mg/l)	38,2	62,4	53,9	25,6	56	41,2	3,4	45	31,2	24	97,6	45,57	8,8	72,8	41,78	9,6	44,8	27,2	408,0
Mg^{2+} (mg/l)	7,5	23	12,8	5,6	12,2	9,1	3,3	23,9	12,75	3,2	16,1	8,06	3,9	21,7	13,27	12,9	20,2	16,55	121,7
Na^{+} (mg/l)	5,3	10,8	7,83	7,2	10,6	8,3	2,4	8,6	4,42	1,3	8,2	5,41	1,9	11,8	7,07	1,6	3,2	2,4	8,4
K^{+} (mg/l)	0,4	1	0,6	0,1	0,7	0,35	0,3	0,5	0,37	0,3	0,8	0,48	0,3	1,4	0,88	0,3	0,5	0,4	1,5
HCO_3 (mg/l)	136,6	262,3	195,6	122	201,3	167,8	26,8	244	146,8	122	353,8	175,3	61	298,9	186,4	122,5	195,2	158,9	1750,7
Cl^{-}(mg/l)	7,1	24,8	15,2	14,2	24,8	18,6	3,5	17,7	12,4	5,3	17,7	12,3	5,3	28,4	14,9	5,3	7,1	6,2	14,2
SO_4^{2-} (mg/l)	17,3	26,9	22,47	2	43	16,13	4	33,5	12,23	4,5	27,5	12,71	6,2	24,1	16,4	8,6	9,5	9,05	4,0
NO_3^{-} (mg/l)	0,2	8,7	3,37	0,4	3,1	1,18	0,2	4	1,07	0,2	3,4	1,04	1	7,2	2,51	0,2	0,3	0,25	0,5
TDS (mg/l)	213	408	312	190	341	262	48	374	221	184	521	260	109	457	283	171,0	270,0	220	2309,0
Tot. Hard. °dH	7,1	14	10,5	6,2	9,5	7,8	1,3	11,8	7,2	5	17,4	8,2	2,8	14,6	9,1	5,6	9	7,3	85,2
Temp. Hard. °dH	6,3	12	8,9	5,6	9,2	7,7	1,3	11,2	6,7	5,6	16,2	8,1	2,8	13,7	8,5	5,6	9	7,3	80,4
Perm. Hard. °dH	0,8	2	1,5	0	0,6	0,3	0	1,1	0,4	0	1,2	0,4	0	2	0,6	0	0	0	4,8

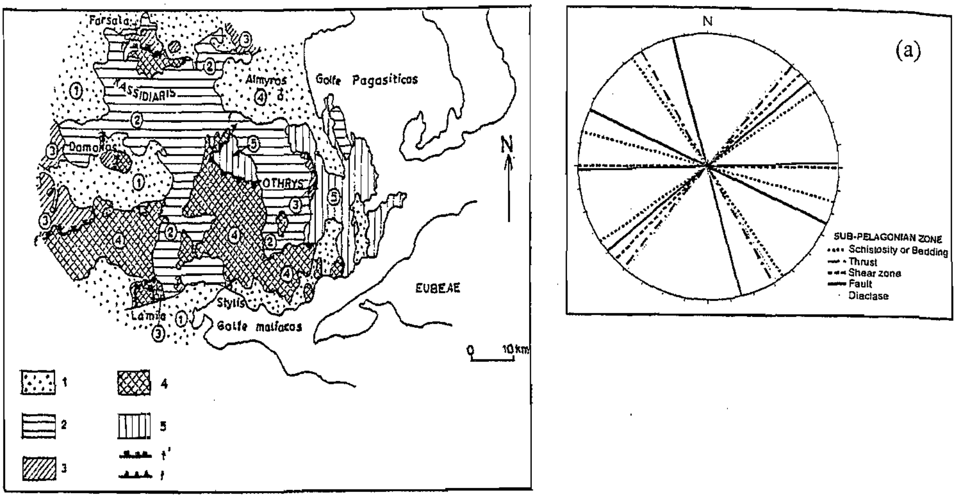

Figure 5. Geological map of Othrys Mt.: 1. Post Alpine formations, 2. Cretaceous formations, 3. Ultra basic masses, 4. Sedimentary-volcanosedimentary Triassic-Jurassic formations, 5. Neopaleozoic-Triassic formations, f-f': Thrusts. (a) Rose diagram of tectonic elements.

Table 3. Hydrochemical characters of the springs in the Othrys area.

	S1 A	S1 B	S1 C	S1 D	S1 E
Electrical conductivity (μS/cm)	565	532	540	729	385
pH	11.1	11.1	11.0	10.9	10.8
Water temperature (°O)	22	20.8	19.2	24.2	23.5
Air temperature (°O)	28	28	28	28	29
Discharge (l/h)	226	226	1	960	50–100
Permanent hardness °O dH	6.18	6.12	5.5	2.13	4.55
Ca^{2+} mg/l/meq/l	43.2/2.1	42.4/2.1	38.4/1.9	15.2/0.7	32.4/1.6
Mg^{2+} mg/l/meq/l	0.5/0.04	0.7/0.06	0.5/0.04	0/0	0/0
Na^{+} mg/l/meq/l	21.6/0.9	21.6/2.1	29.4/1.3	111.3/4.8	19.78/0.8
K^{+} mg/l/meq/l	0.78/0.02	0.78/0.02	0.78/0.02	2.35/0.06	0.78/0.02
HCO_3^- mg/l/meq/l	**0/0**	**0/0**	**0/0**	**0/0**	**0/0**
Cl^- mg/l/meq/l	27.66/0.8	26.6/0.7	30.1/0.8	90.4/2.5	23.05/0.6
SO_4^{2-} mg/l/meq/l	2.4/0.05	3.36/0.07	4.80/0.10	21.61/0.45	3.84/0.08
NO_3^- mg/l/meq/l	0/0	0/0	0/0	6.20/0.10	0/0
NO_2^- mg/l/meq/l	0/0	0/0	0/0	0/0	0/0
OH^- mg/l/meq/l	25.16/1.5	23.80/1.4	23.46/1.4	22.44/1.32	13.7/0.8
SiO_2	4	6	19	36	19
TDS	153	152.97	171.79	345.17	143.28

the serpentinized peridotites, represent the most permeable sequence of the fractured rocks. The second group, including the chert-schist sequence and the volcanic rocks, represent the relatively less permeable sequence of the fractured rocks. Data from the wells and the springs of the Othrys area given in Table 3.

(d) Euboea Island. Euboea Island is a complicated geological structure with the Pelagonian formations to the north, Sub-Pelagonian to the center and the tectonic window of Almyropotamos, equivalent to Olympos-Ossa, to the south. Therefore, we present the

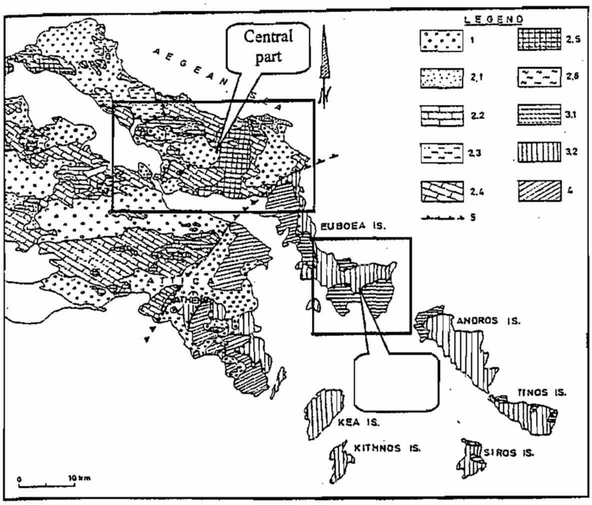

Figure 6. Geotectonic map of Euboea-Attica and N. Cyclades: 1. Neogene and Quaternary formations; 2. Pelagonian zone; 2.1. Flysch; 2.2. Upper Cretaceous limestones; 2.3. Eohellenic nappe formations; 2.4. Middle Upper Triassic-Upper Jurassic limestones and dolomites; 2.5. Neopaleozoic-Middle Triassic formations; 2.6. Crystalline basement; 3. Neohellenic nappe; 3.1 Ochi unit; 3.2. Styra unit; 4. Autochthonous system; 5. Overthrust. (a) Lineament map of Central part.

hydrogeological conditions of the fractured rocks in two different areas, central and southern parts (Katsikatsos 1977, Stamatis & Gartzos 1999, Stamatis et al. 2005).

(d_1) Central part of Euboea Island. The central part of Euboea island corresponds to the typical structure of Sub-Pelagonian zone and consists of Palaeozoic basement covered by non metamorphic Mesozoic formations that present tectonic intercalations of ophiolites (Figure 6). The fractured rocks aquifers on the central (and north) Euboea mainly belong to the following sequences:

- The crystalline basement with a thickness over 800 m of gneiss and gneissic schist. The upper part is micaceous and amphibolitic schist; carbonate rocks are entirely absent.
- The Neopaleozoic sequence consists of sandstones, sandstones-schists, arkoses, graywackes, and clay schists.
- The Lower-Middle Triassic sequence consists of clayey-sandstones, basic volcanic rocks, and tuffs.
- The ophiolitic tectonic nappe is composed of volcano-sedimentary formations, ultra-basic bodies (serpentinized peridotites), gabbros, amphibolites, and basalts.

The main fractured aquifers are found in theophiolitic cover. Figure 6(a) depicts the lineaments in the ophiolitic cover, derived from a Landsat – 7 ETM+image, showing a NE-SW preferential orientation.

(d_2) Southern part of Euboea Island. The southern part of the island constitutes the Almyropotamos tectonic window, equivalent to the the Olympos-Ossa tectonic window (Figure 6). The Ochi and Styra units, corresponding to the Ampelakia unit, are composed of marbles, cipolines, schists and quartzites. The hydrogeological conditions of the southern part (Figure 7, 8), show that spring locations are related to fracture patterns and to the drainage network. Some hydrochemical data are given in Table 4.

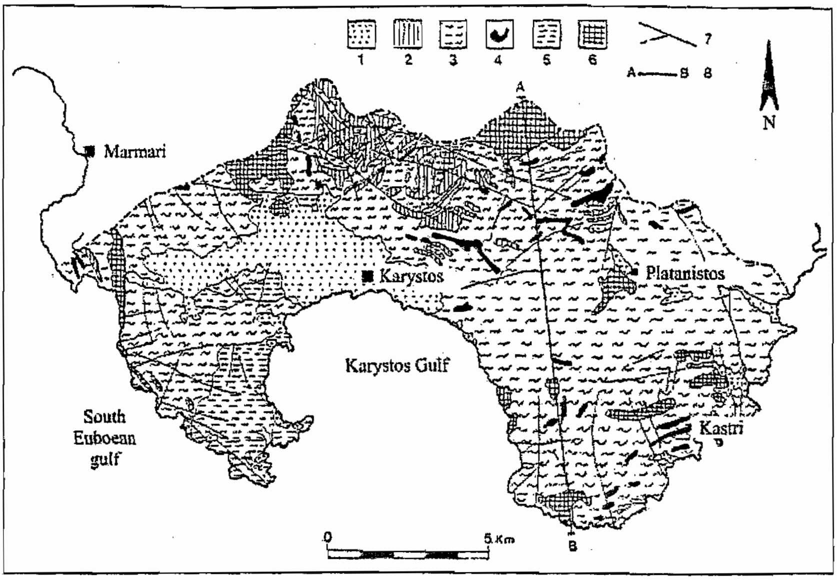

Figure 7. Geology of the study area 2: 1. alluvium, 2. marbles and sipolines, 3. schists 4. quartz schists 5. orthogneisses and 6. metamorphic basic rocks, 7. faults.

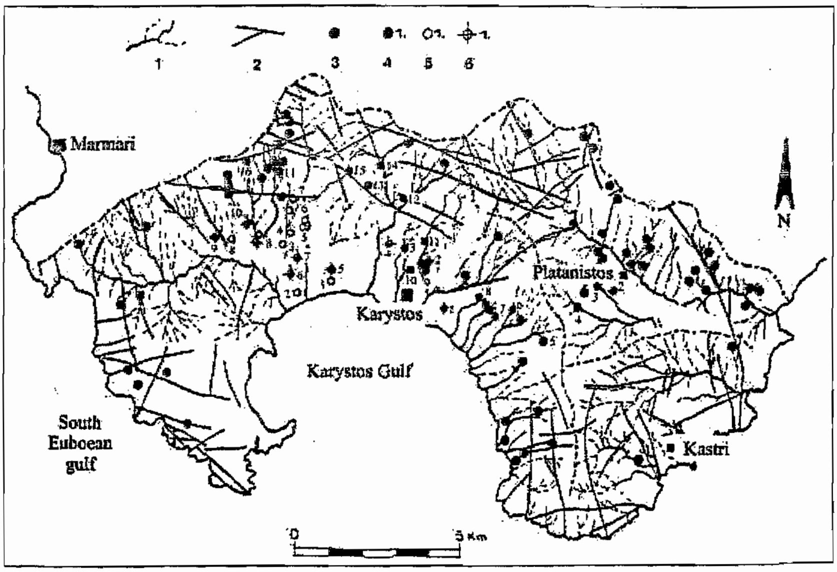

Figure 8. Drainage network and sampling points of the study area (1. Drainage network, 2. Faults, 3. Spring locations, 4. Sampling springs, 5. Sampling wells and 7. Sampling boreholes).

(e) Cyclades Island Complex – Tinos Island. The islands of Cyclades arein the central Aegean and constitute the Cycladic plateau. The largest islands of Cyclades (Naxos, Andros and Tinos) are located at the eastern part of the plateau and have the highest elevation. There are four islands, Kea, Kythnos, Serifos, and Sifnos, located at the western edge that

Table 4. Hydrochemical data of Southern Evoia.

Parameters	Springs									Wells		
	Marbles and Cipolines			Schists			Metabasites					
	min	max	aver	min	max	aver	min	max	aver	min	max	aver
T°C	14.8	16.8	15.4	12.8	18.5	16.3	18.2	18.5	18.4	17.5	20.9	18.9
Q(m^3/h)	4.8	35.0	17.9	1.7	60.0	28.1	0.1	2.0	1.1			
pH	7.7	8.1	7.9	7.6	8.2	7.9	7.5	7.6	7.6	7.2	8.4	7.9
EC (μS/cm)	413	489	451	289	617	386	830	848	839	587	1794	969
Ca^{2+} (mg/l)	48.1	64.1	54.1	27.3	40.1	36.4	56.1	72.1	64.1	32.1	120.0	80.8
Mg^{2+} (mg/l)	8.8	16.5	13.5	2.9	19.9	9.4	30.2	39.4	34.8	11.7	68.1	30.5
Na^{+} (mg/l)	20.7	34.5	25.3	12.0	66.7	29.2	48.3	57.5	52.9	34.5	179.0	76.9
K^{+} (mg/l)	0.8	2.3	1.4	0.4	0.8	0.7	0.8	0.8	0.8	0.8	5.9	2.5
HCO_3^- (mg/l)	207.0	234.0	217.0	73.0	167.0	125.0	266.0	293.0	279.5	95.0	397.0	266.7
Cl^- (mg/l)	28.4	53.2	36.4	21.3	141.8	50.5	88.6	117.0	102.8	53.2	195.0	99.3
SO_4^{2-} (mg/l)	13.4	21.6	17.6	8.2	36.5	18.1	38.4	48.0	43.2	21.6	205.0	78.2
NO_3^- (mg/l)	0.0	6.2	4.7	0.0	6.2	2.6	0.0	9.3	4.7	0.0	74.4	18.3
SiO_2 (mg/l)	7.6	14.9	10.2	10.1	14.6	12.8	20.3	20.3	20.3	12.2	34.5	20.9
TDS (mg/l)	347.6	418.2	380.1	207.7	366.0	278.2	581.0	604.8	592.9	436.7	814.8	674.2
Total Hard.	178.0	208.0	190.5	112.0	150.0	129.2	302.0	304.0	303.0	194.0	520.0	327.1
Temp. Hard.	170.0	192.0	178.0	60.0	137.0	102.5	218.0	240.0	229.0	78.0	325.0	219.2
Perm. Hard.	8.0	16.0	12.5	8.0	90.0	26.7	64.0	84.0	74.0	16.0	316.0	107.9

much smaller in size. The islands of Syros, Paros, Ios and Mykonos are located between these two groups of islands. The islands of Milos, Santorini and Amorgos are situated around the southern edge of the plateau and are peripheral expansions of the plateau (Botsialas et al. 2005, Leonidopoulou et al. 2005, Louis et al. 2005, Melidonis 1980, Melidonis & Triantaphyllis 2003, Stournaras et al. 2002, Stournaras et al. 2003).

Geology. The islands of Cyclades are generally characterized by metamorphic rocks such as mica-schists, marbles, gneisses, amphibolites, glaucophane schists and plutonian rocks (Figure 9). The principal metamorphic events occurred during the Tertiary (Eocene, Lower Miocene). The structures of metamorphic rocks are dominated by isoclinic folding, thrusts and re-folding during the Eocene–Oligocene.

Tectonics. The islands of Cyclades belong to the internal metamorphic zone of central Aegean that is part of the internal crystallic zone of the Hellenides. The recent tectonic history of Cyclades starts with the Eocene Alpine orogeny, a period of dominantly tectonic compression. This compression gave way to a tensile phase during Oligocene or Miocene; the result of this phase was the development of shallow normal faults. During Miocene, the sea depths at central Aegean were shallow with extensive emerging regions and small elongated basins, resulting from the intense compression. The compression resulted in the generation of a graben, which gave rise to the blueschists. During that period, low pressures transformed a mass of rocks into the greenschists. After the end of the faulting processes, the phase of low pressures was followed by granitic intrusions through the older faults. Volcanic activity in Cyclades took place mainly on the islands of Milos and Thira.

In order to describe the relationship between faults and fractures and lithological units, rose plots have been created for each lithological unit in Figure 9(a) and 9(b). These show that the dominant orientation for the faults of all lithologies is NW-SE. In the carbonate rocks there is a second dominant orientation of NEE–WSW; the soft rocks appear to have an important number of faulting zones which are oriented normal to the dominant faulting

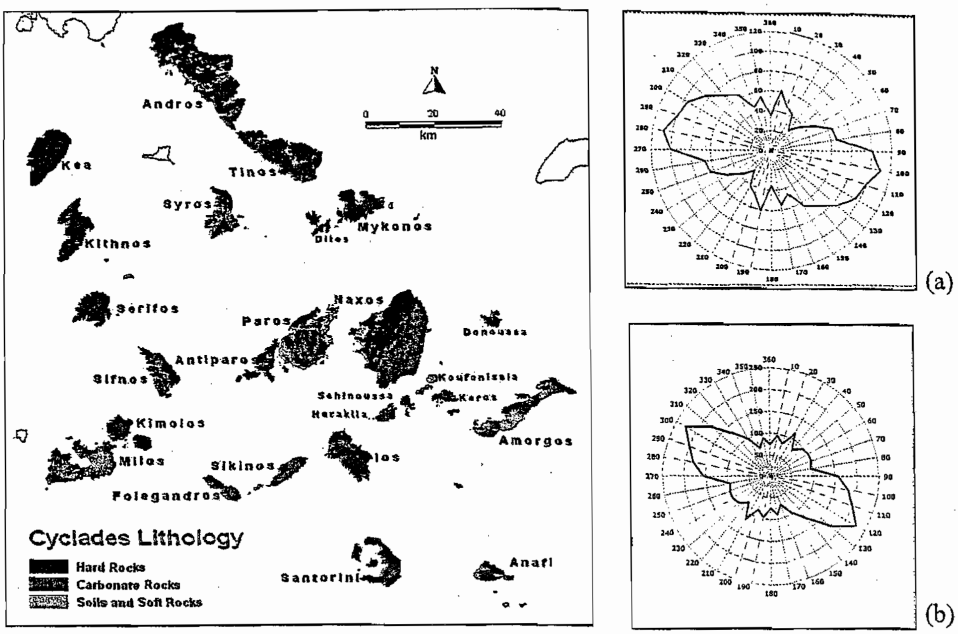

Figure 9. The main lithological units at Cyclades area. (a) Faults Rose Plot in soft rocks and (b) Faults Rose Plot in hard rocks in Cyclades area.

zones. The fissured rocks cover most of the Cyclades to explain the fact that the dominant faulting orientations are almost uniform for the whole area.

Hydrogeology. Cyclades islands are small in extent and are characterized by low annual rainfall, high medium annual temperatures, and high sunlight; the developed aquifers are of low capacity. Simultaneously most aquifers are unconfined and discharge to the sea. The main water-bearing rocks of the region, apart from carbonate rocks, are the hard, fissured rocks (granites, schists, gneisses, etc.).

Tinos Island. Tinos Island (Figure 10) belongs to the Attic-Cycladic Complex. Metamorphic rocks are classified into three tectonic units: (1) the Upper Unit composed of serpentinites, metagabbros, metabassalts, phyllites, and amphibolites, approximately 500 m thick; (2) Cycladic Blueschists more than 2000 meters thick and that cover the greatest part of the island. Meta-volcanic, clastic rocks and marbles also are present; (3) the Lower unit, derived from Mesozoic limestones, marls, shales, cherts, tuffs, basaltic vulcanite, and acidic rocks of probable volcanic origin. Magmatic rocks of the island are being classified into: (1) a complex of granite and granodiorite intrusion, which took place at early Miocene; (2) small outcrops of rocks of volcanic origin, with rhyolitic and andesitic composition.

A study area (Figure 11) was selected in Tinos to investigate, the hydrogeological environment of the hard rocks aquifers. From July to August of 2003, a spring inventory was conducted in the study area. Topographic maps at the 1/5.000 scale were used to plot 150 spring locations. Their spatial distribution shows that 95.3% of the springs, are located in hard rock formations (gneisses, gneisschists, glaucophane schists, greenschists, ophiolites, and prasinites).

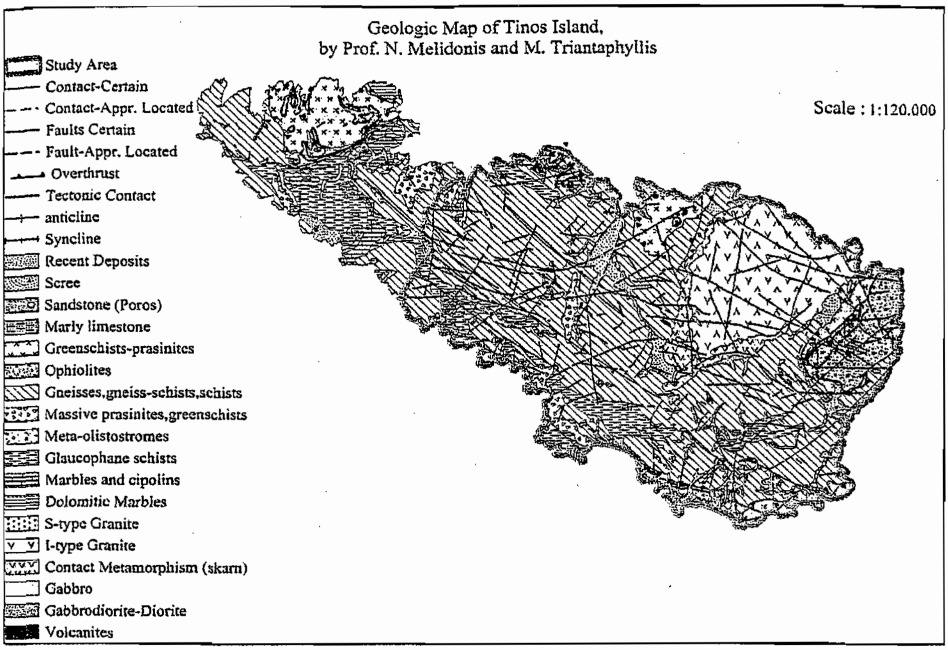

Figure 10. Geological map of Tinos Island.

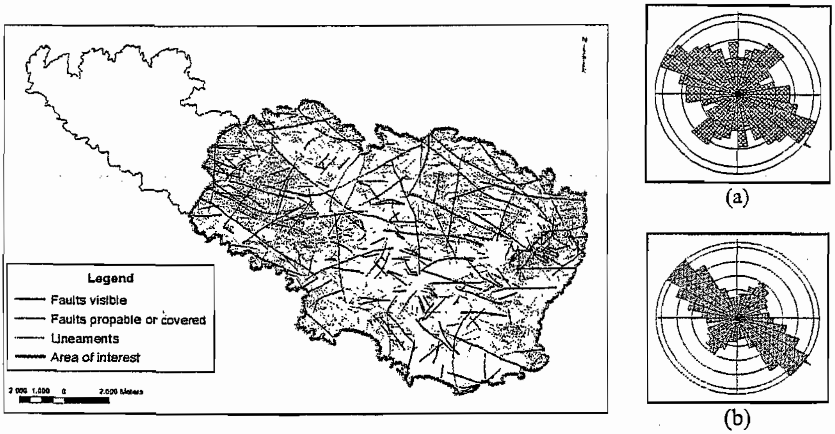

Figure 11. Faults and lineaments of the study area. (a) Faults Rose Plot and (b) Fractures Rose Plot.

Discharge, varies from 0.5 m^3/sec to 3.5 m^3/sec in the humid periods of the year. The majority of the springs (69.34%) are located on or near the streams of the drainage network, which is heavily influenced by the tectonic regime of the island. 82% of the springs are located very close to faults, fractures, or the intersection of two or more fractures. This is a strong evidence of the influence of the hard rock environment on the groundwater flow in the study area.

In order to obtain a reliable picture of the groundwater flow, it was necessary to depict the fractures systems of the study area. GIS and remote sensing techniques were integrated along with results from field study. A map of fractures (Figure 11) was found 3178 features that 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: (i) length, (ii) directional distribution, (iii) the detection of anomalous directions, (iv) 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.

In most of the cases, the orientation of fractures is identical with the orientation of the preferential flow path. In Figure 11(a), the fractures rose plot shows that there are two sets of orientation. The main one has a NW-SE strike while the secondary one has NE-SW strike. The faults rose plot in Figure 11(b) reveals four orientation classes. The two main classes have NW-SE and NE-SW strike, and the secondary ones are of N-S and E-W strike.

The conclusions that were obtained from this study are:

(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 are located in the distance of 250 m 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) Springs are strongly related or controlled by fracture location.

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