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8. Mantle-derived noble gases in the South Aegean volcanic arc: Indicators for incipient magmatic activity and deep crustal movements

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The Active South Aegean Volcanic Island Arc

The islands of Nisyros, Yali, Kos, Santorini, Milos, Poros, Methana and Aegina constitute the South Aegean volcanic island arc, which is a result of northward-directed subduction of the African plate beneath the Aegean microplate (Fig. 8.1).

The islands of Nisyros, Santorini, Milos and Methana are considered today the most active areas in terms of a potential volcanic reactivation. Therefore, these islands were chosen for a detailed noble gas investigation.

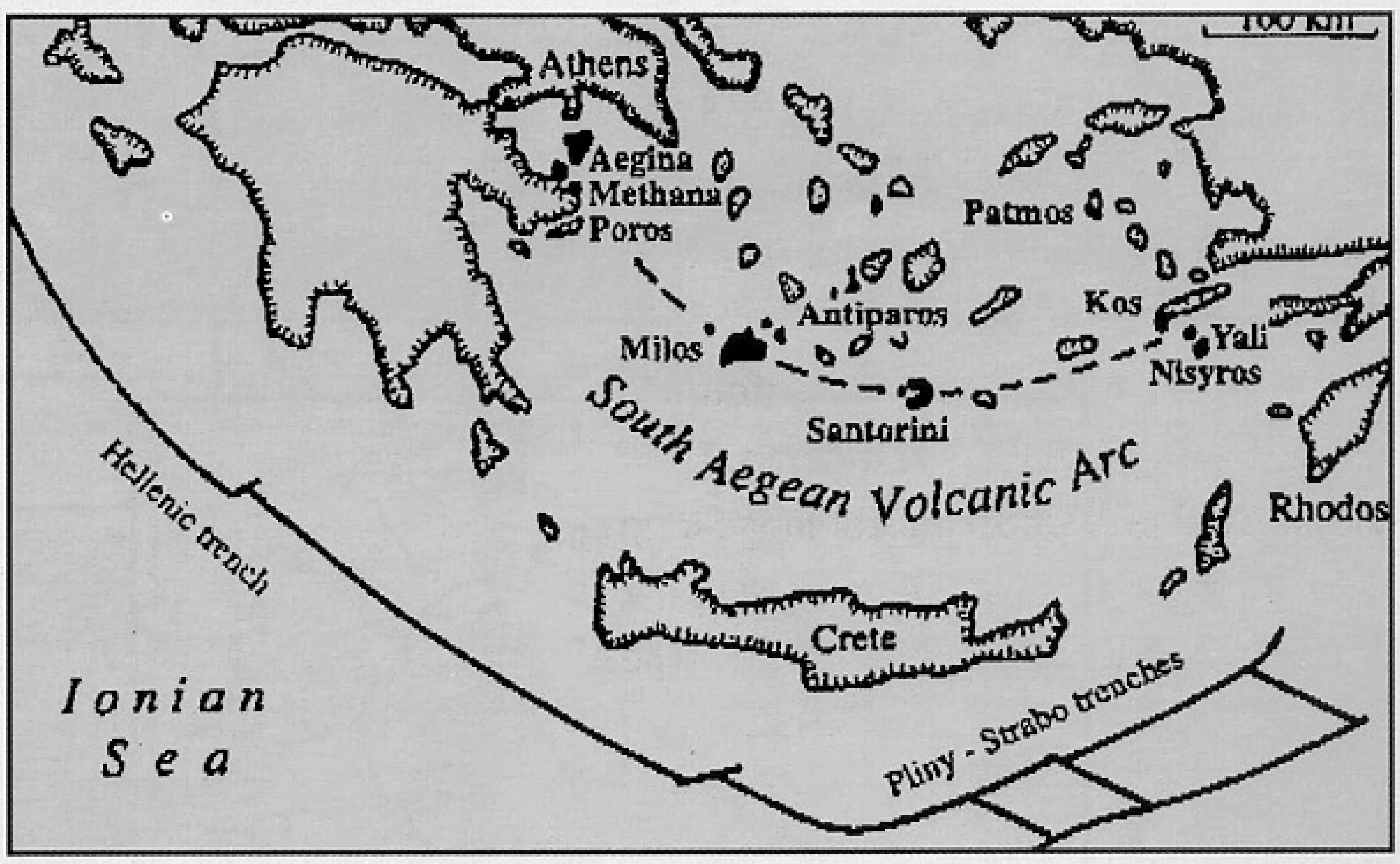

Fig. 8.1: The south Aegean volcanic island arc with the volcanic islands of Aegina, Methana, Milos, Santorini, Kos, Nisyros, and Yali.

The Volcanic Island of Nisyros

Although the last volcanic activity on Nisyros dates back at least 25000 years, the geodynamic activity, expressed by high seismic unrest, fumarolic activity and hydrothermal explosions is continuously present.

A schematic model is used to show the crustal and lithospheric structure of Nisyros volcanic island (Fig. 8.2). The upper crustal structure is based on geological and volcanological investigations of Di Paola (1974), Papanikolaou et al. (1991) and Vougioukalakis (1993) as well as on two geothermal wells (Geotermica Italiana, 1983 and 1984).

The existence of a large hydrothermal system with brine temperatures above 300°C at 1400 m depth is documented by the formation of five hydrothermal craters within the central Caldera. The most recent hydroclastic eruptions in 1873 and 1888 were accompanied by violent earthquakes, gas detonations and fire. The latter effects are due to high gas emanations of H_2S, CO_2, H_2 and CH_4 from fracture zones which cut the caldera and extend towards north north-west through the vicinity of the village of Mandraki into the island of Yali and even towards Kos. This feature indicates the existence of deep reaching zones of crustal weakness destined for magma and gas input from the upper mantle and lower crust.

Two distinct hydrothermal aquifers may be present underneath the Nisyros caldera (Fig. 8.2), according to the temperature distribution, the fluid geochemistry, the physical-chemical characteristics of the fumarolic gases and the thermal waters at the surface as well as the waters in the deep geothermal drillholes (Geotermica Italiana, 1983 and 1984; Marini et al., 1993; Chiodinit et al., 1993).

The deep hydrothermal aquifer is characterised by high temperatures above 300°C and fluids of high salinity, whereas the shallow hydrothermal aquifer shows temperatures around 100°C, high concentrations of CH_4, CO_2, H_2, H_2S and boiling phenomena.

From June to September 1997 high-seismic activity (magnitudes of earthquakes up to 5.5 on the Richter scale) occurred on Nisyros and were accompanied by increased tectonic and fumarolic activity along the western edge of the hydrothermal crater field (Polyboted, Phlegethon).

In this respect, the scheme of events as comparable with the violent activity in 1873 and 1888 requires serious scientific examination, the establishment of geophysical and geochemical monitoring systems as well as a long term hazard, risk and preparedness assessment. Besides the permanent residents of the island of Nisyros, several hundred fo tourists enter the hydrothermal field of the Nisyros caldera daily without awareness of the entire risk situation.

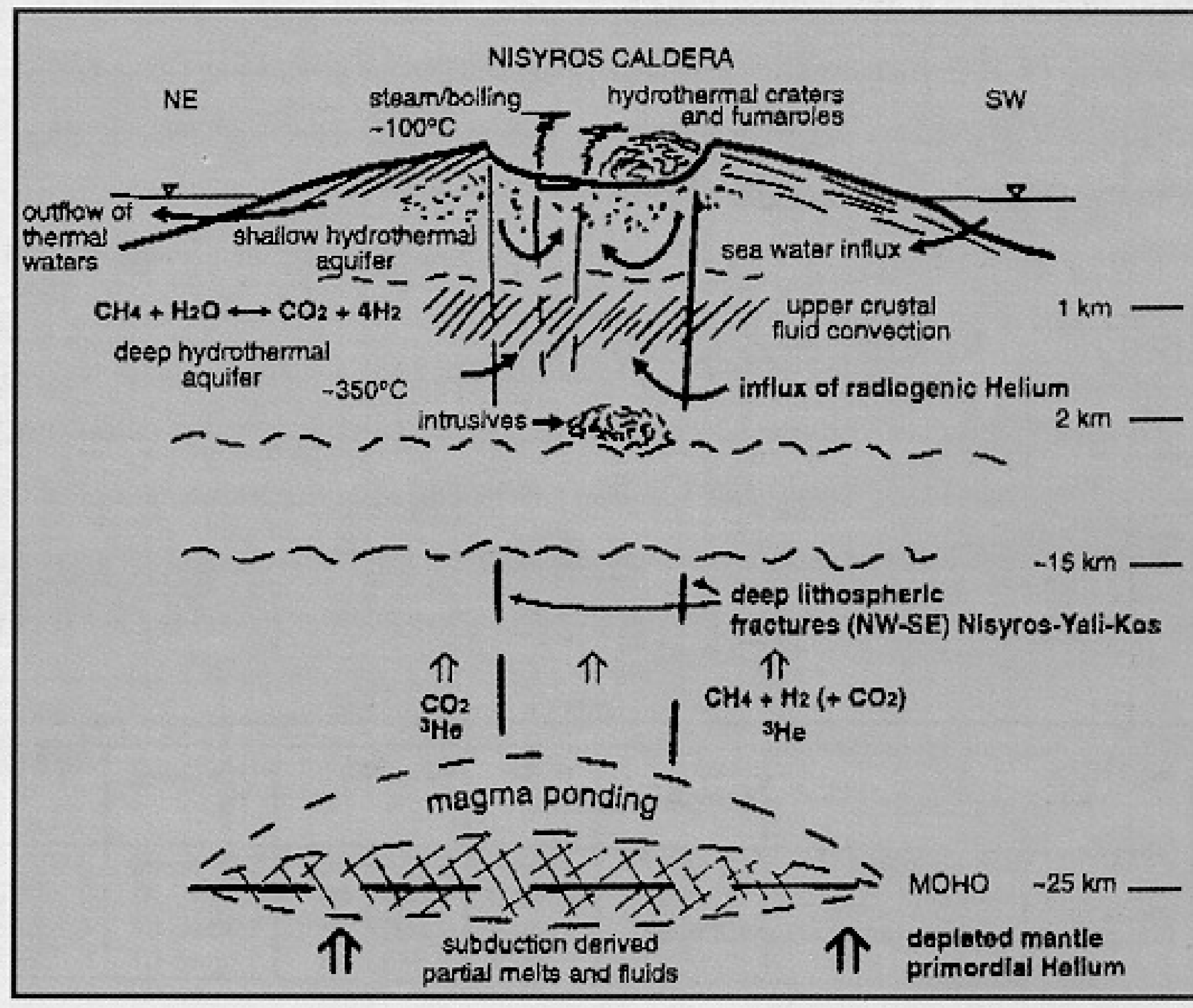

Fig. 8.2: Schematic model of Nisyros volcanic island. Possible paths of noble gases (i.e. helium) associated with the C-H-O fluids.

Noble gas characteristics

Helium, as well as the other noble gases are dissolved mainly in CO_2-rich waters and CO_2 gases (Griesshaber et al., 1992) and are accompanied by CH_4 and H_2 emanations. One of the major gas reactions occurring in the crust is: $CH_4 + 2\,H_2O = CO_2 + 4\,H_2$.

Helium shows distinct isotopic signatures in the main global reservoirs; the atmorphere ($^3He/^4He \approx 1.4 \times 10^{-6}$), the Earth's crust ($^3He/^4He \approx 10^{-7}$ - 10^{-8}) and the Earth's mantle ($^3He/^4He \approx (1\text{-}4) \times 10^{-5}$). Because of these differences, the analysis of helium isotopes in fluids can help to identify the origin of gas fluxes from the interior of the Earth. Thus, changes of the 3He/4He ratios during periodical measurements may indicate changes of gas fluxes due to major deep crustal tectonic, magmatic or mantle processes. The input of helium, derived from the mantle or other deep crustal sources in many volcanic areas located in convergent plate margins (e.g. Japanese Island arc) has also been found to be indicative of renewed or incipient magmatism (Sano & Wakita, 1985; Igarashi et al., 1992).

The other gases of non-atmospheric origin such as ^{20}Ne and ^{26}Ar can also be used to trace mantle or magma degassing. Often these primordial mantle components are masked by atmospheric components, and therefore, difficult to detect. This is mainly the case in lakes, thermal springs and hydrothermal waters related to volcanic activity.

The combination of noble gas ratios $^3He/^4He$, $^{20}Ne/^{22}Ne$ and $^{40}Ar/^{36}Ar$ compared to stable isotope ratios of C and O will allow an appropriate discussion on the primary origin of the noble gases, the amount of atmospheric, meteoric and hydrothermal contamination, as well as the determination of equilibrium temperatures in the hydrothermal systems. It is expected, that the noble gases are more sensitive and precise as indicators of changes of the magmatic regime (e.g. replenishment of new melts into magma reservoirs or emplacement of magmas from deep crustal levels to the suface) or changes of major tectonic processes (e.g. rapid extensional movements or crustal displacements).

Analytical Results and Discussion

Thirteen selected water samples from Milos and Methana and fumarolic condensates from Nisyros (Table 1 and Fig. 8.3) have been analysed for their isotopic abundances and ratios of helium, neon, argon, krypton and xenon. The analyses were performed by R. Kipfer at the laboratory of Isotope Geology (Swiss Federal Institute of Technology, ETH Zürich) according to procedures described by Aeschbach-Hertig et al. (1996)

NISYROS	Date sampling	Temp. (°C)	$^3He/^4He$	^4He (cc/g)	Ne (cc/g)	$^4He/He$	Ar (cc/g)	Kr (cc/g)	Xe (cc/g)
Kaminakia, S-slope (cond.)	10/14/97	98.5	5.956E-06	8.249E-08	9.530E-08	0.866	1.498E-04	3.132E-08	3.937E-09
Kaminakia, N-slope (cond.)	10/14/97	97.0	7.461E-06	8.976E-08	2.122E-08	4.231	2.755E-05	5.325E-09	6.332E-10
Phlegethon, SE-fum. (cond.)	10/14/97	104.0	7.035E-06	1.384E-07	4.280E-08	3.234	5.320E-05	1.030E-08	1.186E-09
Stefanos, W-rim (cond.)	10/14/97	99.7	7.548E-06	1.604E-07	5.038E-08	3.184	6.815E-05	1.319E-08	1.519E-09

MILOS	Date sampling	Temp. (°C)	$^3He/^4He$	^4He (cc/g)	Ne (cc/g)	$^4He/He$	Ar (cc/g)	Kr (cc/g)	Xe (cc/g)
Adamas, publ. bath (water)	9/20/97	35.4	3.348E-06	1.008E-07	1.336E-07	0.755	1.960E-04	4.219E-08	5.448E-09
Haros, well (water)	2/20/97	40.3	1.492E-06	4.013E-08	1.398E-07	0.287	1.803E-04	3.565E-08	4.335E-09
Ag. Georgios, well (water)	9/20/97	44.0	3.362E-06	1.234E-07	1.551E-07	0.795	1.854E-04	3.608E-08	4.277E-09
Paleochori beach (steam)	9/20/97	103.0	1.467E-06	4.575E-08	1.624E-07	0.282	2.128E-04	4.282E-08	4.987E-09
Kanara, therma, spring (water)	9/20/97	44.5	4.393E-06	9.816E-07	7.769E-08	12.634	1.064E-04	2.243E-08	2.651E-09
Skinopi, spring (mix+seawater)	9/20/97	37.5	1.419E-06	3.347E-08	1.224E-07	0.274	1.855E-04	3.928E-08	5.020E-09

METHANA	Date sampling	Temp. (°C)	$^3He/^4He$	^4He (cc/g)	Ne (cc/g)	$^4He/He$	Ar (cc/g)	Kr (cc/g)	Xe (cc/g)
Ag. Nikolaos (mix + seawater)	4/1/97	28.0	1.646E-06	4.658E-08	1.565E-07	0.298	2.369E-06	5.091E-08	6.579E-09
Methana bath (water)	4/1/97	31.5	3.181E-06	2.162E-07	7.597E-08	2.840	1.451E-04	3.434E-08	4.768E-09
Methana Loutra (water)	4/1/97	30.0	3.170E-06	2.020E-07	8.626E-08	2.342	1.588E-04	3.709E-08	5.350E-09

Table 1 Noble gas data from the Aegean volcanic islands: Sampling sites, features, absolute abundances and ratios. Ne, Ar, Kr, and Xe = total concentrations; cc/g = cm^3 of gas at standard conditions (STP) per gram of water; sampling techniques and analytical procedures in Aeschbach-Hertig et al. (1996).

The observed $^3He/^4He$ and $^4He/Ne$ ratios range from 1.419×10^{-6} to 7.5×10^{-6} and from 0.274 to 12.634, respectively. The Nisyros condensates fit into the array of the Japanese island arc samples which mark a mixing line between atmospheric $^3He/^4He$ ratio of 1.4×10^{-6} and mantle derived helium with a maximum ratio of approx. 10×10^{-6}. This also applies for some waters from Milos and for the gas sample from Nea Kameni (Santorini), although, with much lower $^3He/^4He$ ratios. These latter ratios as well as those from the Methana thermal springs represent a mixing with radiogenic ^4He due to crustal contamination during ascent of primordial ^3He through the crust. The steam sample and the spring/sea water mixtures from Milos and Methana have almost the normal $^3He/^4He$ composition of air. The $^3He/^4He$ ratios reflect well the high amount of mantle derived primordial ^3He in the Nisyros condensates as well as in some geothermal waters from Milos. Also, in Methana, ^3He is detectable. These results suggest that for the island of Nisyros, mantle-derived helium may be related to degassing of magmas, probably located at great crustal depth close to the mantle/crust boundary (Fig. 8.3).

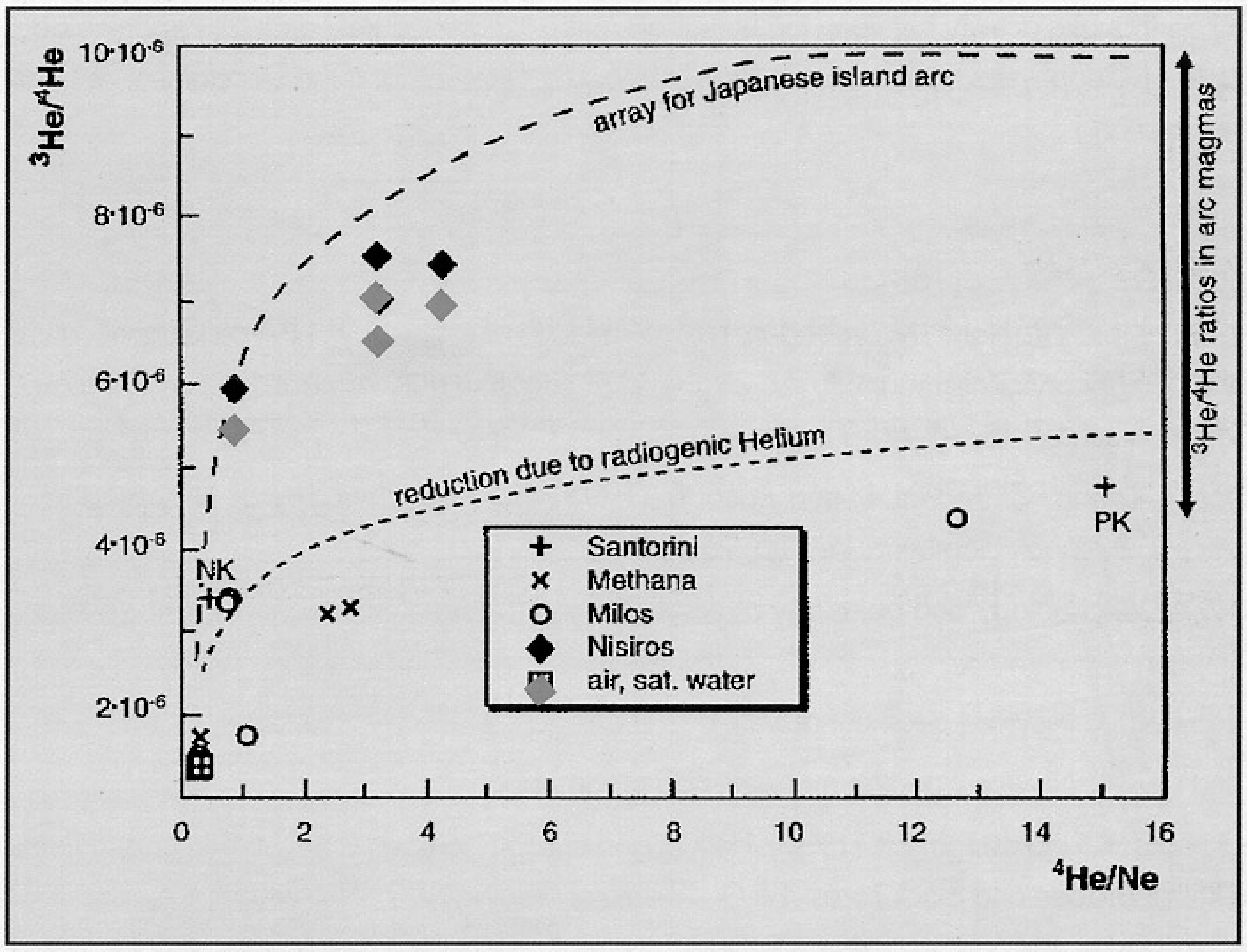

Fig. 8.3: Correlation between 3He/4He and 4He/Ne ratios in the volcanic islands of Nisyros, Santorini, Milos and Methana. Hatched and stippled lines are mixing lines between subduction-type He (Sano & Wakita, 1985) and atmospheric He and reduction due to radiogenic He. Ne = total neon concentration. 20Ne = 0.905 x Ne. Analytical errors smaller than symbol size. Data from Santorini (Nagao et al., 1991). NK = Nea Kameni, PK = Palaia Kameni.

The Ne and Ar isotopic ratios are close to the atmospheric values, indicating very small addition of primordial gases other that ^3He. Kr and Xe are entirely of atmospheric origin and may be used to infer the temperature at the last equilibrium with air, for the reason that the solubility of the heavy noble gases in water strongly depends on the temperature. The Xe concentrations indicate equilibrium temperatures higher than 40°C. A detailed analysis of the noble gas abundances is in preparation.

Conclusions and Recommendations

The high $^3He/^4He$ ratios of the Nisyros gases, sampled in October 1997 after the long period of strong earthquake activity, overlap entirely with the helium isotopic ratios measured in the high temperature fumaroles at Vulcano island (Aoelian island arc) during the magmatic/volcanic crisis in 1988 and 1989 (Tedesco et al., 1995). During this period, the temporal variations of the $^3He/^4He$ ratios, the total contents of He, CO_2 and SO_2 showed the same general trend, indicating an influx of the gases from a replenished magma reservoir at shallow depth.

For this reason, the gas emanations within the Nisyros caldera, in particular the concentrations of CO_2, SO_2, CH_4, H_2, and H_2S as well as the $^3He/^4He$ ratios should be measured periodically, at least every three months. In case of reocurrance of strong earthquake activity, the fumaroles and thermal waters of Nisyros island should be monitored. The Caldera has to be closed for public, if the gas concentrations increase and isotopic ratio changes are observed; even at invariable fumarolic temperatures. There will be a potential risk for gas and hydrothermal explosions all over the caldera area, similar to the explosive events in 1873.

Acknowledgments

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