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Seismicity in the Hellenic Volcanic Arc Hydrothermal System in Relation to Geochemical Parameters

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Abstract. The aim of the paper is to study the microseismicity of the island of Milos, Greece, in order to relate the recorded earthquake signals to venting periodicity and to understand better the role of episodic events. A seismic network of five three-component, triggering mode digital stations, installed on the island in the summer of 1996, recorded almost 400 local microearthquakes and 500 signals, tentatively associated with hydrothermal activity. The analysis indicates low seismicity, probably associated with the existing hydrothermal field of the area. The hydrothermal signals are of two types, with peak frequencies of 2-3 Hz and 20-30 Hz, respectively. Preliminary analysis of records from the same experiment in 1997 showed that a high concentration of seawater in particulates Mn was followed by a group of microearthquakes 6-8 hours later.

1 Introduction

The seismicity pattern of an area with historical or recent volcanism can provide information concerning the volcanic, hydrothermal or magmatic process.

Milos island (fig. 1) is located within the Hellenic Volcanic Arc, comprising of various volcanic rocks which overlie the metamorphic basement of the Cyclades and the sedimentary deposits of Late Miocene-Quaternary. A number of tectonic blocks corresponding to neotectonic units have been identified on the island, each one bounded by large faults and characterized by: the occurrence of certain formations only in these blocks, the non-proportional development of other formations, their particular tectonic deformation and their differentiated morphotectonic features (Papanikolaou; 1988). The closest neotectonic unit to Palaeochori Bay, i.e. the area of interest, belongs to the Fyriplaka Bay Volcano unit, which is characterised by a gradually reducing neotectonic activity to the west and more intense neotectonic activity to the east. This unit corresponds to a large tectonic depression-graben which is bounded by two major fault zones that strike NNW-SSE and which is intersected to the south by the important E-W fault zone of Aghia Kiriaki (Papanikolaou et al; 1993).

The most recent tectonic activity on the island was expressed by the 1992, March 20 M_s=5.3 earthquake, with epicentre off the southern coast of Milos, near the region of Palaeochori and Zephyria. The focal plane solution of this earthquake (fig. 1) produced strike slip dextral faulting, with a normal component. These results, coupled with the major tectonic features, show that the island is mainly affected by extensional stresses in the NE-SW direction, which predominate in the broader area of the island (Delibasis and Drakopoulos; 1993). Along with the other macroseismic effects, the above mentioned earthquake caused changes in the subsurface water level and the temperature of emitted gases. The occurrence of these phenomena at specific locations and areas of Milos clearly showed a direct relationship with the ongoing geodynamic processes that take place in the island. As a result of this activity, the seawater in Palaeochori Bay was enriched in phosphate, suggesting that this area may be an important source of this element in the oligotrophic Aegean sea (Dando et al.; 1995b). Offshore Milos submarine hydrothermal activity occurs, as descibed from other Hellenic Volcanic Arc islands, causing significant changes in the marine environment (Varnavas and Cronan; 1991, Cronan and Varnavas; 1993, Dando et al.; 1995a).

For a more detailed study of the correlation between seismic activity and venting, i.e. for the identification of any possible correlation between factors relating to the time-dependence of venting processes and earthquakes, in this hydrothermal active area of the Aegean, two local seismic networks covered the area near and around Palaeochori Bay for two months, in the summer of 1996 and 1997, respectively (fig. 2).

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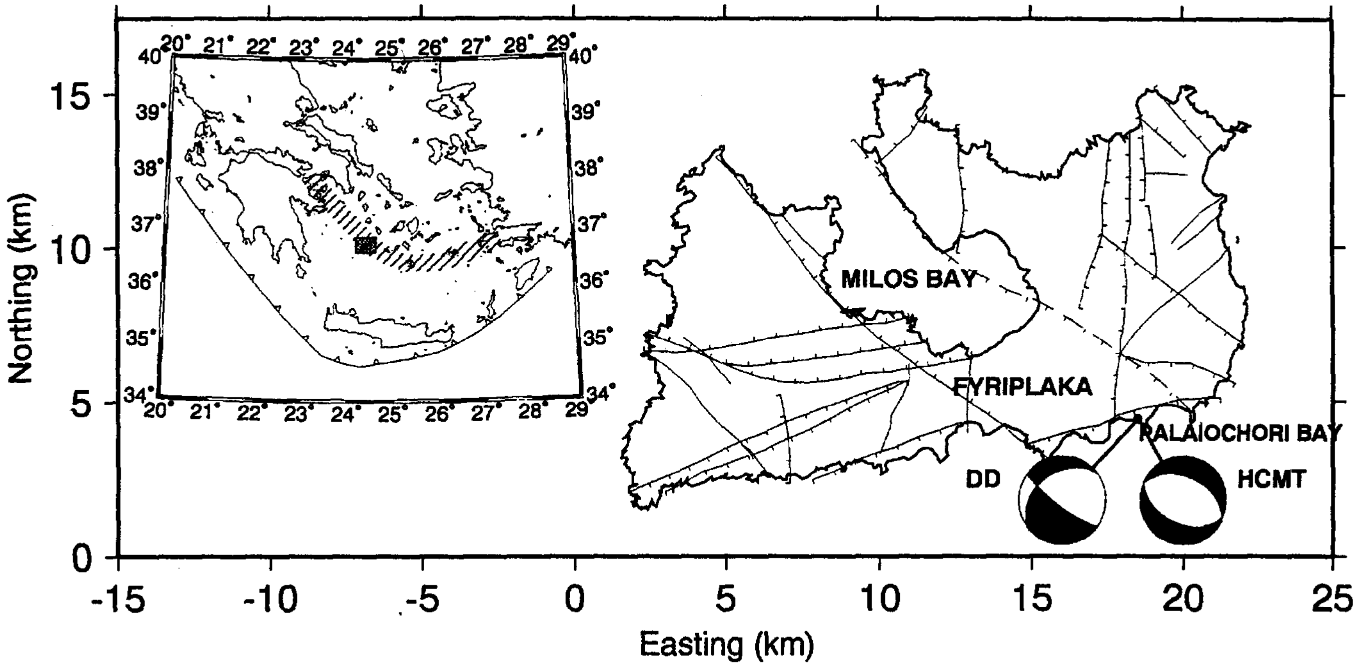

Fig. 1. The island of Milos and its most significant faulting structures according to Papanikolaou et al., (1993). Superimposed are the fault plane solutions by Harvard (HCMT) and Delibasis & Drakopoulos, 1993, (DD). The inset map shows the position of Milos (grey rectangle) in the Hellenic Volcanic Arc (hatched area). The toothed line indicates the front of the Aegean subduction system (Hellenic Trench).

The recorded microseismicity was low in both cases. The networks also recorded signals showing that the tectonic activity, which takes place in this area, is highly associated to the volcanic activity of the island.

2 Data and analysis

During a period of two months in the summer of 1996, the five digital seismic stations operating on triggering mode recorded a considerable number of microearthquakes. A total of 21 events were recorded by more than three stations, thus providing accurate epicentral locations (fig. 3), using the 2D velocity model for Milos (Sachpazi and Hirn; 1991).

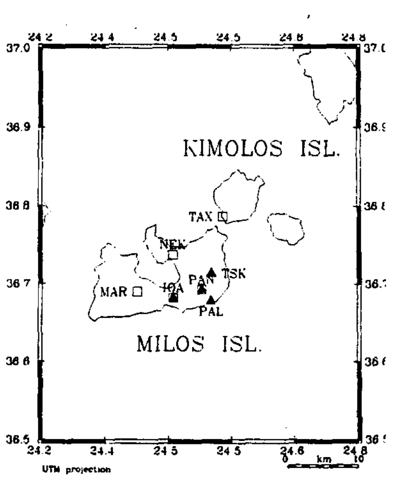

Fig. 2. The seismic stations installed during the first phase of the project (1996) are marked as open squares. Filled triangles represent the seismic stations installed during the first year of the project (1997).

The analysis of the 1996 data set revealed low seismicity with relatively low magnitudes, as well as spectrally peaked signals, often associated with the circulation of fluids. The local earthquakes recorded were shallow events (1-5 km depth) of small magnitude (all less than 1.5 of the Richter scale). The low seismicity imposed limitations in establishing the time dependence of venting processes and earthquakes. During the data analysis, the signals possibly related to the hydrothermal processes were isolated, in order to identify whether they are related to seismic events and correlated to the temporal variation of temperature and water pressure.

More specifically, station PAN, situated near Palaeochori Bay, recorded a total number of 80 microearthquakes, some of which appeared in groups of a few hours duration, each comprising of 5-8 events.

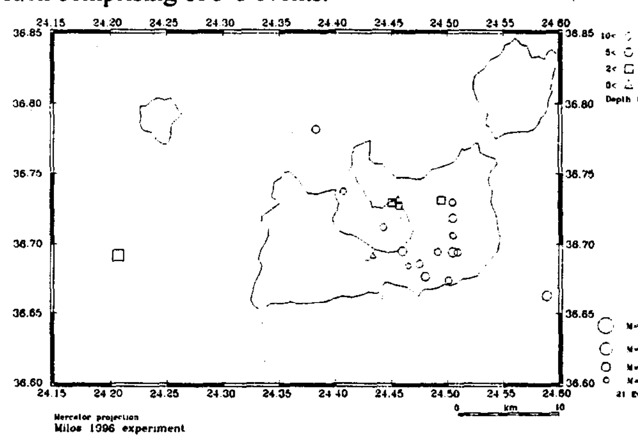

Fig. 3. Epicentral distribution of the best located micro-earthquakes of Milos during the 1996 experiment

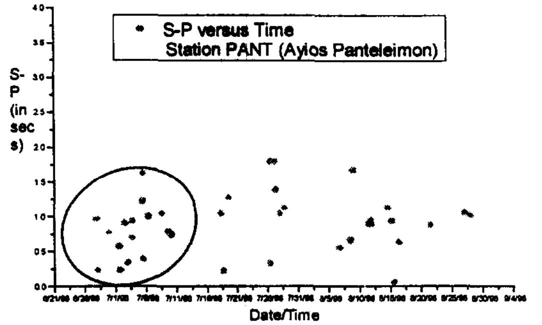

Fig. 4. The S-P arrival times of local earthquakes recorded at station PANT versus time, showing possible cluster patterns

These microearthquakes originated from sources near the station, most probably from the north. Their average S-P values, showing their distance from the hypocentre, were around the values 0.2 and 1.5 sec, implying that the sources were within radii of 1-2 and 5-8 km from the station respectively (fig. 4).

Along with the above mentioned microearthquake activity, two more types of signals were recorded by the network, especially at stations PAN, IOA and NEK. We focused on stations PAN and IOA, which are the closest ones to the area of interest.

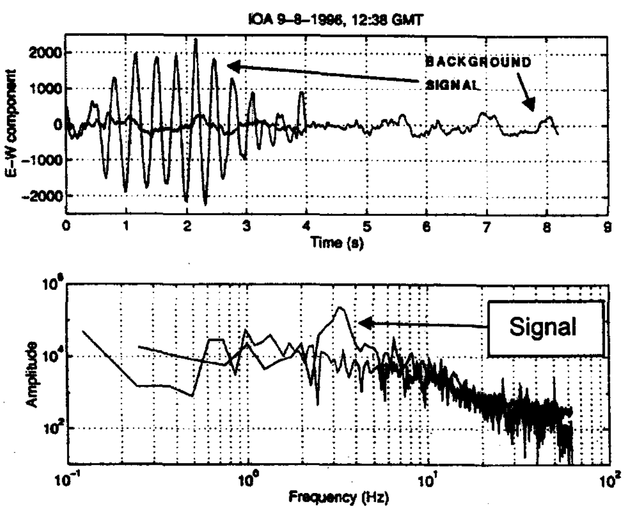

Fig. 5. a) A typical long period wave train recorded at IOA station and its background noise. b) The spectrum of such signals is peaked around 2-3 Hz. The spectrum of the noise does not show any peak.

The first type (fig. 5a,b) were long period wave trains, which were in fact spectrally peaked signals at 2-3 Hz. These signals appeared in groups of 3-10 events within a time span of 20-40 hours. Such characteristic signals have also been identified in this area by Hirn (1987) at a single station in the vicinity of Adamas town, a site near NEK seismic station. Moreover, during a first attempt to map and interpret the geothermal noise by Clacy (1968) in New Zealand, such signals of 2 Hz frequency have been detected and correlated to the circulation of fluids.

The second type of signals consisted of microearthquake trains of 5-8 events, hardly distinguished from the background noise, of very short duration (fig. 6), showing spectral peaks around 20-30 Hz in all components, i.e. ten times the frequency of the previously mentioned signals.

The same type of signals were recorded by the 1997 digital seismic network, which was concentrated near Palaeochori Bay, which operated on continuous mode, thus providing a more complete picture of the hydrothermal activity taking place in the area. In this sense we were able to obtain complete records of microearthquakes, hydrothermal signals and the background noise, which are currently being processed.

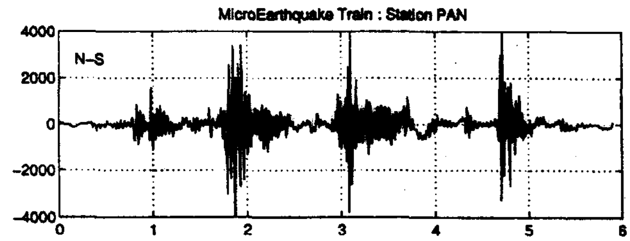

Fig. 6. A typical microearthquake train recorded at station PAN.

Variability in the composition of certain elements (such as particulates Mn and Fe) from water sampling, taken from specific vents at the same area (fig. 7), were correlated to clusters of microearthquakes and hydrothermal signals, recorded by the seismic stations.

3 Discussion and conclusions

The microearthquakes located during the 1996 experiment (fig. 4) are mostly concentrated in the central and eastern part of the island. Some of them originate from the tectonic graben of the Fyriplaka Bay volcano unit.

From the distribution of the best located microearthquakes (fig. 4), it is clear that most of them lie along the major tectonic contemporary active faulting on the island (Papanikolaou et. al.; 1993). More specifically, one group of epicentres lie in the NW-SE direction in the central part of Milos, which is characterised by normal faulting and a phase of extension during the Quaternary (fig. 1). A second group of epicentres lie along the N-S direction in the eastern part of the island, which also expresses continuous seismic activity in the present day. Moreover, the joint interpretation of Magnetotelluric and Geomagnetic Deep Sounding data indicated a significant lateral resistivity interface of NW-SE orientation (Tzanis and Makropoulos, 1999). The location of this interface appears to coincide with the western boundary fault of the Milos Bay - Fyriplaka graben.

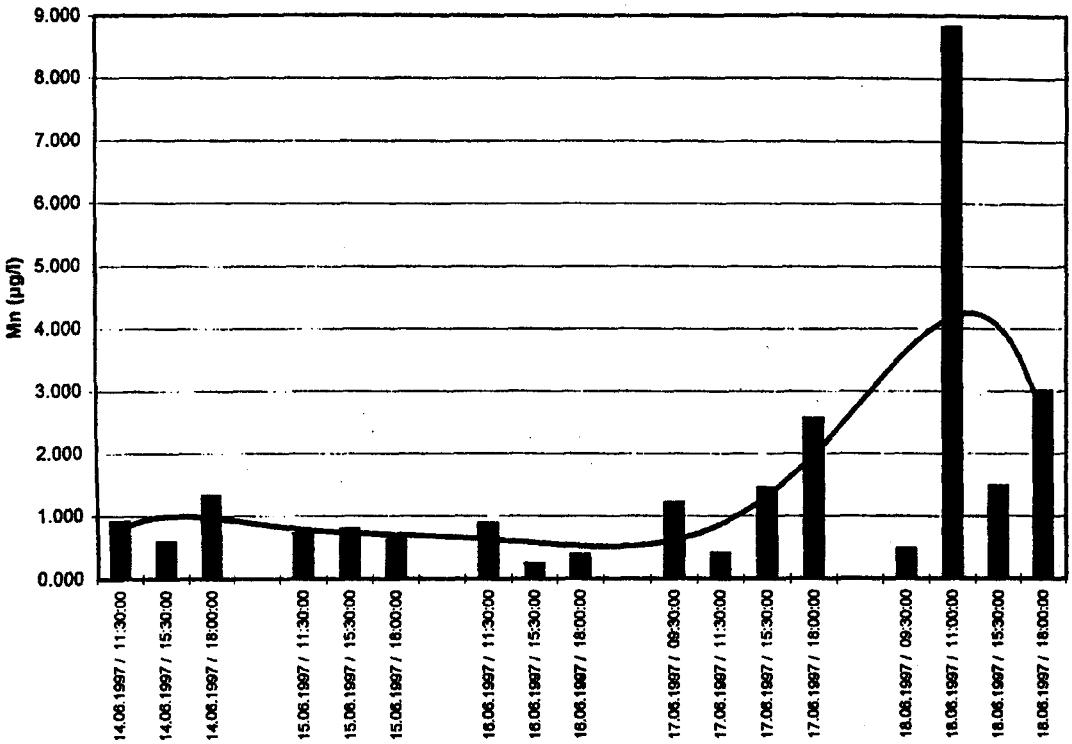

Fig. 7. Time variability of particulates Mn at Palaeochori hydrothermal waters

The sources producing these microearthquakes are typical sources of volcanic activity, most probably related to the existing volcanoes of Fyriplaka (near PAN and IOA stations) and Trachilas (near NEK station).

The longer period signals (fig. 5a,b) may be related to venting procedures, whilst the microearthquake trains (fig. 6) may originate from very small sources of 20-30 m radii, acting as microfractures in a self-organized critical system, interacting within distances comparable to the radii of their mutual instabilities. This process possibly appears in response to changes in pore pressure. The activity recorded by PAN and IOA stations (fig. 3 & 4) may be related to the nearby Fyriplaka volcano (fig. 1).

The above may be confirmed through detailed tomographic inversion techniques (provided that a complete earthquake data set is available) and geophysical prospecting methods which will model the shallow structure beneath the hydrothermal field of the area, similar to the study of the nearby Kimolos island (Louis, 1997).

As far as the records from the 1997 experiment are concerned, the significant deviation from the mean value in the average concentration of the characteristic hydrothermal elements Mn and Fe usually preceded groups of local microearthquakes and microearthquake trains.

An example of such a high concentration of seawater in Mn in 18/6/1997 is given in fig. 7, which was followed by a group of microearthquakes 6-8 hours later.

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References

Clacy, G.R.T., 1968. Geothermal ground noise amplitude and frequency spectra in the New Zealand volcanic region, *J. Geophys. Res.*, **73**, 5377-5383.

Cronan, D.S., Varnavas, S.P., 1993. Submarine fumarolic and hydrothermal activity off Milos, Hellenic Volcanic Arc, *Terra Abstracts*, **5**, 569.

Dando, P.R., Hughes, J.A., Leahy, Y., Niven, S.J., Taylor, L.J. and Smith, C., 1995a. Gas venting rates from submarine hydrothermal areas around the island of Milos, Hellenic Volcanic Arc, *Cont. Shelf Res.*, **15**. 8: 913-929.

Dando, P.R., Hughes, J.A., Leahy, Y., Taylor, L.J. and Zivanovic, S., 1995b. Earthquakes increase hydrothermal venting and nutrient inputs into the Aegean, *Cont. Shelf Res.*, **15**, 6: 655-662.

Delibasis, N.D. and Darkopoulos, J.C., 1993. The Milos island earthquake of March 20, 1992 and its tectonic significance, *PAGEOPH*, **141**, 1, 43-58.

Hirn, A., 1987. Seismology on Milos island (Greece), EN3G:A2:141:F, Second Semestrial Report, 1987, EU project.

Louis, I.F., 1997. Prospecting for geothermal energy resources by seismic modelling and resistivity inversion techniques. The case of Milos archipelago geothermal field (Aegean Sea, Greece), Proc. Society of Exploration Geophysicists, International Exposition and 67th Annual Meeting, Dallas, Texas, 2-7 Nov., **I**, 619-622.

Papanikolaou, D., 1988. Structural analysis of the Milos Geothermal field, Final synoptic report submitted to P.P.C. Geothermal division, 114p.

Papanikolaou, D., Lekkas, E., Syskakis, D. and Adamopoulou, E., 1993. Correlation on neotectonic structures with the geodynamic activity in Milos during the earthquakes of March 1992, *Bull. Geol. Soc. Greece*, **XXVIII/3**, 413-428.

Sachpazi, M. and Hirn, A., 1991. Shear-wave anisotropy across the geothermal field of Milos, Aegean volcanic arc, *Geophys. J. Int.* **107**, 763-685.

Tzanis, A. and Makropoulos, K., 1999. Magnetotellurics and seismotectonics in the analysis of active domains: an essential combination?, *Phys. Chem. Earth*, (in press).

Varnavas, S.P. and Cronan, D.S., 1991. Hydrothermal metallogenic processes off the islands of Nisyros and Kos in the Hellenic Volcanic Arc, *Marine Geology*, **67**, 295-305.