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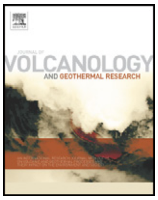

Heat flux from magmatic hydrothermal systems related to availability of fluid recharge

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ABSTRACT

Magmatic hydrothermal systems are of increasing interest as a renewable energy source. Surface heat flux indicates system resource potential, and can be inferred from soil CO_2 flux measurements and fumarole gas chemistry. Here we compile and reanalyze results from previous CO_2 flux surveys worldwide to compare heat flux from a variety of magma-hydrothermal areas. We infer that availability of water to recharge magmatic hydrothermal systems is correlated with heat flux. Recharge availability is in turn governed by permeability, structure, lithology, rainfall, topography, and perhaps unsurprisingly, proximity to a large supply of water such as the ocean. The relationship between recharge and heat flux interpreted by this study is consistent with recent numerical modeling that relates hydrothermal system heat output to rainfall catchment area. This result highlights the importance of recharge as a consideration when evaluating hydrothermal systems for electricity generation, and the utility of CO_2 flux as a resource evaluation tool.

1. Introduction

A common model of a magmatic hydrothermal system consists of a convecting cell of fluid. Meteoric water exchanges heat with a magmatic body at depth then rises toward the surface through permeable rock formations as a high-temperature plume of low density water, steam and gas (mostly CO_2). Most of the rising steam condenses in the shallow subsurface, and the resulting liquid condensate is discharged from the system either by lateral outflow (Chiodini et al., 1996, 2005), or evaporation (Chiodini et al., 2005; Hochstein and Bromley, 2005; Werner et al., 2006). A proportion of the condensate may recycle back into the system through a "heat-pipe" mechanism (Hochstein and Bromley, 2005). Water discharged from the system (according to the above processes) is typically recharged at the margins by meteoric water (Giggenbach, 1995; Dempsey et al., 2012), or seawater in some coastal settings (Sveinbjornsdottir et al., 1986; Parello et al., 2000; Dotsika et al., 2009). In many systems, magmatic water is a minor component of recharge (Giggenbach, 1995). For most systems examined here, water is predominantly of meteoric origin. The quiescent-state heat flow from the system is useful for volcanic hazard monitoring, where a sudden increase in heat flow could precede a period of volcanic unrest. Heat flow evaluation is also useful for exploration of hydrothermal energy resources (Hochstein and Sudarman, 2008); magmatic hydrothermal systems are of increasing interest as low carbon sources of base load electricity (Chamorro et al., 2012).

When the CO_2/H_2O (unitless mass ratio) of the rising plume is known from fumarole gas analysis, and soil CO_2 flux can be quantified at the surface (using a portable CO_2 flux meter), the two can be combined to provide a proxy for heat flow, usually reported as megawatts (MW) (Brombach et al., 2001; Chiodini et al., 2005; Fridriksson et al., 2006; Hernández et al., 2012; Rissmann et al., 2012). The geostatistical methods used to quantify soil CO_2 flux were previously explored and compared (Lewicki et al., 2005). Accordingly, fumarole chemistry provides complementary information to CO_2 flux measurements (i.e. by allowing CO_2 flux to be used as a proxy for heat flow). However, in

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order to compare the intensity of heat flow from various volcanic and hydrothermal systems it is also useful to consider heat flux (MW/km^2), as distinct from heat flow (MW). Although the terms are often (erroneously) used interchangeably, heat flux is heat flow normalized to unit area (Bird et al., 1960).

Hydrothermal systems are generally characterized according to a number of factors including geochemistry (Giggenbach, 1996), reservoir phase (liquid or vapor), temperature, lithology, and structural setting (Henley and Ellis, 1983). Here we compile and reanalyze results from 22 hydrothermal areas representing a wide variety of settings. The objective is to determine how CO_2 flux, CO_2/H_2O and the associated heat flux vary according to structural setting, reservoir phase, recharge source and recharge availability. Refer to Table 1 for a detailed summary of the physical and chemical characteristics of these systems. Hydrothermal studies were included on the basis that they provided both system CO_2/H_2O, and mapping of the hydrothermal CO_2 flux and a total CO_2 flow, allowing an estimate of heat flow.

2. Methods

The data provided in Table 4 is used to construct Fig. 1. The data for 9 of the 22 systems in Table 4 comes from a previous study of CO_2 flux and fumarole analysis for a variety of hydrothermal systems (Chiodini et al., 2005). Our study expands the previous study with the addition of new systems, and by considering the relationship between system heat flux and system setting.

Where possible, we have adopted the methodology of the earlier study so additional systems can be included and meaningfully compared (refer to *Notes* in Tables 2 and 3 for exceptions). This methodology provides the mean soil diffuse CO_2 flux of diffuse degassing structures (DDS) present within the various systems. DDS correspond to discrete areas of anomalous CO_2 flux, commonly associated with areas of high permeability (faults). The methodology delineates DDS areas using sequential Gaussian simulation; for most surveys, DDS are defined as areas of anomalous CO_2 flux where simulated flux values

Table 1
System setting.

System	Heat flux	Recharge type[a]	Reservoir dominant phase[b]	Temperature[c]	Acid gases[d]	Fumarole chemistry[e]	Structural setting	Reference
Nisyros (all DDS), Greece	19–166	Magmatic (70%), seawater (30%)	Liquid	150–250, 300 (deep)	No	Mantle	Subduction	(Brombach et al., 2003; Dotsika et al., 2009)
Vesuvio Cone, Italy	55	Meteoric and magmatic	Vapor core	360+	No	Arc type – mar. carb.	Subduction	(Chiodini et al., 2001b, 2004)
Pantelleria, Fav Grande, Italy	69	Meteoric and/or seawater (≤30%)	Liquid	260	No	Mantle type	Extension	(Duchi et al., 1994; Parello et al., 2000; Gianelli and Grassi, 2001)
Latera, Italy	70	Meteoric	Liquid	210–230, ~340 (deep)	No	Arc	Subduction	(Chiodini et al., 2007)
Furnas, Azores archipelago, Portugal	95	Meteoric	Liquid	160–180	No	Mantle	Extension	(Cruz et al., 1999; Viveiros et al., 2010)
Masaya, Comalito, Nicaragua	97	Meteoric[f]	Vapor core	Unknown	Yes	Mantle + crust. carb.	Subduction	(Lewicki et al., 2003; Chiodini et al., 2005; MacNeil, 2006)
Solfatara (CF), Italy	118	Meteoric and magmatic	Vapor core	210–240 (vapor zone)	No	Arc	Subduction	(Panichi and Volpi, 1999; Chiodini et al., 2001a)
Yellowstone Mud V., USA	152	Ancient meteoric[a]	Vapor	300+ (deep)	Yes	Mantle	Hotspot	(Werner and Brantley, 2003; Rye and Truesdell, 2007; Werner et al., 2008b)
Vulcano, PL Beach, Italy	186	Meteoric and/or seawater and/or magmatic	Vapor core	230	No	Unknown	Island arc	(Bolognesi and D'Amore, 1993; Chiodini et al., 1995)
Vulcano Crater, Italy	193	Meteoric and/or seawater and/or magmatic	Vapor core	400+	Yes	Arc	Island arc	(Bolognesi and D'Amore, 1993; Chiodini et al., 1995)
White Island, New Zealand	205	Meteoric and seawater	Vapor core	600+	Yes	Arc	Island arc	(Giggenbach, 1987; Houghton and Nairn, 1991; Hedenquist et al., 1993; Giggenbach et al., 2003)
Yellowstone HSB, USA	211	Ancient meteoric[a]	Vapor	300+ (deep)	Yes	Mantle	Hotspot	(Werner and Brantley, 2003; Rye and Truesdell, 2007; Werner et al., 2008b)
El Tizate, Nicaragua	333	Meteoric	Liquid	250–285	Unknown	Unknown	Extensional	(Ostapenko et al., 1998)
Ohaaki West, New Zealand	343	Meteoric (86%), magmatic (14%)	Liquid	300	No	Arc	Extensional	(Giggenbach, 1995; Dempsey et al., 2012)
Yellowstone (HLGB), USA	352	Meteoric[a]	Liquid	200	No	Mantle	Hotspot	(Sheppard et al., 1992; Lowenstern et al., 2012)
Krafla, Iceland	425	Meteoric	Vapor core	190–210 300–350 (deep)	No	Mantle	Extensional	(Sveinbjornsdottir et al., 1986; Nielsen et al., 2000)
Rotokawa, New Zealand	427	Meteoric (92%), magmatic (8%)[a]	Liquid	320	Yes	Arc	Extensional	(Giggenbach, 1995; Dempsey et al., 2012)
Karapiti, Wairakei, New Zealand	432	Meteoric (92%), magmatic (8%)	Liquid (vapor shallow)	260	No	Mantle	Extensional	(Giggenbach, 1995; Glover and Mroczek, 2009; Dempsey et al., 2012)
Ischia, Donna Rachele, Italy	766	Meteoric and seawater[g]	Liquid	250 (shallow) 300 (deep)	No	Mantle	Island arc	(Inguaggiato et al., 2000; Chiodini et al., 2004; Chiodini et al., 2005)
Reykjanes, Iceland	1048	Seawater[a]	Liquid	290	No	Mantle	Extensional	(Sveinbjornsdottir et al., 1986; Fridriksson et al., 2006)

[a] Based on isotopic data from reservoir fluid.
[b] Dominant phase of the reservoir underlying survey area.
[c] Temperature of the reservoir underlying survey area.
[d] Fumarole gas rich in acid magmatic gases (SO_2, HCl, HF) in survey area (Chiodini et al., 1995).
[e] Fumarole chemistry arc/mantle type based on relative N_2, He, and Ar contents (Giggenbach, 1996).
[f] Based on mass balance of systems inflow versus outflow.
[g] Based on chloride:boron ratio of thermal waters (Inguaggiato et al., 2000).