Active geothermal systems with entrained seawater as analogues for low-sulphidation epithermal mineralization

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Abstract (207 words)

The paradigm for low-sulphidation (LS) volcanic-arc associated mineralization is the active geothermal systems located along the Taupo Volcanic Zone (e.g. Broadlands). However, this analogue is inapt where fluid salinities are consistently in excess of 3.5 wt % NaCl.

LS mineralization on Milos (Aegean arc) records high paleofluid-salinities. The δD and $\delta^{18}O$ data do not exemplify ^{18}O-shifted meteoric waters—typical of terrestrial geothermal systems. Nor is a submarine origin indicated—stable isotope data show mixing between meteoric, seawater and volcanic-arc gases. Strontium isotope data are comparable to a nearby active seawater-entrained geothermal system. These are features seen in hydrothermal systems associated with emergent volcanoes.

For the Milos LS mineralization, high-salinity fluids show it cannot be explained by a Broadlands-type model. The absence of saliferous sequences and significant intrusive rocks preclude these as salinity sources. The similarities between paleo and active systems in terms of salinity, δD–$\delta^{18}O$ and strontium isotope systematics strongly suggest that seawater is the main source for Na and Cl. We suggest geothermal systems, containing seawater, associated with emergent volcanoes are an alternative analogue for LS epithermal mineralization. Furthermore, they bridge the gap between submarine, and large-scale terrestrial geothermal systems—the modern analogues for VHMS and epithermal mineralisation in the scheme of intrusion-centered hydrothermal mineralization.

Keywords

Epithermal processes, seawater, Milos, isotopes

Introduction

Geothermal systems in convergent plate margin settings are the active equivalents of high-level (2–3 km) intrusion-centred hydrothermal ore-deposits (e.g. Hedenquist and Lowenstern, 1994). Close to magmatic activity, volcanic emanations are the surface expressions of porphyry-Cu and high-sulphidation epithermal-Au mineralizing processes at depth (Hedenquist et al., 1993). Located farther from the magmatic source are low-sulphidation (LS) epithermal deposits, for which the Broadlands–Ohaaki geothermal system is the paradigm (e.g. Simmons and Browne, 2000). Generally, in LS mineralization, fluid inclusions document low-salinity fluids (< 1 wt % dissolved salts + CO_2) and these are equivalent to the low-chorinity (< 1000 ppm) fluids seen in Broadlands-type geothermal systems. However, they also identify saline fluids (up to 15 wt % salts) and, in this case, there are no documented active analogues (Hedenquist and Lowenstern, 1994). Conversely, deep water (> 1000 m) geothermal systems, such as TAG (e.g. You and Bickle, 1998) are exemplars for VHMS deposits. However, where boiling submarine geothermal fluids vent into shallow water (< 200 m) mineralization is epithermal in style (Stoffers et al., 1999), but there are no clearly defined ancient equivalents (Huston, 2000). Thus, in both the submarine and subaerial environments there is a missing link between active geothermal systems and their ancient counterparts.

Below, we provide new strontium isotope data and summarize features of epithermal systems on Milos island. By comparing these with well-characterised modern analogues we suggest that active geothermal systems with entrained seawater, such as those in the Aegean arc (Aegean arc-type), are an alternative to the Broadlands–Ohaaki LS paradigm in the scheme of intrusion-centred hydrothermal systems.

The Aegean arc

The Aegean arc is a zone of Pliocene to modern volcanism related to active back-arc extension caused by the subduction of the African plate beneath the Aegean micro-plate (e.g. Pe-Piper and Piper, 2002). It is built on continental crust, comprises seven major volcanic centres and is located 120–250 km north of the Hellenic trench (Fig. 1). The volcanic rocks are calc-alkaline with localised high-K variants and range from basalt to rhyolite in composition, with dominant andesites and dacites. Present day hydrothermal activity comprises both low-enthalpy (Aegina, Sousaki, Methana) and high-enthalpy systems (Milos, Nisyros).

Milos geology and LS epithermal Au-Ag mineralization

Upper Pliocene (2.66 ± 0.07 Ma; Stewart and McPhie, 2003) submarine and Late Pleistocene to present (1.9–0.1 Ma) subaerial volcanic rocks overlay Mesozoic metamorphic basement and Upper Miocene–Lower Pliocene marine sediments, and record a transition from a shallow submarine (< 200 m) to subaerial volcanic setting (Fytikas et al., 1986; Rinaldi and Venuti, 2003; Stewart and McPhie, 2003). Emergence probably occurred at 1.44 ± 0.08 Ma (Stewart and McPhie, 2003). Plutonic rocks are not known on Milos and have only been reported as ignimbrite-hosted granitic xenoliths from the nearby islet of Kimolos (Pe-Piper and Piper, 2002).

The oldest submarine volcanic rocks occur on western Milos and host LS Au–Ag mineralization (the Profitis Ilias [PI]–Chondro Vouno [CV] epithermal system), which extends over a 20 km^2 area (this study; Kilias et al., 2001). Fluid inclusion data show the hydrothermal fluids underwent extreme boiling and vaporisation. Importantly, final ice-melting (T_{mice}) data show that 70 % of the fluid inclusions have net salinities in excess of seawater (Tab. 1), showing that throughout its lifespan, fluids in the system were saline. The tops of the paleosystem (now ~600 masl) show crustiform/colloform quartz–barite±alunite veins and quartz-cemented breccias, with locally high gold (PI: 56 ppm; CV: 250 ppm) and silver (PI: 197 ppm; CV: 90 ppm). Deeper in the system (now ~300 masl), the mineralization is dominated by a base-metal-bearing stockwork. Elevated gold values at PI are concentrated above the base metal zone and are spatially related to boiling (Kilias et al., 2001).

Active geothermal system

In the active geothermal system (Liakopoulos, 1987; Pflumio et al., 1991), data indicate a two-component reservoir: (1) A high enthalpy system with deep seawater recharge located 1–2 km below sea-level. Reservoir temperatures range 250–350 ºC and salinities can be significantly higher than seawater (up to 9 wt % salts). This results from Rayleigh distillation as seawater percolates, through progressively hotter rocks, into the reservoir. Due to its high salinity, venting of the deep geothermal fluid is accompanied by boiling close to the top of the reservoir and in some cases the reservoir may be two-phase. (2) A shallow reservoir (100–175 ºC) overlies the high-enthalpy system. It is located close to sea-level, recharged by meteoric water and seawater intrusion, is commonly saline (up to 5 wt % salts) and heated by gas escapes from the underlying deep reservoir. Seawater, as a major component of both the deep

and shallow reservoirs, is documented on the basis of $^{87}Sr/^{86}Sr$ and $\delta D–\delta^{18}O–Cl$ systematics (Pflumio et al., 1991). In the shallow (<100 m) submarine environment, venting geothermal fluids contain suspended particulate matter strongly enriched in Fe, Mn, Si and Ba and locally deposit APS minerals, pyrite, marcasite, barite, gypsum, and calcite (Baltatzis et al., 2001; Varnavas et al., 2000). In addition, the deep reservoir is metalliferous (Pb: 180 ppb; Zn: 1458 ppb) (Christanis and Seymour, 1995) and has gold concentrations in the region of 0.3 ppb (Liakopoulos, 1987).

Strontium isotopes

Sr-isotope data show that the least altered igneous rocks have low $^{87}Sr/^{86}Sr$, whereas their hydrothermally altered counterparts are closer to a seawater signature (Fig. 2). The basement rocks have variable strontium ratios (0.7033–0.7136)) (Fig. 2). In the modern system, $^{87}Sr/^{86}Sr$ in the fluids vary from 0.7092–0.7102 (Pflumio et al., 1991). Barites from the Profitis Ilias mineralization display similar $^{87}Sr/^{86}Sr$ to the modern system (Fig. 2). All values for geothermal water and hydrothermal minerals are slightly more radiogenic than seawater but relatively constant.

Discussion

Seawater as a fluid component on Milos

T_{mice} in fluid inclusions provides information on salinity. However, above –1.5 ºC, it is unable to distinguish between dissolved salt (< 2.5 wt % NaCl eq.) and gas (< 4.4 wt % CO_2 eq.). This permits gas-charged low-chlorinity terrestrial geothermal systems to be the paradigm for LS epithermal mineralization, as excess chlorinity can be assigned to dissolved gas (Hedenquist and Henley, 1985). Moreover, in Broadlands–Ohaaki-type geothermal systems derivation of chlorinities in excess of 5000 ppm through fluid–rock interaction is extremely difficult and where high salinities are recorded they are attributed to boiling to dryness and have a localised effect (Simmons and Browne, 1997). Hence, when comparing ancient systems with Broadlands–Ohaaki-type equivalents, when the apparent salinity is up to 3–4 wt % NaCl eq there is an implicit requirement to assign freezing point depressions to dissolved gas rather than chlorinity. However, in our case > 70 % of the fluid inclusions have net salinities in excess of 3.5 wt % NaCl eq (Tab. 1). Thus, we cannot assign excess T_{mice} to dissolved gas. Nonetheless, our high salinities have to be explained. There are three main sodium and chlorine reservoirs available to large-scale geothermal systems: (1) evaporites and

evaporitic sediments (2) magmatic brines and (3) seawater. An evaporitic origin of salinity is considered highly improbable, as there is no record of saliferous rocks within the Milos sediments. Concerning a magmatic brine, it is estimated that during its lifetime a geothermal systems turns over between $10^{6\pm1}$ km^3 of water (Barnes and Seward, 1997). If it is assumed that andesitic magmas contain about 1000 ppm chlorine, then approximately $10^{7\pm1}$ km^3 of magma would be required maintain salinities in the geothermal system at 9 wt % NaCl. This is not impossible, but on Milos, geological and geophysical evidence is lacking (Pe-Piper and Piper 2002). Thus, a magmatic origin of salinity is also considered unlikely. This leaves a seawater origin for Na and Cl. We consider that the chemical similarities between the ancient and modern systems on Milos (see above) support a seawater origin for the PI–CV epithermal fluids.

Comparison of δD–$\delta^{18}O$ of inclusion fluids from the Profitis Ilias epithermal mineralization and several active geothermal systems associated with emergent volcanoes reveals remarkable similarities (Fig. 3). In the active systems, the geothermal fluids have a three component source (sea, meteoric and magmatic) and the waters fall in a zone projecting from the meteoric water line to values intermediate to seawater and volcanic-arc gases (Fig. 3). The fluid inclusion data for the Profitis Ilias LS mineralization show an analogous trend and lie in a similar zone; this is in sharp contrast to typical LS mineralization where stable isotope data show ^{18}O-shifted fluids at constant δD (see Broadlands field in Fig. 3).

In terms of strontium isotope data (Fig. 2, the basement metamorphic sequence has $^{87}Sr/^{86}Sr$ (0.7033–0.7137) encompassing the entire range, permitting a variety of fluid–rock interaction interpretations. However, we think the clustering of measured $^{87}Sr/^{86}Sr$ for the modern geothermal fluids (0.7092–0.7100) and mineralization (0.7096–0.7100 [epithermal Au–Ag]; 0.7092–0.7098 [Mn–Ba] close to the value for late-Pliocene seawater (0.7090–70906), also indicates of a seawater source. In addition, as $^{87}Sr/^{86}Sr$ for the modern and ancient systems are significantly different from most of the unaltered igneous rocks (0.7050–0.7080) mitigates further against a magmatic fluid source. Indeed, most of the $^{87}Sr/^{86}Sr$ (0.7082–0.7098) for hydrothermally altered igneous rocks cluster within or close to the range recorded by the modern geothermal fluids and seawater.

Taken together, the above lines of evidence show that in addition to being a fundamental component in the active system, seawater has played a key role in LS mineralization.

Hybrid epithermal systems and modern analogues

It is clear that Broadlands–Ohaaki-type meteoric geothermal systems are not a valid analogue for the Milos Au–Ag mineralization and for moderately saline (> 15 000 ppm NaCl eq.) LS epithermal mineralization in general. Furthermore, there is a missing link between saline epithermal LS systems and their modern counterparts. We suggest that the best candidates, which recognize the key parameters of consistently high fluid inclusion salinities, δD–$\delta^{18}O$ systematics indicating seawater and a seawater Sr isotope signature, are geothermal systems with entrained seawater. Typical examples are the active systems on Milos and Nisyros (Fig. 3). These analogues are hybrids, containing elements of both submarine and terrestrial geothermal systems. Indeed, the occurrence of fossil hybrid systems is predicted (Huston, 2000) though, to date, no ancient equivalents have been clearly identified. Here, in the emergent environment, circulating sea and meteoric water are the main fluid components. The fluids boil and result in auriferous quartz veins with epithermal textures and proximal quartz-adularia, intermediate quartz–sericite–pyrite and distal propylitic/quartz–albite alteration halos—features that are comparable to the Milos epithermal mineralization. Thus, we suggest that epithermal mineralization where the involvement of seawater can be clearly demonstrated (e.g. Milos) are good candidates for fossil hybrid epithermal systems, and active geothermal systems with entrained seawater such as the Aegean-arc type, are their modern analogues.

Features of hybrid epithermal systems can be reconstructed by putting geothermal systems associated with emergent volcanoes into a conceptual framework. Fig. 4 illustrates the model—gold-bearing epithermal veins are located between a shallow low-temperature (100–175 ºC) steam-heated zone recharged by meteoric water and seawater intrusion, and a deep, seawater recharged, higher-temperature (250–350 ºC) base-metal bearing reservoir.

Concluding remarks

Broadlands-type models are not appropriate for LS epithermal systems with elevated salinities that cannot be reasonably explained by dissolved gas or localised boiling to dryness. Moreover, where high salinities of this nature are encountered, an explanation for them must be sought. One possibility is a seawater origin for the hydrothermal fluids, though to use this explanation, other parameters have to be consistent. In the case of Milos, the epithermal mineralization can be explained by analogy to seawater-entrained geothermal systems associated with emergent volcanoes (e.g. Nisyros, Milos) and the mineralization data

(geologic, isotope and fluid inclusion) are in accord with this model. We suggest that our Aegean-arc model should be considered as an additional paradigm in the scheme of intrusion-centred metallogenesis. Moreover, it may provide a link between submarine and terrestrial mineralization processes. Appropriate indicators for its use are fluid inclusion data showing consistently elevated salinities (> 3.5 wt % NaCl eq.) and mineralization hosted in submarine or transitional to subaerial volcanic rocks in an island arc tectonic setting. However, it must be stressed that these are not definitive and other corroborating data must be sought, in our case, strontium isotope, δD and $\delta^{18}O$ analyses.

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Fig. 1. Maps showing **A**) the main geotectonic elements of the eastern Mediterranean along with volcanic centres and regions of geothermal activity; **B**) the main geological features of Milos island plus the location of LS epithermal mineralisation and the main surface manifestations of the geothermal system (Milos map adapted from Fytikas et al., 1986; LPl: Lower Pleistocene, LPo: Lower Pliocene; LMi: Lower Miocene, M: Mesozoic)

Fig. 2. 'S'-curve of measured strontium isotope data from mineralisation on Milos, showing $^{87}Sr/^{86}Sr$ for barite, fresh and altered igneous rocks, marine platform sediments basement rocks and geothermal waters (data: this study; Briqueu et al., 1986; Farrell et al., 1995; Hein et al., 2000; Pflumio et al., 1991)

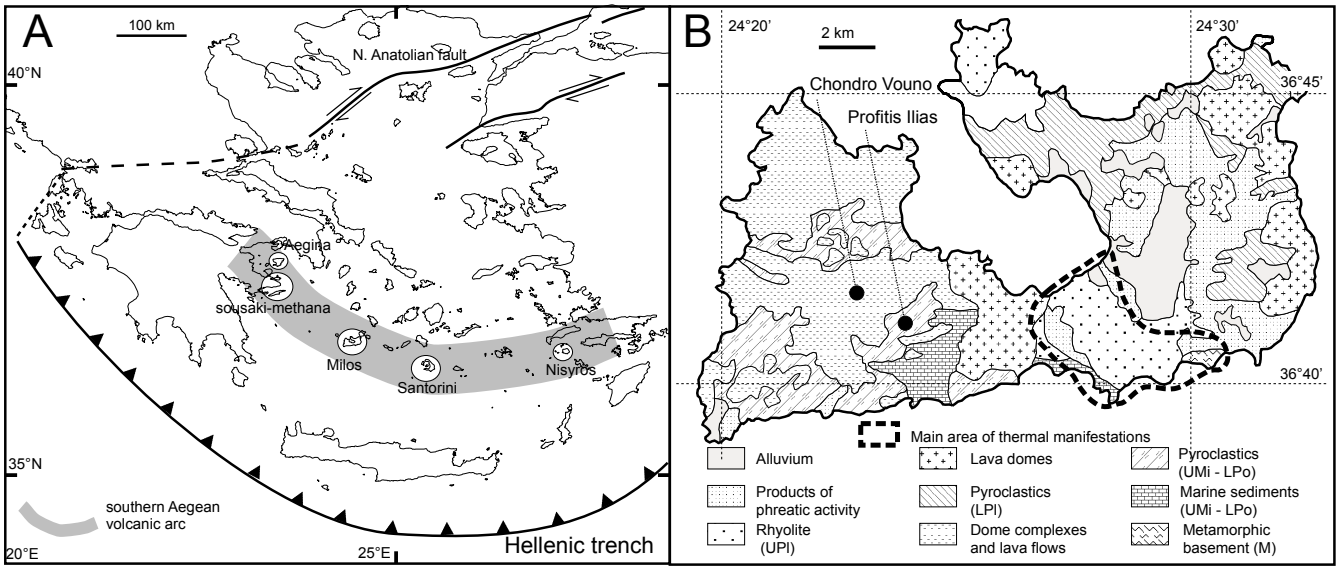
Fig. 3. Fluid-inclusion δD–$\delta^{18}O$ data for Profitis Ilias, comparing the epithermal mineralisation with active systems on the Aegean arc with reference points for eastern Mediterranean seawater (crossed squares labelled S) and estimated present day geothermal liquids (filled triangles labelled M [Milos] and N [Nisyros]). (Milos epithermal mineralisation data: Naden et al., 2003; geothermal data: Brombach et al., 2003; Kavouridis et al., 1999; Liakopoulos, 1987; fields for volcanic arc gases and Broadlands derived from Giggenbach, 1992 and Field and Fifarek, 1985 respectively)

Fig. 4. Conceptual model of hybrid Aegean-arc-type epithermal systems (adapted from Kavouridis et al., 1999; Liakopoulos, 1987)

TABLE 1. SUMMARY SALINITY DATA FOR PI–CV EPITHERMAL AU–AG MINERALISATION

Deposit	Salinity (wt % NaCl eq.)					% FI with Tmice
	n	Min.	Max.	Mean	σ	< -2.5 ºC
*CV	132	0.5	14.7	6.1	3.0	86%
†PI	139	0.0	11.3	5.2	2.1	71%

*this study
†Kilias et al., 2001



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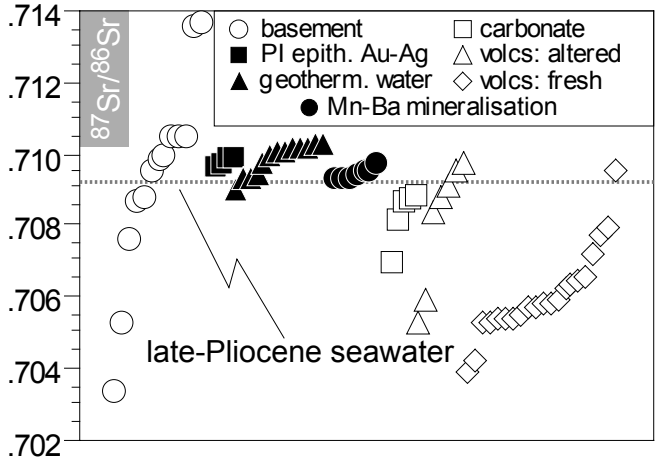

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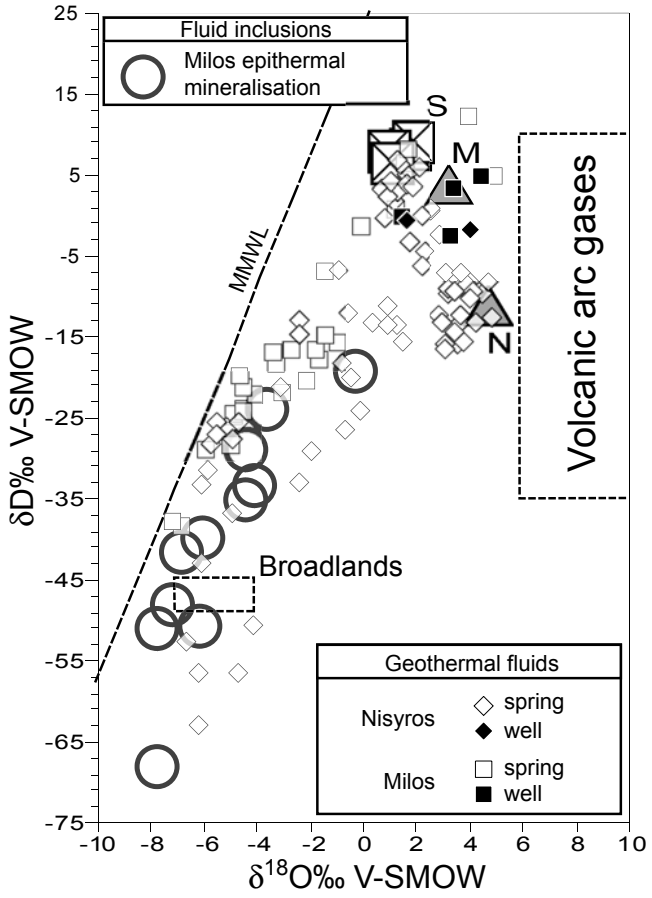

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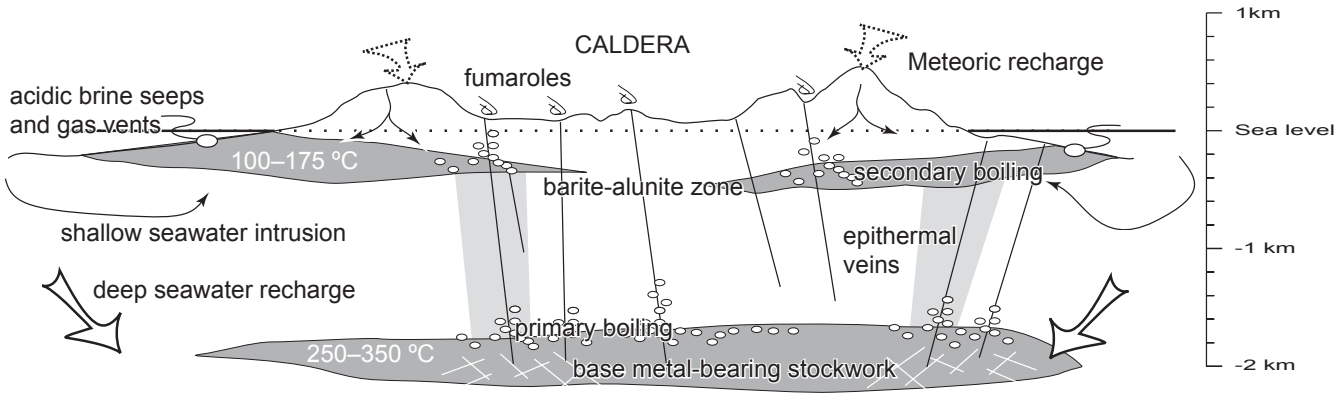

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