

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

J. Naden

British Geological Survey, Keyworth Notts., NG12 5GG, UK

S.P. Kiliyas

Dept of Geochemistry and Economic Geology, National and Kapodistrian University of Athens, Athens Greece

A. Liakopoulos

Institute of Geology and Mineral Exploration, Athens, 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 & Lowenstern, 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°C . However, dissolved gases can further depress ice-melting by up to 1.5°C (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°C).

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°C) in a geothermal

Table 1. Selected salinity data for epithermal mineralisation in the United States, showing that in some epithermal deposits the hydrothermal fluids are saline (from Hedenquist & Henley 1983b).

Locality	Mineralisation	salinity (wt % NaCl)	
		min	max
Aurora, NV	Au vein	0.2	1.7
Comstock, NV	Ag bonanza	2.7	3.6
Creede, CO	Ag-Pb-Zn	1.1	13.4
Ute-Ulay, CO	Ag-Au-Pb-Zn vein	0.0	12.4
McLaughlin, CA	Au stockwork	0.2	2.0
Red Mountain, CO	Ag-Pb breccia pipes	0.1	1.6
Round Mountain, NV	Au vein	0.2	1.4
Sunnyside, NV	Au-Ag-Cu-Pb-Zn	0.0	3.6
Tenmile, NV	Au vein	0.4	2.1

NV = Nevada; CO = Colorado; CA = California

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_{mice} below $-0.6\text{ }^{\circ}\text{C}$, 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_{mice} : $-2.1\text{ }^{\circ}\text{C}$) — this is evidently wrong for the cases when T_{mice} values close to or below $-2.1\text{ }^{\circ}\text{C}$ 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 ($>10\text{ }000\text{ ppm}$) in a Broadlands–Ohaaki geothermal environment we suggest that it is inappropriate as a model for moderately saline ($>15\text{ }000\text{ ppm NaCl eq}$) low-sulphidation epithermal mineralisation.

3 ACTIVE SALINE GEOTHERMAL SYSTEMS & EPITHERMAL MINERALISATION

Recently, a number of geothermal systems associated with volcanic islands have been investigated

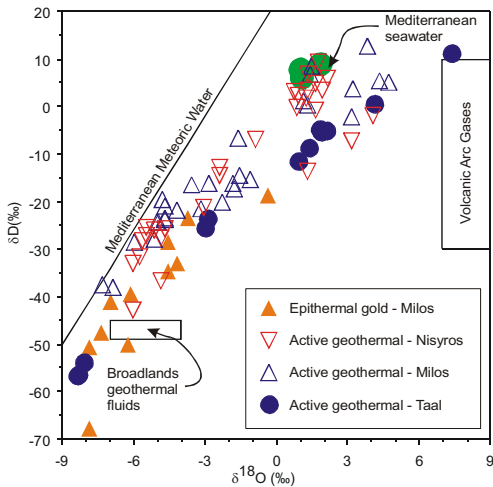


Figure 1. $\delta\text{D}-\delta^{18}\text{O}$ plot of geothermal fluids and fluid inclusion waters in the Aegean and Luzon arcs showing mixing between meteoric, sea- and magmatic waters (data from Naden et al., in press; Kavouridis et al. 1999, Giggenbach, 1992; Delmelle et al., 1998).

(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 (Christanis & 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 saline — up to 14 wt% NaCl eq. with over 90% of the inclusions having salinities in excess of seawater (Kiliyas et al., 2001). These match the high salinities observed in the active system. In addition, $\delta\text{D}-\delta^{18}\text{O}$ 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 Hedenquist & Henley 1983b, Liakopoulos, 1987, Caprarelli et al., 1997; Kavouridis et al. 1999; Gianelli & Grassi, 2001).

Locality	Na	K	Cl	SO ₄	CO ₂	wt % NaCl
<i>Broadlands–Ohaaki</i>						
Broadlands	540	108	783	11	12,250	0.13
Well 25, Ngawha,	849	64	1,152	48	14,370	0.20
Well 2, Kawerau,	529	85	865	7	3,520	0.14
Well 3, Waiotapu,	667	85	1,026	68	1,389	0.17
Well 7, Wairakei,	763	69	1,260	28	230	0.20
Well 80,						
<i>Aegean–Aeolian arc</i>						
Milos,	24,	6,06	49,30	10	--	8.12
Milos-2	300	0	0			
Nisyros,	25,	4,30	81,50	149	--	10.67
NIS1	290	0	0			
Nisyros	21,	2,87	50,39	25	--	7.20
NIS2	610	0	0			
Pantelleria PPT-1	14,	2,14	20,71	2,30	--	3.47
Campi	000	5	9	2		
Flegrei	13,	2,88	28,10	--	--	4.17
MF-9	632	2	0			

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

element	concentration (ppm)	element	concentration (ppb) ¹
Cl	85087	Mn	42797
Na	38393	Ba	38993
K	10593	Fe	19100
Ca	5291	As	13000
SiO ₂	1150	Sb	3600
Li	90	Pb	1800
Rb	63	Zn	1458
Sr	9	Cu	200
Mg	3	Ag	200
F	2	Cd	26
SO ₄	1	Au	0.3
		salinity	14.0 wt%

¹Maximum values collated from several analyses

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–Ohaaki 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 T_{mice} consistently below $-2.4\text{ }^{\circ}\text{C}$ (“net” salinities $>15\text{ }000\text{ ppm}$) or where combined Laser Raman and microthermometric analysis show low gas-contents and true salinities to be in excess of $15\text{ }000\text{ ppm NaCl eq}$. In addition, a close spatial association between mineralisation and submarine volcanic rocks also appears to be characteris-

Table 4. Large epithermal-gold deposits hosted in sub-marine/transitional 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-roscellite epithermal mineralisation only)

Deposit	size (t Au)	salinity	% FI with salinity $> 3.5\text{ wt } \%$
Ladolam, Philippines	1300	0–8.5	47
Emperor, Fiji	112	4.6–7.1	100
Porgera, PNG	386	3.4–10.0	100

tic. However, neither fluid inclusion salinities nor geological criteria provide definitive evidence. Here, D/H, $\delta^{18}\text{O}$ (see Fig. 2), $\delta^{34}\text{S}$, $^{87}/^{86}\text{Sr}$ and Br/Cl may provide more definitive information.

In terms of mineralising potential, there are several significant ($>100\text{ t Au}$) 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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