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Natural tracers for identifying the origin of the thermal fluids emerging along the Aegean Volcanic arc (Greece): Evidence of Arc-Type Magmatic Water (ATMW) participation

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ABSTRACT

The Aegean volcanic arc is the result of a lithosphere subduction process during the Quaternary time. Starting from the Soussaki area, from west to east, the arc proceeds through the islands of Egina, Methana, Milos, Santorini, the Columbus Bank, Kos and Nisyros. Volcano-tectonic activities are still pronounced at Santorini and Nisyros in form of seismic activity, craters of hydrothermal explosions, hot fumaroles and thermal springs. A significant number of cold water springs emerge in the vicinity of hot waters on these islands.
Chemical and isotopic analyses were applied on water and fumaroles samples collected in different areas of the volcanic arc in order to attempt the assessment of these fluids. Stable isotopes of water and carbon have been used to evaluate the origin of cold and thermal water and CO_2.
Chemical solute concentrations and isotopic contents of waters show that the fluids emerging in Egina, Soussaki, Methana and Kos areas represent geothermal systems in their waning stage, while the fluids from Milos, Santorini and Nisyros proceed from active geothermal systems.
The δ^2H–$\delta^{18}O$–Cl^- relationships suggest that the parent hydrothermal liquids of Nisyros and Milos are produced through mixing of seawater and Arc-Type Magmatic Water (ATMW), with negligible to nil contribution of local ground waters and with very high participation of the magmatic component, which is close to 70% in both sites. A very high magmatic contribution to the deep geothermal system could occur at Santorini as well, perhaps with a percentage similar to Nisyros and Milos, but it cannot be calculated because of steam condensation heavily affecting the fumarolic fluids of Nea Kameni before the surface discharge.
The parent hydrothermal liquid at Methana originates through mixing of local groundwaters, seawater and ATMW, with a magmatic participation close to 19%. All in all, the contribution of ATMW is higher in the central–eastern part of the Aegean volcanic arc than in the western sector. This difference, which is spotted in the variable isotopic composition of the sampled fluids from west to east along the arc, is probably due to several causes, including the tectonic regime, the depth of the deep reservoir below sea level, the age of volcanic activity and in general the geomorphologic state of each island.

1. Introduction

The Aegean volcanic arc comprises, from west to east, the small volcanic centers of Egina, Soussaki and Methana, and the large accumulations of Milos, Santorini, Columbus Bank, Kos and Nisyros. In the Aegean Sea, this arc represents the youngest example of volcanism and the only one that can be related to the zone of subduction. Such a geodynamic setting is related to the collision between the African and the Eurasian plates, which occurs approximately 200 km to the south of the arc (McKenzie, 1970; Lort et al., 1974; Le Pichon and Angelier, 1979). This process takes place since the Pliocene and is responsible of volcanism and seismicity (Makris, 1978). All volcanic centers of the south Aegean islands are situated above the Benioff zone whose depth ranges from 100 to 160 km at Kos and Nisyros, in the eastern part, to 100 km at Soussaki, in the western sector, suggesting that subduction controls magma generation in the overlying mantle wedge (Papazachos et al., 1995). Several studies have shown that tectonic activity is very vigorous in the Aegean region and all these areas and islands were and are still affected by numerous tectonic events. Extensive surface hydrothermal and volcanic activity is present in the Soussaki, Kos, Santorini, Methana, Milos and Nisyros Island. The products of

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these volcanoes are late-Miocene to Quaternary in age (Matsuda et al., 1999).

A significant number of thermal water springs emerge in the areas and islands of the Aegean arc. The temperature of these water springs, which present high-salinity, ranges from 30° to 53 °C.

The mobile constituent chloride is one of the most important tools used in geochemical investigations. The high chloride concentrations, which are typically found in most deep aquifers, are generally attributed to direct seawater intrusion, particularly near the coastal zones, dissolution of evaporite rocks, boiling (vapour separation), absorption of magmatic gases in groundwater, modified seawater and geothermal water. Superficial evaporative concentration and human pollution may also increase the chloride content of waters.

Additionally, the correlations among $\delta^{18}O$, $\delta^{2}H$ and mobile specie are particularly useful both to detect processes of vapour separation and mixing and to provide information on water sources. In particular, the $\delta^{18}O$–$\delta^{2}H$ isotope composition of cold groundwaters is mainly affected by recharge altitude, water–rock interaction and mixing of different fluids. In deep thermal aquifers, $\delta^{18}O$ and $\delta^{2}H$ values are governed by the isotopic exchange with rock, which is generally important for oxygen and negligible for hydrogen, mixing and boiling (liquid–vapour separation). The $\delta^{13}C$ values of dissolved inorganic carbon in thermal and cold waters are used to identify the provenance of CO_2. The combined use of $\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C$ values with the chemical solutes of geothermometric–geobarometric relevance allows one to reconstruct the conceptual geochemical model of the investigated area, that is the Aegean Island Arc in the present case.

2. Sampling, analysis and field observations

Water samples of springs, boreholes and fumaroles were collected at Soussaki, Egina Island, Methana, Milos, Santorini, Kos and Nisyros (Fig. 1). Fifty-one samples were collected for chemical analyses and 68 samples were taken for the isotopic determination of $\delta^{2}H$ and $\delta^{18}O$

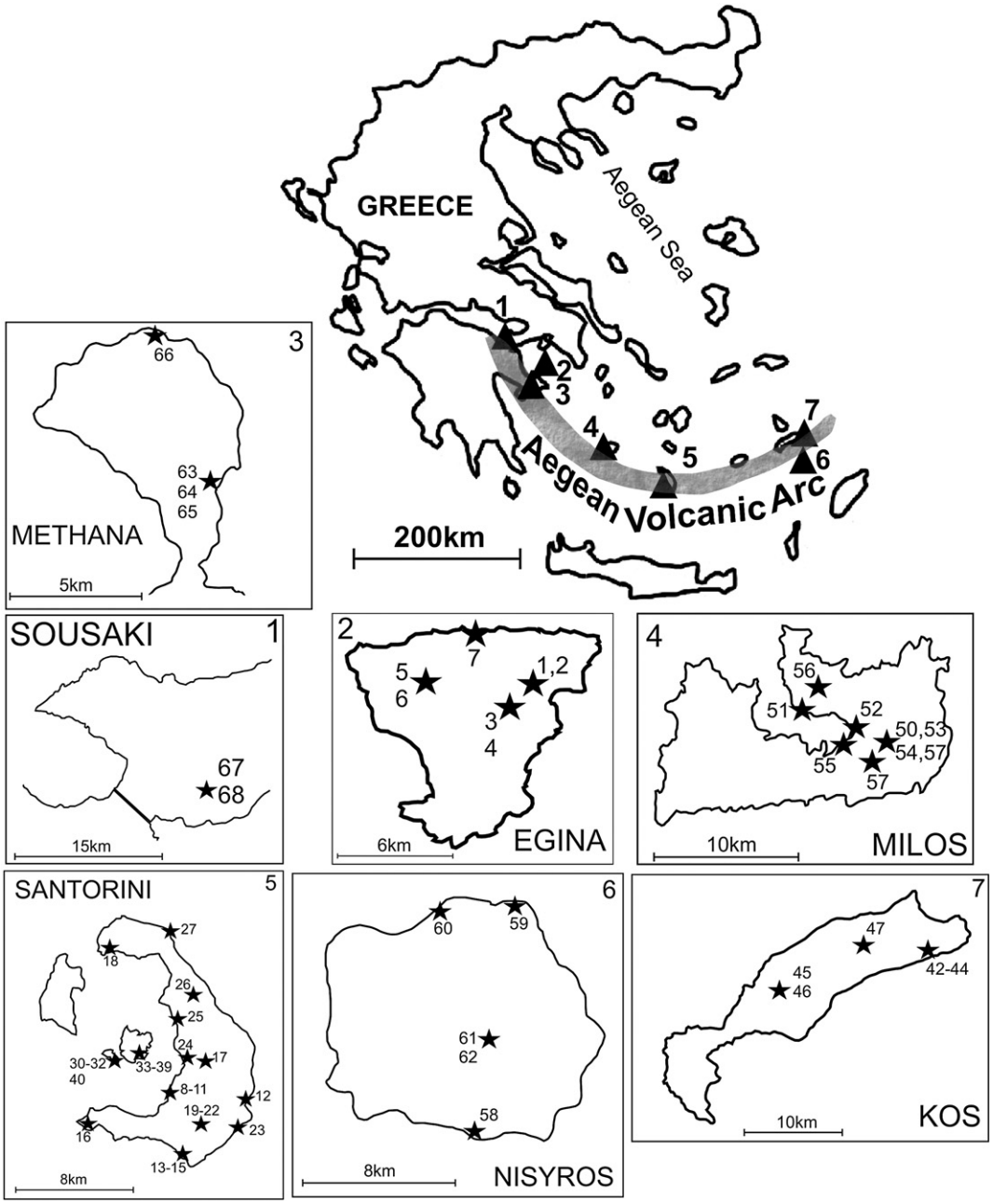

Fig. 1. Schematic map showing the location of sampling sites. Numbers are keyed to Table 2.