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CORRELATION ON NEOTECTONIC STRUCTURES WITH THE GEODYNAMIC ACTIVITY IN MILOS DURING THE EARTHQUAKES OF MARCH 1992

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ABSTRACT

The seismic activity of March 1992 in Milos Island resulted, besides the substantial destructions, in many other macroseismic phenomena of special interest due to the location of the island within the active volcanic arc and the interelationship between the seismicaly activated faults and the volcanic activity.
Extensive surveying showed that most of the phenomena, in both number and intensity, took place at the neotectonic block of the Milos Gulf - Fyriplaka Volcano, which is bounded by two large fault zones striking NW-SE. The earthquake epicenters were located along the southeast prolongation of this NW-SE graben structure.
Our observations concern seismic fractures, variations in intensity and temperature of the gases, landslides and rockfalls, liquefactions, variations in the acquifer level and distribution of damages.
The general conclusion is that there is an interelationship between the earthquakes, the activated neotectonic fault zones and the variation in the volcanic activity of Milos.

1. INTRODUCTION

The island of Milos was hit by an earthquake on March 20, 1992 (07.37am M_L=5.2), which was followed at 11:00am by an aftershock of M_L=4.8; during the following hours 18 events ranging from $3.8 \leq M_L \leq 4.8$ were recorded. Based on the data taken from the National Observatory of Athens, the epicentral area lay off the southern coast of Milos, as well as at the region of Palaeohori-Zefyria villages (southern Milos)(Fig. 1). The focal depth of these shocks was, after the N.O.A., quite shallow, 1-4 km.
The seismic activity caused considerable damages to

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constructions, as well as various macroseismic manifestations; seismic fractures, liquefaction events, changes in subsurface water level, changes in the temperature of emmitted gases, landslides and rockfalls were observed.

The occurrence of these macroseismic phenomena, at specific locations and areas of Milos showed clearly a direct relationship to the ongoing geodynamic processes due to the position of Milos on the active volcanic arc of the Aegean (Fig. 1a).

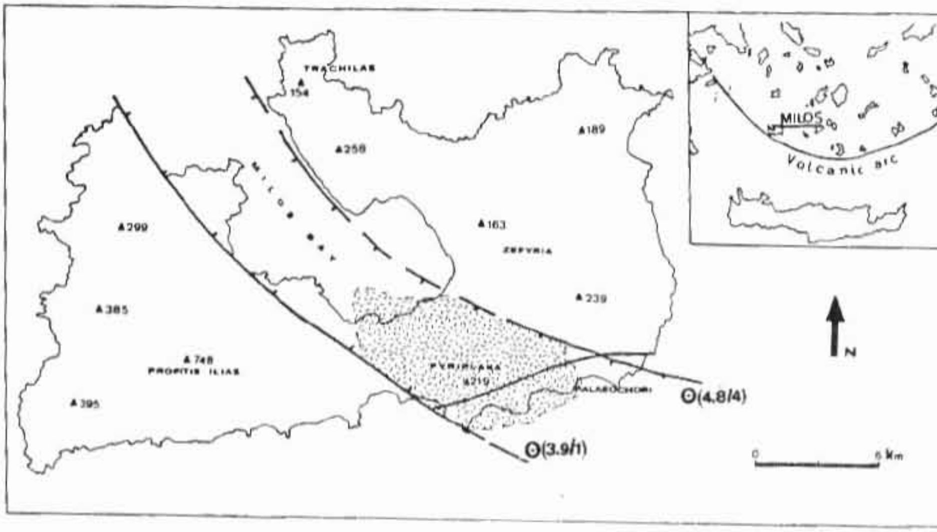


Fig. 1 Location of the main earthquake epicenters (magnitude in Richter's scale / depth in km) and their relation with the major active fault zones of Milos. All the macroseismic phenomena, described in the text, have been exclusively observed within the shaded area.

2. BRIEF DESCRIPTION OF THE GEOLOGY AND NEOTECTONICS OF MILOS

Milos Island belongs to the active volcanic arc of the Aegean. It comprises various volcanic rocks which overlie the metamorphic basement of the Cyclades and sedimentary deposits of Late Miocene - Quaternary.

Summarizing previous (SONDER 1924, LIATSIKAS 1949, FYTIKAS 1977) and more recent research (PAPANIKOLAOU et al 1989, PAPANIKOLAOU et al 1990), the geology of Milos comprises the following formations whose outcrops are given in figure 2:

1. Alluvial and coastal deposits and talus scree. They are mainly located at Zefyria plain and their occurence is under tectonic control.
2. Formation of recent porous tuffs and sandstones. These are well-bedded, cohesive clastic formations of 10-15 m. in thickness. Their outcrpops are located mainly at the area east of Adamas. Age: Late Pleistocene.

3. Pyroclastic cone, rhyolitic lavas and pyroclastic material of the Fyriplaka Volcano. The pyroclastic cone comprises continuous alternations of sand, ash and perlitic beds of rhyolitic composition. Age: Middle-Late Pleistocene (0.14-0.08 Ma). The pyroclastic material is of the same age with a thickness of 10-20 m. and crops out at Aghia Aekaterini area.
4. Pyroclastic cone and rhyolitic lavas of the Trachila Volcano. The cone comprises continuous alternations of ash, sand and perlitic layers of rhyolitic composition and the rhyolitic lavas develop north of the volcanic cone. Age: 0.38 Ma (Middle Pleistocene). The Trachila Volcanics are bounded by the large NE-SW fault zone running from Fyropotamos village.
5. Younger Tuffites. Age: Middle Pleistocene. Their thickness may reach 50 m. and their outcrops are usually under tectonic control, bounded by fault zones.
6. Green Lahar. Deposits of unconsolidated heterogeneous material inside the volcanic ash. Age: Early-Middle Pleistocene. Its thickness reaches up to 70 m.; its upper limit corresponds to a well developed planation surface and the outcrops are usually under tectonic control.
7. Lava formations, coarse deposits, pumice flow deposits. Rhyolitic, dacitic and andesitic lavas in extrusion dome form and lava flows. Age: older than 2.0 Ma (Pleistocene) at western Milos and younger than 2.0 Ma at eastern Milos.
8. Older Tuffs-Tuffites. Age: Pliocene-Early Pleistocene; visible thickness: more than 100 m.
9. Late Miocene-Early Pliocene formations. Limestones, marls and conglomerates croping out mainly at W. Milos.
10. Metamorphic rocks of the alpine basement. Greenschists, blueschists, quartzites and metabasalts. Mostly croping out at Theorichia at Palaeochori Bay at southeastern Milos.

Recent detailed research carried out on the geothermal field of Milos (PAPANIKOLAOU, 1988) showed that there is a number of tectonic blocks which correspond to neotectonic units, each one bounded by large faults and characterized by (i) the occurrence of certain formations only in these blocks, (ii) the unproportional development of other formations, (iii) their particular tectonic deformation (iv) their differentiated morphotectonic features.
More specifically, Milos Island consists of the following neotectonic units (Fig. 2):

1. NW Milos unit: it is characterized by the outcrops of volcanic rocks and the assymetrical development of the Younger Tuffites.
2. Aghia Marina Neotectonic Unit: It is characterized by the absence of the younger tuffites.
3. Profitis Elias Neotectonic Unit: it is characterized by the outcrops of ingimbrites which overlie the lavas, the Old Tuffs and the Late Miocene-Early Pliocene formations.
4. SW Milos Neotectonic Unit: it is characterized by the outcrops of Late Miocene-Early Pliocene formations which overlie the metamorhpic basement.
5. Chalepa Neotectonic Unit: it is characterized by the outcrops of lavas aged 0.9-1.1 Ma. The rest of the formations are absent.
6. Provatas Neotectonic Unit: it is characterized by the

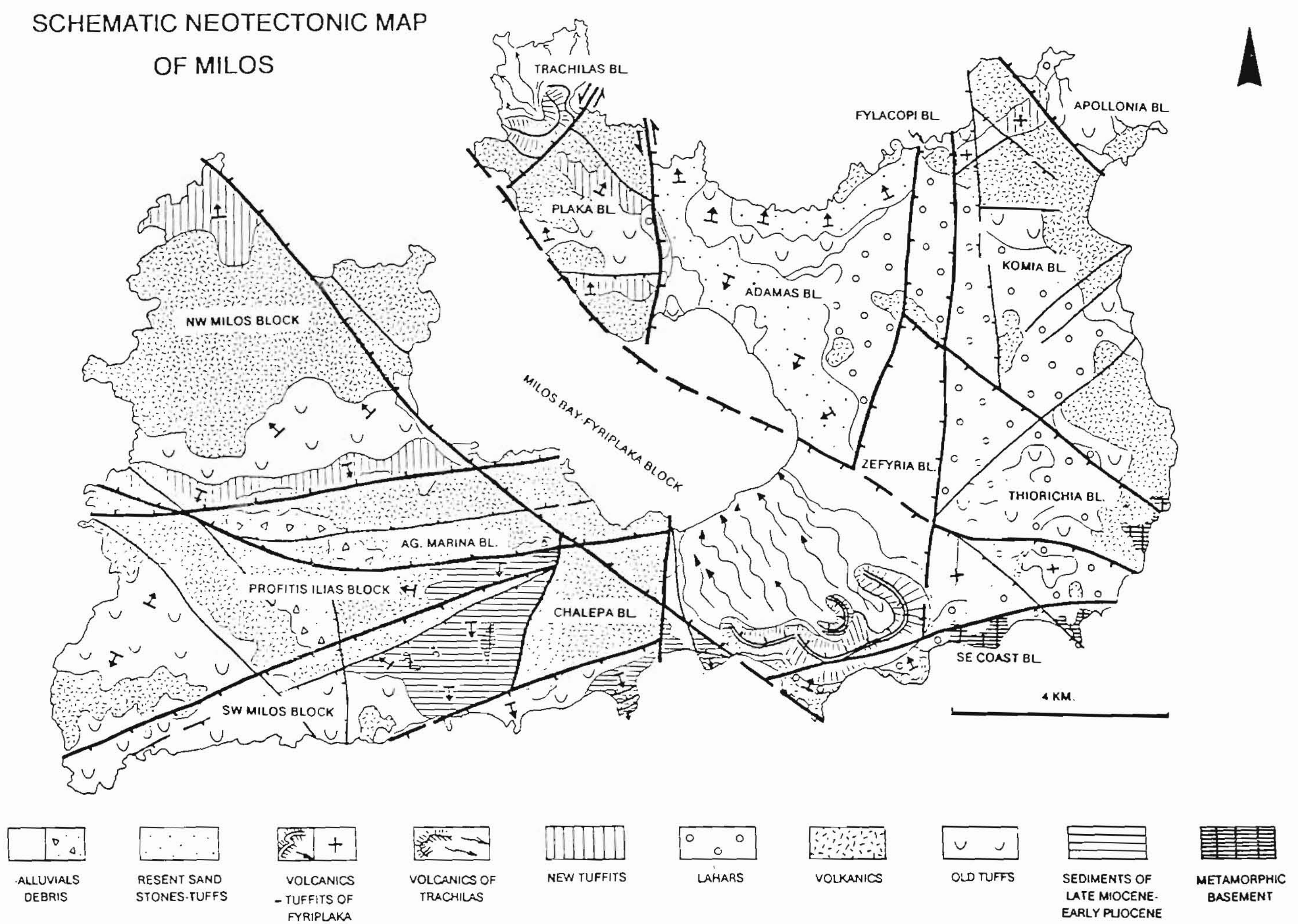


Fig. 2 Neotectonic map of Milos (simplified after PAPANIKOLAOU et al, 1989).

outcrops of Late Miocene-Early Pliocene formations and some occurrences of Older Tuffs and Lahar.

7. Trachilas Neotectonic Unit: it is characterized by the presence of Trachilas volcano(0.38 Ma).
8. Plaka Neotectonic Unit: it is characterized by the outcrops of lavas overlying the Older Tuffs and some outcrops of Younger Tuffites. It corresponds to a horst.
9. Adamas Neotectonic Unit: it is characterized by the outcrops of the Recent Porous Sandstones formation (Late Pleistocene) which overlie the Lahar and the Older Tuffites.
10. Fylakopi Neotectonic Unit: it is characterized by the outcrops of Lahar.
11. Theorichia Neotectonic Unit: it is characterized by the outcrops of Lahar overlying the Old Tuffs and the lavas over the metamorphic basement.
12. Appolonia Neotectonic Unit: it is characterized by the outcrops of the Recent Porous Sandstones, Younger Tuffites, Older Tuffs and lavas.
13. Komia Neotectonic Unit: it is characterized by the outcrops of Lahar, lavas and Older Tuffs.
14. "SE Coast" Neotectonic Unit: it is characterized by the outcrops of the metamorhpic basement and underlies the Lahar and the lavas.
15. Zefyria Neotectonic Unit: it is characterized by the outcrops of alluvial deposits (up to 100 m. thick) and overlies unconformably the Lahar. It is an active tectonic depression (graben) whose creation was initiated in Middle Pleistocene and has been subsiding till nowadays at a rate of 1 cm/yr. It is bounded by large fault zones of total throw of more than 300 m. At the area of this neotectonic unit and mainly along the large border fault zones, the geothermal activity is of considerable interest.
16. Neotectonic Unit of Milos Bay-Fyriplaka Volcano. It is characterized by the presence of Fyriplaka volcano which has been developed over the Lahar, the older lavas and the metamorphic basement. It is the most important Neotectonic Unit, from the view point of the neotectonic structure and the evolution of Milos island. The western part is characterized by a gradually lessening neotectonic activity, whereas at the eastern part the neotectonic activity is intense.

   Actually, this Unit corresponds to a large tectonic depression-graben which is bounded by two major fault zones that strike NNW-SSE. To the west, the fault zone of Kontaros was first activated in Late Miocene - Early Pliocene with a total throw exceeding 300 m. To the east the fault zone of Aghia Paraskevi, was initiated in Pliocene - Early Pleistocene with a total throw of more than 400 m. To the south this neotectonic unit is prolongating towards the neotectonic unit of SE coast interrupted by the important E-W fault zone of Aghia Kyriaki which is their division line.

3. OUTLINE OF THE GEODYNAMIC-MACROSEISMIC PHENOMENA

During the seismic activity of March 1992, a large variety of macroseismic geodynamic phenomena were observed at some regions of Milos island. The phenomena observed and recorded are shown

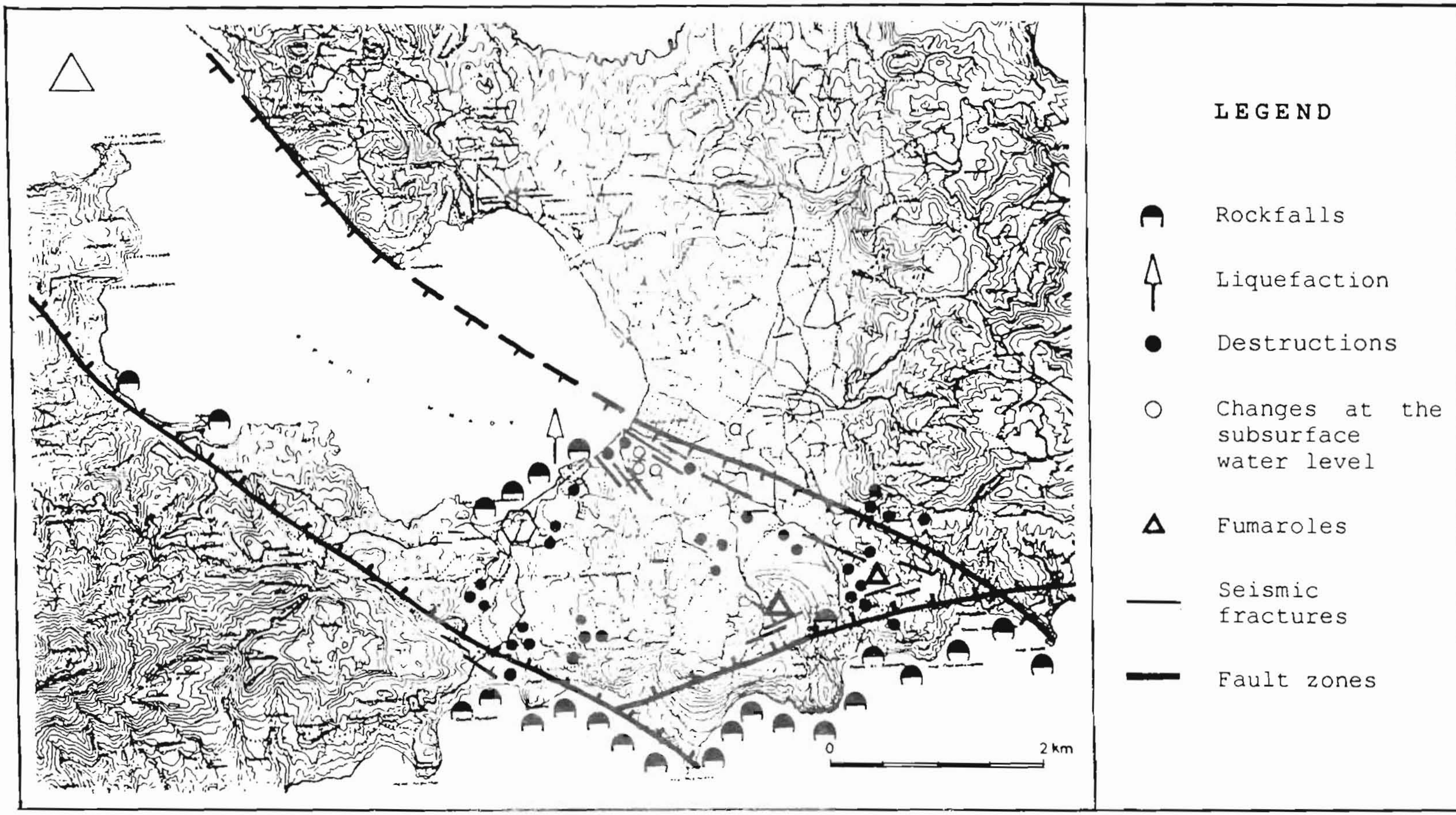


Fig. 3 Distribution of macroseismic phenomena observed during the survey immediately after the seismic activity.

in summary in figure 3.

3.1 EARTHQUAKE FRACTURES

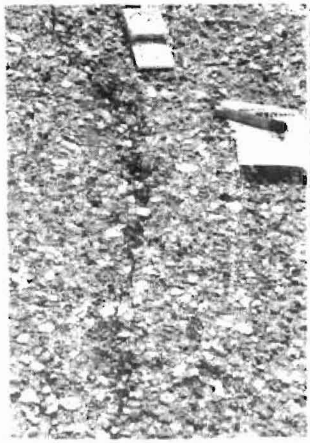
The most important macroseismic event that took place during the March 1992 earthquakes was the creation of numerous seismic fractures. The phenomena were located at a strictly constrained area of Central Milos, as described in the following:

A. **Airport.** The fractures there generally strike NW-SE (N130o-N160o). Their number was higher than thirty and were mainly developed on the alluvial formations round the airstrip. They were usually a few meters long, only a few exceeding 30 m. in length. Unfortunately, mainly due to the nature of the formations, no horizontal or vertical displacement could be measured.
Some more fractures of the same strike and bearing identical features were created, on the tarmac of the airstrip (Fig. 4a,b) .
In some of these fractures, small angular fragments seemed to have been ejected into the air, leading us to the supposition that some lateral displacement took place. The location and the strike of the fractures in this area virtually coincides with the positioning and strike of the large fault zone of Aghia Paraskevi which is the boundary to the NE of Milos Bay-Fyriplaka Volcano Unit.

B. **Provatas area.** Only one fracture was located there, with a length of 50 m. and 15 cm of breadth, striking N130. It was developed in alluvial and Late Miocene-Early Pliocene formations. The tectonic movement showed that the NE segment was downthrown relatively to the SW one. This fracture actually coincides with the southern prolongation of the large fault zone of Kontaros, which is the boundary to the NW of Milos Bay-Fyriplaka Volcano Neotectonic Unit.

C. **Fyriplaka Volcano area.** The earthquake fractures in this area were striking N70o-N85o and were observed at the location where the most important fumarolic activity takes place. Four large fractures of more than 20 m in length and 30 cm in breadth occurred in lavas at the inner slopes of the crater; they gave the impression of propagating to cosiderable depth (Fig. 4c).
It must be noted that these fractures cannot be attributed to casual detachments of rock masses due to loss of lateral support-instability. At the same location a fracture was observed at the outer slope of Fyriplaka volcano, striking N180o. This fracture was accompanied by landslides and will be described later. The fractures of the area of Fyriplaka volcano actually coincide with the large fault zone of Aghia Kyriaki which divides the Milos Bay - Fyriplaka Volcano block from the neotectonic block of the SE coast.

D. **West of Aghia Kyriaki area.** The fractures at this area generally strike N70o-N85o, have a length of 10-30 m. and a breadth of 5-20 cm. They are parallel to the fractures of Fyriplaka Volcano and also to the large fault zone of Aghia Kyriaki, which lies at a distance of about 300-500 m.. The most interesting in this case is that these seismic fractures appear only around the pre-existing fumaroles, while, according to reliant information and personal observations,



a

b

c

d

Fig. 4 Seismic fractures created during the seismic activity of March 1992(a, b: Airport area, c: Fyriplaka Volcano area, d: Kambos - Mavrorachi area).

new gas emmissions ocurred along them.

E. **Kambos- Mavrorachi area**. The fractures at this area actually lie at the prolongation of the fractures observed in the airport to the southeast and lie along the same strike (N140o-N160o). Their number is smaller but their length is larger than the fractures of the airport(Fig. 4d).
These fractures are developed in Tuffites and Lahar and have a length up to 150 m. or more and breadth locally reaching up to 30 cm. The soutwestern segment locally appears downthrown, relatively to the northeastern one, by 20-30 cm.
The fractures at the Kambos-Mavrorachi area coincide with the large fault zone of Aghia Paraskevi which bounds the neotectonic unit of Milos Bay-Fyriplaka Volcano to the northwest.

3.2 LANDSLIDES - ROCKFALLS.

The landslides-rockfalls which take place during an earthquake are usually due to: (i) the existing morphology and mainly to the morphological slopes and discontinuities, (ii) the existing geological-geotechnical conditions, established by the nature of the geological formations, the geological structure and the dominant geometry of the discontinuities, and (iii) the seismic motion itself, i.e. the acceleration during the motion.
During the earthquakes of March, 1992, several landslides-rockfalls occured at Milos Island. They resulted in the destruction of constructions and the alteration of the physicogeographical image, at numerous locations (Fig. 5). The detailed survey of the whole island showed that the main landslides-rockfalls were located at the following areas:

A. **Fyriplaka Volcano area**. Extensive landslides were observed at the southern slope of the volcano along Geraki adn Provatas bays; the most important cases occured at Mouri and Kalamos capes. At this region, where continuous alternations of lavas, Lahar and tuffites crop out, the landslides-rockfalls were of considerable magnitude and in some cases the unstable rock-volume was estimated to exceed 5000 m^3. A large slide was also observed at the eastern slope of the volcanic cone - in a lava formation- which presented a linear development, from west to the east. It actually coincides with a large seismic fracture previously described which belongs to the fault zone of Aghia Aekaterini.
B. **Palaeochori-Agia Kyriaki area**. Numerous significant rock falls took place, which caused a radical alteration to the pre-earthquake existing physicomorphological landscape. A striking example is the destruction of a natural "arch", which separated the Palaeochori beach in two segments, after the fall of the overlying rock mass, of more than 200 m^3 in volume.(Fig. 5a,b)
C. **Alikes-Chivadolimni area**. The landslides-rockfalls between Chivadolimni-Alikes were caused along the coastal line and struck mainly the road network, which was totally destroyed at some places. **(Fig**. 5c,d).

Despite the extensive survey all over the island, no other worth-mentioning slides were found at any other location of the new gas emmissions ocurred along them.

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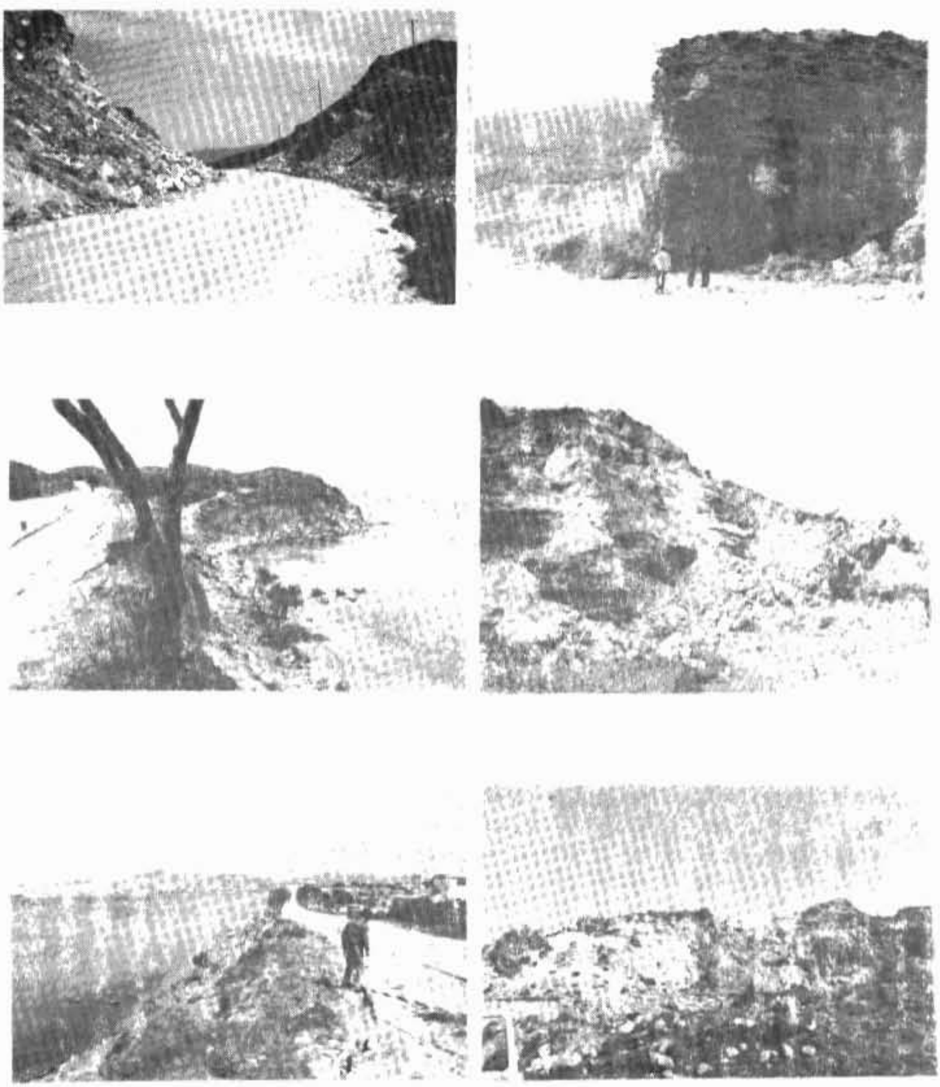


Fig. 5 Landslides - rockfalls which took place during the earthquakes of March 1992 in the area of the neotectonic unit Milos Bay - Fyriplaka Volcano.

island, in spite of the existence of higher slopes and of the de-favourable geological-geotechnical conditions even more than at the previous areas where landmass movements did occur.
The above descriptions indicate that the landslide-rockfall phenomena were particularly intense only at the area strictly bounded by the major fault zones of the neotectonic unit of Milos Bay-Fyriplaka Volcano. This fact is attributed to the high accelerations-seismic intensities developed at this particular area, given that the other two factors mentioned before (i.e. morphological slopes and geological-geotechnical conditions) are practically uniform all over the island.

3.3 CHANGES IN THE INTENSITY AND TEMPERATURE OF EMMITED GASES.

Apart from the earthquake fractures, the seismic activity of March 1992 resulted in the change of the intensity and temperature of the emmitted gases at some locations of Milos. These changes were perceived either by eyewitnesses during or shortly after the earthquakes, or by our measurements after the events. These are the following:

A. **West of Aghia Kyriaki area**. According to eyewitness reports, during both the main event and the main aftershock and simultaneously with the newly created earthquake fractures, new gas emmitions took place at a distance of about 150 m. from the existing fumaroles. Besides, at the old fumaroles, there was a significant change in the gas exhaust pressure. This differentiation is known to have been accompanied by a change in the gas temperature that lasted few hours after the mainshock.

B. **Fyriplaka volcano area**. At the crater of Fyriplaka Volcano, during the seismic activity, there was an intense differentiation of the pressure of the emmited gas, which, together with the slides and the seismic fractures, drew the interest of the inhabitants. The temperature of the gases reached 100 °C (counted at the vent opening) and remained at the same level throughout the duration of the seismic activity and a few days later returned to the level of 98° C, which is their normal value.

3.4 LIQUEFACTION PHENOMENA

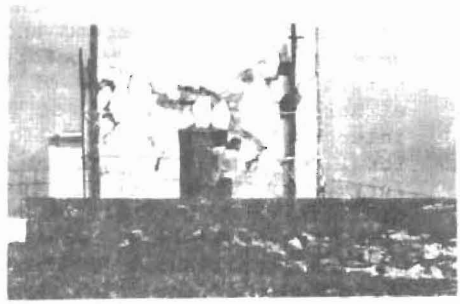
During the March 1992 earthquakes, several liquefaction phenomena were observed, mainly along the coastal zone of Milos Bay, between Alikes and Chivadolimni. Such events take place when fine or silty sands containing water are subsequent to repeated shearing deformation of a certain amplitude (e.g. seismic wave), leading the solid mass to acquire heavy-fluid properties.
The liquefactions were developed along a coastal zone 200m long and 30 m. wide, in coastal deposits- fine and silty sands containing a low proportion of coarser material. The manifestation of the liquefaction events was carried out mainly through two different ways: either via "fissures", or vent-like structures at elevations of 1 m. above sea level.
The fissures had a maximum length of 30 m. and width 0.5 m. with

a strike NW-SE, parallel to the coastline while no vertical displacement through the fissures was observed. The liquified material emerged was easily recognisable because of its gray colour and its content in silty material.
The vents had a diameter of 1 m. and initially there must had taken place a subsidence of the contained material, followed by their filling-up by partially different, grey,silty sandy material. The total subsidence was about half a meter.
Our field observations, showed us that these liquefaction events occurred in some intercalations within the coastal deposits which contain grey silty sand at a higher proportion, lying at or below sea level, down to a depth of 2 m.. In spite of our detailed observations all along the coasts of Milos where similar formations occur, no marks of similar phenomena were traced; this shows that these phenomena were limited in the abovementioned locations within the neotectonic block of Milos Bay-Fyriplaka Volcano.

3.5 DISTRIBUTION OF DAMAGES

The earthquakes of March 1992 in Milos led to numerous damages in residential and other constructions. According to the official data, out of 713 buildings inspected, 495 (69%) were not damaged at all, 107 (15%) were considered temporarily uninhabitable because of minor damages and 116 (16%) were to be demolished. The inspections were mainly carried out at the areas of the airport, Provatas, Zefyria, Palaeochori, Agia Kyriaki, given that at the remainder of the island, no damages were reported, not even minor ones.
The constructions of the second category -minor damages- belong to the urban units of Adamas and Plaka - Triovasalos, while the damages falling into the third category -major damages- belong to the area of the Airport-Provatas-Aghia Kyriaki-Palaeochori-Zefyria.
More specifically, at the area of Airport-Provatas-Aghia Kyriaki-Palaeochori-Zefyria, which actually corresponds to the neotectonic Unit of Milos Bay-Fyriplaka Volcano, we recorded more that 30 total failures and over 50 constructions with major damages (out of a total of 116 (16%) belonging to this category)(Fig. 6). Of course, the occurence of so many damages was due to the fact that the constructions were old and were constructed by inadequate method.
At the Plaka-Triovasalos area, some important damages happened at about 30 constructions that were old or abandoned. On the contrary, small, repairable damages happened to a larger number of buildings (over 60), once more at old constructions. The most significant fact for the distribution of the damages in the urban unit of Plaka-Triovasalos is that most damaged constructions were founded on the Younger Tuffites formation and only a few were built upon the lava dome of Plaka and the Older Tuffites formation.It has to mentioned that the Younger Tuffites are easily weathered and overlie the lavas with a thickness of less than 20 m. inside the inhabited areas. On the contrary, the lavas are a rocky formation while the Older Tuffites have similar geomechanical features with the Younger Tuffites but much larger thickness.

a



c

b

Fig. 6 Constructions with major damages within the area of the neotectonic unit [illegible] Volcano (a: Vounalia area, b: [illegible] area c: Aghia Pyrakia).

3.6 CHANGES AT THE SUBSURFACE WATER LEVEL

Chañges at subsurface water level are a frequent phenomenon caused during or after seismic activity. In many cases, these changes are considered also as precursory phenomena.
At Milos area, no detailed measurements on the height and fluctuation of the water table were existing before the earthquake activity; nor were carried out later,as no comparative results could be drawn. Nevertheless, based on reliable information, we confirmed that during the main shock of March 1992, some changes did take place at the water level in wells of the airport area, within the neotectonic unit of Milos Bay-Fyriplaka Volcano. At the wells of this region a rise of the water table was observed and became obvious by the overflow of water whose level lay before at 2-3 m. depth. At two wells, a simultaneous turbidence of the water was observed, because of either the presence of silt in some soil horizons - intercalations that were liquified, or of the rapid movement of the fluid facies from place to place.
In general, the rise of the water table is attributed to the diminish of the effective porosity of the surficial geological formations that crop out at the area (alluvial formations), due to the repositioning -better arrangement of the fine material by the seismic motion.

4. DISCUSSION

The first general conclusion that can be obtained from the seismic activity of March 1992 in Milos is the direct relation of the earthquakes with the major active faults of the neotectonic structure. This is demonstrated by the distribution and geometry of the seismic fractures and by the location of the epicenters on the prolongation of the main NW-SE faults which are bordering the neotectonic block of Milos Bay - Fyriplaka Volcano. These NW-SE faults have created the active tectonic graben structure which separates Western Milos from Eastern Milos and which is characterised from the recently submerged morphology of the Bay of Milos in the NW and the most recent volcanic activity of the Fyriplaka crater to the SE. As PAPANIKOLAOU et al (1989) have demonstrated, this graben structure is the most active feature of Milos whereas, both to the west and to the east, the neotectonic structures seem to be relatively inactive with the only exception of the N-S faults bordering the small Zefyria alluvial graben and the blocks of Plaka and Adamas.
The epicentre location along the NW-SE faults bordering this graben structure is assured by: (i) the very shallow focal depth of the shocks which did not exceed 4 km, (ii) the fault planes are dipping at high angles, more than 75^{o}. Additionally, microseismic surveying of the area has shown that the Aghia Aekaterini fault zone, bordering the graben to the NE, is rather active since numerous microtremors have been recorded along it

(OCHMAN et al, 1989).
The manifestation of a series of phenomena like liquefactions, rockfalls-landslides, changes in the water level and the vast majority of costruction failures inside this very neotectonic graben, indicate that the seismic energy was released primarily inside this block.
Another interesting conclusion concerns the realtionship between the neotectonic structure and the volcanic activity. The first remarkable fact is that the seismically activated zone of Aghia Kyriaki coincides with the zone of gas emission in the area, indicating that this very fault zone is used for the expulsion of the volcanic material. More specifically, the observed creation of new fumaroles along the fault zone of Aghia kyriaki and the differentiation in the temperature and pressure of previously existing fumaroles lying along or at the intersection of the fault zones of Aghia Aekaterini and Aghia Kyriaki, confirms, beyond doubt, this relationship.
This had already been pointed out by PAPANIKOLAOU et al. 1989 during research on the exploitation of the geothermal field of Milos, given that the large fissures form underground means both of transport of geothermal fluids and emergence of volcanic material. The fault zones of Aghia Aekaterini and Aghia Kyriaki are probably loci of phreatic events, during even minor earthquakes, as it was the case between the 1st and 3rd century A.D. at the area of Aghia Kyriaki (TRAINAU & DALABAKIS, 1989) .
The seismic activity of March 1992, despite the fact that is was not characterized by large magnitudes, demonstrates that the geodynamic processes at Milos and at the wider area of the volcanic arc, have not become inactive. On the contrary, they proceed at the same intensity and complexity which is revealed by the variety of the geodynamic-macroseismic phenomena which took place and which are similar to analogous phenomena that can be traced back in the recent geodynamic evolution of the island.

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