NATURAL DEGASSING OF CARBON DIOXIDE AND HYDROGEN SULPHIDE AND ITS ENVIRONMENTAL IMPACT AT MILOS ISLAND, GREECE

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https://doi.org/10.12681/bgsg.11636

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To cite this article:
Kyriakopoulos, G. (2010). NATURAL DEGASSING OF CARBON DIOXIDE AND HYDROGEN SULPHIDE AND ITS ENVIRONMENTAL IMPACT AT MILOS ISLAND, GREECE. Bulletin of the Geological Society of Greece, 43(5), 2361-2372. doi:https://doi.org/10.12681/bgsg.11636
Abstract

The Aegean region represents an active convergent zone, where continental micro-plates exhibit a complex interaction between the African and the Eurasian plates. The calc-alkaline volcanic activity of the Southern Aegean region developed in various volcanic centers from Soussaki to Nisyros through Methana-Poros, Milos and Santorini. Milos Island has been an active volcano till the middle of Quaternary and is at present characterized by a high enthalpy geothermal system. The volcanism started 3.5 Ma ago and still continues up today in the form of post-volcanic manifestations.

Most quiescent volcanoes released large amounts of CO$_2$ and H$_2$S through fumarolic activity and soil diffuse degassing. Numerous small fumaroles occur in various places, mainly at Kalamos and Adamas volcanic areas. Also along the southern coast of the island there are volcanic gas manifestations in the sea. Gases were sampled from fumaroles at Kalamos area as well as from north east part of Adamas village. Furthermore many soil gases were sampled at 50 cm depth and analyzed for their chemical composition. Apart from atmospheric gases (N$_2$ and O$_2$), which sometimes contaminate the samples, the main gas phase is CO$_2$. Sometimes also H$_2$S, CH$_4$ and H$_2$ are present in high amounts while CO and He are always present in trace amounts. The He isotopic composition highlights a significant mantle component.

CO$_2$ and H$_2$S concentrations higher than in the normal atmosphere can be stimulating for plant growth until certain levels and detrimental above them. As for many active geothermal areas of the world also H$_2$S and CO$_2$ concentrations measured in the area of Milos could be of concern for human health.

Key words: Volcanic gases, Health hazard, Environmental impact, South Aegean Volcanic Arc, Milos Island.
of the mid-ocean ridge flux of 2.1 x 10^{10} moles of carbon (Marty and Jambon, 1987).

Mörner and Etiopie (2002) have recently evidenced that the contribution of geothermal systems to lithospheric carbon degassing, although at present poorly constrained, is probably higher than volcanic degassing. An accurate quantification of CO_{2} and CH_{4} fluxes from low-enthalpy geothermal systems would therefore add important data for the accurate quantification of their contribution to the earth’s carbon budget and to the global climate change. Both gas species have in fact important greenhouse effects and prediction of future climate scenarios rely heavily on a better quantification of their fluxes between all geochemical spheres.

H_{2}S is a toxic gas producing multiple effects. It is colourless gas with unpleasant odour of bad eggs. In nature large amounts are produced during processes of biological decomposition. A major part of the atmospheric hydrogen sulphide is of natural geothermal origin. Air pollution is of anthropogenic type as well. Industry is the main source - coke ovens, cellulose production, artificial fibbers, natural gas and oil-product refining.

Contact of man with this gas is affected through the respiratory system. Scanty information exists on possible penetration through the digestive tract. The gas is absorbed by the organism through the lungs. In the liver and kidneys it is transformed into tiosulphates and sulphates. It is eliminated through the lungs, urine and fecal matter. Health effects are as follows - low concentrations may irritate the mucous tissues and cause conjunctivitis, and high concentrations may cause serious damages of the respiratory organs.

The aim of this paper is present the geochemical characterization of the main fumarole degassing and the soil gases of Milos Island geothermal field. Possible impact on the surrounding environment and on human health is also discussed.

2. Geological setting

The Aegean region represents an active convergent zone, where continental micro-plates exhibit a complex interaction under the influence of the overall N-S convergence between the African and the Eurasian plates. Apart from the compressional trench zone, the rest of the Aegean region is dominated by an extensional regime as evidenced by predominantly extensional fault plane and the presence of numerous normal faults (Mckenzie, 1972; Angelier et al., 1977; Dewey and Sengor, 1979). The volcanic arc lays ca. 150 km above the subduction zone, which forms an amphitheatre-like conical plane, with a maximum depth of 190 km at the central part of the South Aegean Volcanic Arc. (Spakman et al., 1988; Truffert et al., 1992; Papadopoulos et al., 1986; Papazachos, 1990), (Fig. 1).

The stratigraphy of Milos Island is composed, from the bottom to the top, by altered crystalline metamorphic basement, Neogene sediments, old volcanic tuffaceous formations, ignimbrites, old rhyolitic rocks, old dacitic and andesitic members, pyroclastic rocks, younger tuffs, lahar in different places, younger volcanics of acid composition and quaternary formations. Regarding its geological characteristics, the intensively eroded crystalline metamorphic basement appears in a very limited area (SE coastline). A not continuous series of Mio–Pliocene marine sediments is lying above the crystalline basement; it begins with reddish conglomerates and ends up with well-bedded limestones, which at places turn to sandstones (Fytikas, 1977).

From Upper Pliocene Milos was affected by an extensive volcanism, which lasted until late Quaternary (Fytikas et al., 1986). The composition of Milos volcanic rocks shows a calcalkaline character ranging from andesites to rhyolites. The youngest Upper Pleistocene volcanic activity is concentrated in corre-
Fig. 1: Map of Greece showing Milos Island and the South Aegean Volcanic Arc.

Fig. 2: Main geological units of Milos volcanic island (From Fytikas, 1976 modified). 1=Metamorphic basement; 2= Neogene sediments; 3= Basal pyroclastic series (Middle-Upper Pliocene); 4= complexes of domes and lava flows (Upper Pliocene); 5= Upper Pleistocene volcanics: pyroclastic series (5a), lava domes (5b) and Halepa and Plaka domes (5c); 6= Fyriplaka and Trachilas Rhyolitic complexes of Upper Pleistocene; 7= Freatic activity products; 8= Quaternary sediments; 9= Radiometric ages from Angelier et al. (1977), Bigazzi and Radi (1981), Fytikas et al. (1976).
spondence of the volcanic centres of Fyriplaka in the South and Trachilas in the North. In Trachilas the explosive activity began with the formation of a tuff ring mainly composed by pyroclastic surges; the surge deposits gradually pass to block and lapilli and finally to lava flows (Fytikas et al., 1986; Mitropoulos et al., 1987; Kelepertzis and Kyriakopoulos, 1991; Kyriakopoulos, 1998).

In the Fyriplaka area at least two tuff rings can be identified: a larger one (about 1500 m in internal diameter) and an inner and smaller one. The explosive activity leading to the formation of these tuff rings alternated with effusive episodes producing lava flows which ran to the NW and reached the sea inside the Gulf of Milos (Fytikas et al., 1986), Fig. 2.

A decrease in the water content interacting with the magma is generally observed in the evolution of the eruptions: they usually start as phreatic and successively evolve into phreatomagmatic and magmatic activity; lava flows close the eruptive cycles (Fytikas et al., 1986).

### 3. Sampling and analytical methods

A total of 26 samples were collected from Kalamos and Adamas areas were intense gas emanation is occurring. The localities sites of the volcanic areas Kalamos and Fyriplaka in the south part and Adamas at the central part of the island are reported in Figure 3. Free gas samples were taken from natural gas manifestations like fumarolic discharges, soil gases, and mofettes and were collected at

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**Fig. 3:** a,b) Fumaroles at Kalamos degassing area, c) Crater of Fyriplaka volcano, d) Surface secondary minerals due to alteration phenomena of H$_2$S emanation, north of Adamas geothermal field. The locations of these photographs are noted on the map of Fig. 2.
a depth of 50 cm through steel or nylon tubes connected to a syringe while bubbling gases were collected through inverted funnels. Samples were then stored into glass flasks equipped with vacuum stopcocks. Furthermore, 78 samples of soil gases were analysed in the field for CO₂ concentration with a portable IR spectrometer.

Gas concentrations were measured at INGV in Palermo using the GC Perkin Elmer Clarus 500 equipped with Carboxen 1000 columns, HWD and FID detectors with methanizer. The gas samples were injected through an automated injection valve with a 1000 μL loop. Calibration was made with certified gas mixtures. Analytical precision (1σ) was always better than ±5%. The detection limits were about 1 ppm vol. for CO and CH₄, 2 ppm vol. for H₂, 6 ppm vol. for He, 20 ppm vol. for CO₂, 200 ppm vol. for O₂, and 500 ppm vol. for N₂. Analyses of carbon isotopes of CO₂ were carried out by using a Finnigan Delta plus mass spectrometer. Values are expressed in δ‰ vs. V-PDB, accuracy ±0.1 δ‰.

4. Health hazard from volcanic gases

Regarding health hazard related to volcanic gases at least 455 million people worldwide live within potential exposure range of a volcano that has been active in recent times. The effects of SO₂ on people and the environment vary widely depending on (1) the amount of gas a volcano emits into the atmosphere; (2) whether the gas is injected into the troposphere or stratosphere; and (3) the regional or global wind and weather pattern that disperses the gas.

The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are sulfur dioxide, carbon dioxide, and hydrogen fluoride. Locally, sulfur dioxide gas can lead to acid rain and air pollution downwind from a volcano.

Because carbon dioxide gas is heavier than air, the gas may flow into low-lying areas and collect in the soil. The concentration of carbon dioxide gas in these areas can be lethal to people, animals and vegetation, Table 1.

Table 1. Physiologic effects of human exposure to H₂S (Beauchamp et al. 1984; WHO 2003).

| Exposure ppm | Effect/observation |
|--------------|--------------------|
| 0.01–0.13    | Odor threshold     |
| 0.3          | Distinct odor      |
| 2            | Bronchial constriction in asthmatic individuals |
| 3.5          | Increased eye complaints |
| 5–10         | Increased blood lactate concentration, decreased skeletal muscle citrate synthase activity, decreased oxygen uptake |
| 3.5–20       | Eye irritation     |
| 20           | Fatigue, loss of appetite, headache, irritability, poor memory |
| 50           | Marked irritant action on conjunctiva and respiratory tract |
| 100–200      | Olfactory paralysis |
| 250          | Prolonged exposure causes pulmonary edema |
| 500–1,000    | Immediate death    |

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4.1 Hydrogen sulfide (H$_2$S)

Hydrogen sulfide (H$_2$S) is a colorless, flammable gas with a strong offensive odor. It is sometimes referred to as sewer gas. At low concentrations it can irritate the eyes and acts as a depressant; at high concentrations it can cause irritation of the upper respiratory tract and, during long exposure, pulmonary edema. A 30-minute exposure to 50 ppm results in headache, dizziness, excitement, staggering gait, and diarrhea, followed sometimes by bronchitis or bronchopneumonia, while concentrations above 500 ppm can be lethal within short time (Table 1). Continuous exposure to high concentration should be avoided. Moreover various studies (Loppi, 1996; Tretiach and Ganis, 1999) highlighted the adverse effects of volcanic/geothermal H$_2$S on nearby growing vegetation.

4.2 Carbon dioxide (CO$_2$)

Volcanoes release more than 130 million tonnes of CO$_2$ into the atmosphere every year. This colorless, odorless gas usually does not pose a direct hazard to life because it typically becomes diluted to low concentrations very quickly whether it is released continuously from the ground or during episodic eruptions. But in certain circumstances, CO$_2$ may become concentrated at levels lethal to people and animals. Carbon dioxide gas is heavier than air and the gas can flow into low-lying areas; breathing air with more than 30% CO$_2$ can quickly induce unconsciousness and cause death.

5. Results and discussion

5.1 Geochemistry of the gases

Although Milos Island is not currently volcanically active, it is the site of intense old and recent hydrothermal processes. At the present time a high geothermal gradient (> 2.5 H.F.U.) occur. The high heat flow caused intense hydrothermal activity, which is responsible for many phreatic explosions. In some places the hydrothermal activity is expressed by the occurrence of many hot springs (30-85°C), fumaroles (98-102°C), hot grounds (100°C at a depth of 30-40cm) and submarine gas emissions, widespread on and around the island. Fyriplaka volcano is the expression of the most recent volcanic activity on the island and includes fumaroles, solfataras and hot grounds (Fytikas et al., 1986).

A preliminary survey of volcanic gas analyses shows that, with very few exceptions, the predominating constituents making up more than 95 % of the volcanic gas discharge are water vapor and
### Table 2. Chemical composition of gas samples of Milos Island.

| sample          | type   | date       | He   | H₂    | O₂    | N₂    | CO    | CH₄   | CO₂   | H₂S   | δ¹³C  | R/Ra | He/Ne |
|-----------------|--------|------------|------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|
| Milos C1        | FG     | 1-06-2007  | 5    | < 2   | 194900| 789400| 3.7   | 3.6   | 1200  | 100   | n.d.  | n.d. | n.d.  |
| Milos C2        | FG     | 1-06-2007  | 8    | 492   | 168500| 725600| 6.3   | 171   | 97200 | 200   | n.d.  | n.d. | n.d.  |
| Milos C3        | FG     | 1-06-2007  | 8    | 1873  | 145500| 581400| 11    | 471   | 263600| 2000  | -1.5  | n.d. | n.d.  |
| Milos C4        | FG     | 1-06-2007  | 8    | 91    | 187500| 771100| 3.4   | 20    | 10600 | 100   | n.d.  | n.d. | n.d.  |
| Milos C5        | FG     | 1-06-2007  | 5    | 29    | 182000| 760900| 4     | 46    | 40600 | 200   | n.d.  | n.d. | n.d.  |
| Milos Fyriplaka | FG     | 20-06-2007 | 6    | 5     | 193800| 777800| 1     | 3.2   | 1500  | n.d.  | -0.1  | n.d. | n.d.  |
| Milos Adamas    | SG     | 20-06-2007 | 12   | 596   | 101600| 416000| 3.9   | 986   | 482800| n.d.  | 0.3   | n.d. | n.d.  |
| Milos Paleocho 1| BG     | 21-06-2007 | 45   | 8     | 33300 | 119400| 17    | 7533  | 838100| n.d.  | n.d.  | n.d. | n.d.  |
| Milos Paleocho 2| BG     | 21-06-2007 | 69   | < 2   | 19000 | 85700 | 14    | 10100 | 874400| n.d.  | -0.3  | 2.57 | 12.51 |
| Milos Paleocho 3| BG     | 21-06-2007 | 49   | < 2   | 12000 | 62900 | 10    | 7929  | 901000| n.d.  | n.d.  | 2.52 | 20.23 |
| Milos Paleocho 4| BG     | 21-06-2007 | 37   | < 2   | 13800 | 52700 | 8     | 6615  | 905300| n.d.  | n.d.  | n.d. | n.d.  |
| Milos Fyriplaka | FG     | 12-10-2007 | 8    | 432   | 142600| 627400| 6     | 334   | 226000| n.d.  | n.d.  | n.d. | n.d.  |
| Milos Mad 1     | BG     | 12-10-2007 | 69   | < 2   | 2800  | 73000 | 1     | 4877  | 896200| n.d.  | -0.9  | 3.37 | 37.76 |
| Milos Mad 2     | SG     | 13-10-2007 | 7    | 237   | 166400| 668500| 5     | 109   | 160000| n.d.  | 1.6   | n.d. | n.d.  |
| Milos Paleocho 5| SG     | 22-10-2007 | 15   | 284   | 32800 | 315300| 4     | 1593  | 650600| n.d.  | -0.2  | n.d. | n.d.  |
| Milos M1        | SG     | 21-03-2008 | < 5  | 1304  | 170000| 680100| 1.6   | 206   | 129600| n.d.  | n.d.  | n.d. | n.d.  |
| Milos M2        | SG     | 21-03-2008 | 10   | 486   | 152600| 635600| 1.8   | 313   | 201500| n.d.  | 1.7   | n.d. | n.d.  |
| Milos M3        | SG     | 21-03-2008 | < 5  | 664   | 167300| 672000| 1     | 99    | 153300| n.d.  | n.d.  | n.d. | n.d.  |
| Milos 1 Sinopi  | BS     | 5-09-2008  | 50   | < 2   | 9200  | 39100 | 1.5   | 2636 | 944100| n.d.  | 2.97  | 12.64|
| Milos 2 Adamas  | DEH    | 12-08-2008 | 15   | 13    | 425   | 20700 | 1.5   | 1405 | 966100| n.d.  | -1.3  | 3.04 | 6.14  |
| Milos 3 Paleochi| BS     | 12-08-2008 | 14   | 29    | 3800  | 12500 | 3.2   | 7448 | 957000| n.d.  | -0.4  | n.d. | n.d.  |
| Milos 4 Adamas  | SG     | 5-09-2008  | 12   | 1418  | 50300 | 199300| 3     | 1717 | 750600| n.d.  | -0.7  | n.d. | n.d.  |
| Milos 5 Paleochi| BS     | 4-09-2008  | 26   | 6660  | 91600 | 348900| 14    | 5167 | 511800| n.d.  | n.d.  | n.d. | n.d.  |
| Milos 6 Paleochi| BS     | 5-09-2008  | 80   | 14910 | 52100 | 143800| 13    | 11000| 657400| n.d.  | n.d.  | n.d. | n.d.  |
| Milos DEH       | BG     | 10-06-2009 | 28   | < 2   | 4700  | 33400 | 1.6   | 2625 | 951200| n.d.  | -0.4  | n.d. | n.d.  |

Type: FG = fumarolic gas; SG = soil gas; BG = bubbling gas; BS = gas bubbling in sea.water – n.d. = not determined. (*) data from Minissale et al. (1997)
species containing carbon and sulfur in their various oxidation states such as CO₂, CO, SO₂, S₈ and H₂S together with H₂. In the case of Milos gases, water vapour is an important component only of the fumarolic gases. In the present study only the dry gas composition (i.e. excluding water vapour) has been determined and the analytical results are shown in table 2. Apart from atmospheric gases (O₂ and N₂) deriving from air contamination, the main gas is CO₂. The O₂, N₂ and CO₂ contents evidence a clear mixing trend between two end-member represented by the atmospheric air and a CO₂-dominated geothermal gas. Isotopic composition of the CO₂-carbon, displaying values close to 0‰ (range from −1.5 to 1.6 ‰), indicates that the main CO₂ source may be the reaction between the acidic hydrothermal solutions with underlying Neogene limestone deposits (Fytikas, 1989) as well as from thermal decomposition of subducted marine sediments. But a contribution from mantle CO₂ cannot be excluded. Such contribution is strongly suggested by the isotopic composition of the helium whose values (R/R₀ ranging between 2.5 and 3.4) highlights a mantle component of at least 50% for this gas.

The He-N₂-CO₂ triangular plot (Fig. 4a) shows two alignments. The first belongs to the mixing trend between atmospheric air and the geothermal gas. The second pointing towards the He vertex is probably due to processes responsible of CO₂ loss like carbonate precipitation or CO₂ dissolution in water. The last process is mostly evident in those gases which where collected from manifestations bubbling in sea-water.

The gas composition of one exploratory well (Table 2) evidences the enrichment in H₂S of the geothermal fluids at Milos. But this gas is partially lost in the shallow environment due to dissolution in condensing water vapour and oxidation processes. Such processes producing H₂SO₄-rich condensates are responsible of the low pH values (2.9) measured in the fumarolic condensate at Aghia Kyriaki, on the south coast of Milos (Dominico and Papastamataki, 1975). The CH₄-N₂-CO₂ triangular plot (Fig. 4b) further evidences the processes that bring to CO₂ loss and the mixing processes between geothermal and atmospheric gases.

Carbon dioxide in the soils of Milos shows a wide range of concentrations from 0.01 to 99.8 % (table 3). Concentrations sustained by biologic activity within the soils are generally less than a few %, while higher concentrations are clearly due to uprising geothermal fluids. Notably the highest concentrations were found at Adamas and Kalamos areas close to the sites of the most recent volcanic activity (Fig. 5).

5.2 Gas hazard and environmental impact

Volcanic/geothermal areas release huge amounts of gases, which apart from having important influences on the global climate could have a strong impact both on the local environment and on human health. Gases have both acute and chronic effects. Carbon Dioxide and Sulphur gases are the main gases responsible for acute mortality due to their asphyxiating and/or toxic properties. The problem has long been neglected until the “Lake Nyos” catastrophe in 1986, in which about 1700 people were killed by a volcanic CO₂ emission, attracted the worldwide attention of the mass media.

Gas hazard is largely underestimated because it acts also during quiescent periods and also in areas were volcanic activity is nowadays extinct. Furthermore, although the frequency of occurrence is relatively high, the number of victims of each lethal accident is generally low and often the real cause of death is not properly recognized. As a consequence, the recently published database of volcanic disasters and incidents of the 20th century (Witham, 2005), which attributed the death of 2000 persons and the injury of nearly 3000 to volcanic gases, is probably largely incomplete. The most dangerous gas species is CO₂, responsible of more than 90% of the victims and of the worst episodes
Table 3. Soil CO₂ concentrations at -50 cm depth (in vol %) of Milos geothermal field.

| ID | LAT  | LONG  | ALTITUDE | CO₂ | ID | LAT  | LONG  | ALTITUDE | CO₂ |
|----|------|-------|----------|-----|----|------|-------|----------|-----|
| 1  | 36.668 | 24.493 | 146 | 7.93 | 41 | 36.677 | 24.485 | 68 | 0.50 |
| 2  | 36.669 | 24.493 | 146 | 6.99 | 42 | 36.695 | 24.545 | 55 | 0.05 |
| 3  | 36.668 | 24.493 | 133 | 2.30 | 43 | 36.695 | 24.544 | 17 | 0.05 |
| 4  | 36.668 | 24.493 | 145 | 3.77 | 45 | 36.694 | 24.544 | 17 | 0.21 |
| 5  | 36.668 | 24.493 | 146 | 12.80 | 46 | 36.694 | 24.538 | 95 | 0.22 |
| 6  | 36.667 | 24.493 | 138 | 11.17 | 47 | 36.675 | 24.513 | 27 | 7.58 |
| 7  | 36.667 | 24.492 | 145 | 4.90 | 48 | 36.675 | 24.515 | 30 | 0.22 |
| 8  | 36.667 | 24.492 | 140 | 7.90 | 49 | 36.675 | 24.513 | 27 | 1.30 |
| 9  | 36.667 | 24.492 | 140 | 6.90 | 50 | 36.675 | 24.513 | 27 | 20.20 |
| 10 | 36.666 | 24.492 | 140 | 0.09 | 51 | 36.731 | 24.448 | 10 | 22.07 |
| 11 | 36.666 | 24.493 | 140 | 6.42 | 64 | 36.731 | 24.448 | 10 | 54.60 |
| 12 | 36.666 | 24.493 | 148 | 0.18 | 65 | 36.731 | 24.448 | 10 | 77.08 |
| 13 | 36.665 | 24.493 | 144 | 0.09 | 66 | 36.731 | 24.448 | 10 | 95.70 |
| 14 | 36.665 | 24.493 | 144 | 0.78 | 67 | 36.731 | 24.448 | 10 | 48.70 |
| 15 | 36.665 | 24.493 | 144 | 0.14 | 68 | 36.731 | 24.448 | 10 | 99.80 |
| 16 | 36.666 | 24.494 | 144 | 0.22 | 69 | 36.731 | 24.449 | 10 | 79.80 |
| 17 | 36.666 | 24.494 | 106 | 0.14 | 70 | 36.731 | 24.449 | 10 | 55.70 |
| 18 | 36.667 | 24.494 | 106 | 0.19 | 71 | 36.731 | 24.449 | 15 | 2.20 |
| 19 | 36.667 | 24.494 | 106 | 0.54 | 72 | 36.731 | 24.449 | 8  | 1.30 |
| 20 | 36.667 | 24.493 | 138 | 1.29 | 73 | 36.731 | 24.450 | 8  | 0.99 |
| 21 | 36.667 | 24.493 | 138 | 1.78 | 74 | 36.731 | 24.450 | 11 | 0.90 |
| 22 | 36.667 | 24.493 | 138 | 2.70 | 75 | 36.731 | 24.448 | 6  | 18.00 |
| 23 | 36.667 | 24.493 | 136 | 0.46 | 76 | 36.731 | 24.448 | 6  | 18.00 |
| 24 | 36.666 | 24.493 | 144 | 0.27 | 77 | 36.731 | 24.449 | 6  | 2.80 |
| 25 | 36.666 | 24.492 | 131 | 0.06 | 78 | 36.730 | 24.449 | 5  | 1.15 |
| 26 | 36.666 | 24.491 | 114 | 7.71 | 79 | 36.731 | 24.448 | 6  | 60.00 |
| 27 | 36.665 | 24.491 | 133 | 18.20 | 80 | 36.731 | 24.448 | 9  | 20.00 |
| 28 | 36.665 | 24.491 | 110 | 2.10 | 81 | 36.732 | 24.448 | 9  | 5.10 |
| 29 | 36.665 | 24.491 | 110 | 1.70 | 82 | 36.732 | 24.447 | 11 | 3.00 |
| 30 | 36.666 | 24.491 | 114 | 0.70 | 83 | 36.732 | 24.446 | 13 | 0.25 |
| 31 | 36.666 | 24.491 | 114 | 1.22 | 84 | 36.732 | 24.445 | 30 | 0.20 |
| 32 | 36.667 | 24.491 | 124 | 1.14 | 85 | 36.732 | 24.448 | 21 | 0.10 |
| 33 | 36.669 | 24.492 | 128 | 1.30 | 86 | 36.733 | 24.448 | 32 | 0.10 |
| 34 | 36.670 | 24.492 | 91 | 5.07 | 87 | 36.734 | 24.448 | 44 | 0.10 |
| 35 | 36.670 | 24.492 | 109 | 2.62 | 8 | 36.735 | 24.447 | 51 | 0.10 |
| 36 | 36.670 | 24.491 | 109 | 1.42 | 89 | 36.736 | 24.446 | 58 | 0.10 |
| 37 | 36.668 | 24.491 | 130 | 0.50 | 90 | 36.737 | 24.445 | 69 | 0.15 |
| 38 | 36.671 | 24.490 | 112 | 0.22 | 91 | 36.731 | 24.450 | 11 | 0.10 |
| 39 | 36.674 | 24.487 | 77 | 0.01 | 92 | 36.731 | 24.451 | 25 | 0.10 |

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Being heavier than air, CO₂ and H₂S can accumulate in topographic depressions and enclosures, and in areas with high fluxes their concentrations can exceed 10% and 100 ppm, respectively, which can be lethal to both animals and humans. At Milos Island hazardous concentrations of CO₂ (more than 90%) and H₂S (up to 2000 ppm) are measured near the main emanation Kalamos and Fyriplaka areas. People living in anomalous degassing areas are generally aware of the danger posed by gas accumulation, but nevertheless volcanic gases cause many fatalities each year worldwide (Witham, 2005). Even though the gas hazard at Milos appears restricted to limited areas, it should not be neglected, especially its effects on the most exposed people: children, workers involved in excavation activities and tourists who use public baths.

The H₂S dispersing in the surrounding atmosphere displays concentrations of some ppm that produces surely annoying smell and represents also a potential chronic health impact for the nearby living persons. Furthermore oxidizing reactions in the atmosphere transforms H₂S in SO₂, locally increasing the acid burden through wet and dry deposition. Such processes are more intense during the summer season when high temperature and strong incoming solar radiation increases the formation of strong oxidant species like OH and O₃.

Furthermore, where gas emanations are very high, the soils are altered and covered with thin layers of secondary minerals as alunite, magnesite and sulphur. In these areas, the extreme acidity of the fumarolic condensates, which is responsible of the high mobility of harmful elements during alteration processes, could negatively impact biota of the surrounding terrestrial and marine environ-

**Fig. 5:** Distribution of the soil gas sampling points of the four sampling areas on a shaded relief map.
ments. Although such impact at Milos has not been studied yet, it is worth noting that vegetation around the hydrothermal manifestations is very stunted probably due to the bioaccumulation of the mobilized toxic elements.

6. Conclusions

The main gas manifestations at Milos show a typical hydrothermal composition. Excluding water vapour, the main gas species is represented by carbon dioxide. Its carbon isotopic composition points to a main origin from carbonate rocks although a significant mantle contribution cannot be ruled out. Other typical hydrothermal gases like hydrogen, methane and hydrogen sulphide display sometimes concentrations up to a few percent.

Soil gases show characteristic mixing trend between atmospheric air and deep geothermal gases. The latter implies their highest contents close to the fumarolic areas of Adamas and Kalamos. These areas show very high risk of gas hazard, and gas emissions could have a strong impact on the local environment.

7. Acknowledgements

The author would like to thank W. D’Alessandro for his helpful remarks and constructive guidance, Dr. E. Vassilakis for his assistance in elaborating GPS data and Dr. A. Marsellos for his fruitfully discussions and suggestions.

8. References

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