Land-based geothermal systems with entrained seawater as an alternative to the Broadlands epithermal-Au paradigm: the case for Milos Island, Aegean Sea, Greece

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ABSTRACT: Data in the literature show that not all low-sulphidation epithermal mineralisation results from low-salinity (< 1 wt%) gassy hydrothermal fluids. For these systems, using the Broadlands–Ohaaki geothermal system as an active analogue is inappropriate. Recent studies of geothermal systems associated with low-lying island-arc volcanoes indicate three-component mixing between seawater, meteoric water and a magmatic component. In addition, the deep geothermal reservoir is commonly saline, with salinities in excess of seawater (up to c. 10 wt % salts). One of these — on Milos island — is highly metalliferous and has a number of key parameters — such as: hydrology, fluid temperature, salinity and stable isotope systematics — in common with a nearby (<10 km) epithermal gold deposit (5Mt @ 4g/t Au & 43g/t Ag), suggesting that the Au-mineralisation and the active saline geothermal system are analogous. In view of this, we propose that geothermal systems with entrained seawater are applicable in some situations as an alternative to Broadlands–Ohaaki analogue in the scheme of intrusion-centred mineral deposit models.

1 INTRODUCTION

The Broadlands–Ohaaki geothermal system is the type example of an actively mineralising epithermal system, and is generally accepted as the modern analogue for many low-sulphidation (adularia–sericite) epithermal Au-deposits (e.g. Hedenquist & Henley, 1985a,b). It is axiomatic to this model that the main hydrothermal fluid comprises gas-rich water of dominantly meteoric origin with low TDS (<10 000 ppm). However, it is also recognised that a number of epithermal mineral deposits have salinities significantly in excess of these values and that these have no known active analogue (Hedenquist & Lowernstern, 1994). Here we suggest, by comparing fluid salinities and stable isotope systematics of modern analogues and their ancient counterparts, that active systems with entrained seawater are an alternative analogue for some epithermal mineralisation in the scheme of intrusion-centred mineral deposits.

2 FLUID INCLUSION SALINITY

When comparing the modern and ancient, fluid inclusion homogenisation (T_h) and ice-melting temperatures (T_{mice}) link fluid temperatures and compositions between the active and paleosystems. The Broadlands–Ohaaki geothermal fluids generally have less than 5 000 ppm TDS — this is equivalent to T_{mice} above −0.3 ºC. However, dissolved gases can further depress ice-melting by up to 1.5 ºC (Hedenquist & Henley 1985b), making a fluid with 25 000 ppm TDS indistinguishable, by fluid inclusion microthermometry, from one with little or no salt and 44 000 ppm gas (T_{mice} for both fluids approx. −1.5 ºC).

Here it is important to state that it is extremely difficult to generate and sustain salinities of more than 10 000 ppm (T_{mice} ≥ −0.6 ºC) in a geothermal system.
system with a high fluid turnover and meteoric water recharge (e.g. Broadlands–Ohaaki). Inputs of magmatic brine and boiling can increase salinity, but these are transient events and do not affect the overall composition of the meteoric-dominated system (Cooke and Simmons, 2001). Thus, because a high proportion of epithermal gold deposits have fluid inclusions with $T_{\text{mice}}$ below $-0.6\,^\circ\text{C}$, there is an implicit requirement to assign ice-melting to gas rather than salts, at least when the apparent salinity is up to 3–4 wt% NaCl eq. Moreover, by being able to apportion up to 25 000 ppm salt to gas it is possible to assign mineralisation to a Broadlands–Ohaaki model where the hydrothermal fluids have seawater salinities (35 000 ppm salts; $T_{\text{mice}}: -2.1\,^\circ\text{C}$) — this is evidently wrong for the cases when $T_{\text{mice}}$ values close to or below $-2.1\,^\circ\text{C}$ are caused by dissolved salt rather than gas. In a significant number of published examples there is clear evidence that true salinities for epithermal mineralisation are consistently in excess of 15 000 ppm NaCl eq (see Table 1). Therefore, because of the difficulties in generating high salinities (>10 000 ppm) in a Broadlands–Ohaaki geothermal environment we suggest that it is inappropriate as a model for moderately saline (>15 000 ppm NaCl eq) low-sulphidation epithermal mineralisation.

### 3 ACTIVE SALINE GEOTHERMAL SYSTEMS & EPITHERMAL MINERALISATION

Recently, a number of geothermal systems associated with volcanic islands have been investigated (e.g. Milos, Nisyros in the Aegean-arc and Luzon in the Bataan-arc). These are significantly different in terms of their chemistry to Broadlands–Ohaaki (Table 2). For example, such systems are typically saline (up to 100 000 ppm salt) and have stable isotope systematics indicating mixing between seawater, meteoric water and magmatic fluid (Fig. 2). Furthermore, in the active Aegean-arc, the majority of volcanic centres contain geothermal systems with entrained seawater (Panichi et al., 2001) and one of these — Milos — is metalliferous (Table 3).

Studies of scaling rates at the Milos experimental geothermal power plant also show that scales formed during flashing episodes contain over 90% sulphides (galena, sphalerite and chalcopyrite) and are gold and silver bearing (Christianis & St. Seymour 1995; Liakopoulos, 1987; Karabelas et al. 1989). When combined, these observations indicate that the modern geothermal fluid on Milos has significant mineralising potential. In addition, the active system on Milos has a number of parameters in common with epithermal gold mineralisation on the island. In particular, fluid inclusion salinities are consistently in excess of 14 wt% NaCl eq with over 90% of the inclusions having salinities in excess of seawater (Kilias et al., 2001). These match the high salinities observed in the active system. In addition, δD–δ18O systematics of fluid inclusion waters and samples from the active system are remarkably similar and follow a trend indicating mixing between seawater, meteoric water and magmatic fluid (Fig. 2).

Table 2. Geothermal well data comparing fluid chemistry between Broadlands-type fluids and saline geothermal systems in the Aegean and Aeolian arcs (data from Naden et al., in press; Kavouridis et al. 1999; Giggenbach, 1992; Delmelle et al., 1998).

![Figure 1. δD–δ18O plot of geothermal fluids and fluid inclusion waters in the Aegean and Luzon arcs showing mixing between meteoric, sea- and magmatic waters (data from Naden et al., in press; Kavouridis et al. 1999; Giggenbach, 1992; Delmelle et al., 1998).](image-url)
Land-based geothermal systems with entrained seawater (from Liakopoulos, 1987)

A spatial association between mineralisation and subaerial systems such as those on Milos are the most fruitful areas for research. However, neither fluid inclusion salinities nor geological criteria provide definitive evidence. Here, D/H, δ18O (see Fig. 2), δ34S, 87/86Sr and Br/Cl may provide more definitive information.

In terms of mineralising potential, there are several significant (>100 t Au) epithermal gold deposits, hosted in sub-marine and transitional volcanic rocks, where fluid inclusion data indicate that the mineralising fluids were dominantly saline (Table 4). Thus, though the relationship between saline terrestrial geothermal systems and epithermal gold mineralisation currently is only recognised on Milos, such systems may have the potential to form significant mineral deposits.

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REFERENCES


Table 3. Metal contents in the boiled Milos geothermal fluid (from Liakopoulos, 1987)

<table>
<thead>
<tr>
<th>element</th>
<th>concentration (ppm)</th>
<th>element</th>
<th>concentration (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>85087</td>
<td>Mn</td>
<td>42797</td>
</tr>
<tr>
<td>Na</td>
<td>38393</td>
<td>Ba</td>
<td>38993</td>
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<tr>
<td>K</td>
<td>10593</td>
<td>Fe</td>
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<tr>
<td>Ca</td>
<td>5291</td>
<td>As</td>
<td>13000</td>
</tr>
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<td>SiO₂</td>
<td>1150</td>
<td>Sb</td>
<td>3600</td>
</tr>
<tr>
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<td>90</td>
<td>Pb</td>
<td>1800</td>
</tr>
<tr>
<td>Rb</td>
<td>63</td>
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<td>1458</td>
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<tr>
<td>Sr</td>
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<td>Cu</td>
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</tr>
<tr>
<td>Mg</td>
<td>3</td>
<td>Ag</td>
<td>200</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>Cd</td>
<td>26</td>
</tr>
<tr>
<td>SO₄</td>
<td>1</td>
<td>Au</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Salinity 14.0 wt%

1 Maximum values collated from several analyses

Table 4. Large epithermal-gold deposits hosted in sub-marine/transition volcanic rocks where fluid inclusion data show saline mineralising fluids (data from Ahmad et al. 1987; Richards and Kerrich 1993; Ronacher et al., 2002 – note: Porgera data is for quartz-roselite epithermal mineralisation only)

<table>
<thead>
<tr>
<th>Deposit</th>
<th>size (t Au)</th>
<th>salinity % FI</th>
<th>% FI with salinity &gt; 3.5 wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladolam, Philippines</td>
<td>1300</td>
<td>0–8.5</td>
<td>47</td>
</tr>
<tr>
<td>Emperor, Fiji</td>
<td>112</td>
<td>4.6–7.1</td>
<td>100</td>
</tr>
<tr>
<td>Porgera, PNG</td>
<td>386</td>
<td>3.4–10.0</td>
<td>100</td>
</tr>
</tbody>
</table>

4 DISCUSSION & CONCLUSIONS

In view of the similarity between the ancient and modern systems on Milos, we propose that terrestrial geothermal systems with entrained seawater, such as those in the modern Aegean arc, provide an alternative to the Broadlands–Ohauki analogue in the scheme of intrusion-centred hydrothermal systems.

One of the diagnostic features of saline terrestrial geothermal systems is that they are recharged by both sea and meteoric waters. This clearly distinguishes them from submarine systems such as Jade, which is a modern equivalent of Kuroko-style mineralisation (Luders et al., 2001, 2002), and from the subaerial systems typically used as analogues for precious- and base-metal low-sulphidation epithermal mineral deposits (e.g. Cooke and Simmons, 2001). In this respect, the saline systems discussed here are hybrid in nature, containing elements of both submarine and subaerial systems. Indeed, hybrid systems are believed to be responsible for gold-rich VHMS deposits (e.g. Eskay Creek) and are predicted to occur in emergent volcanic arcs, though none have yet been clearly identified (Huston, 2000). However, though work is far from definitive, we do suggest that in trying to understand the relationship between VHMS and epithermal mineralisation, saline epithermal deposits and terrestrial geothermal systems such as those on Milos are the most fruitful areas for research.

Translating these concepts to epithermal mineralisation in general, the involvement of seawater appears to be suggested by Tursive-centred hydrothermal systems. In addition, a close spatial association between mineralisation and submarine volcanic rocks also appears to be characteris-


