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Surface Degassing and the High-T Reservoir: Insights for Geothermal Exploration

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ABSTRACT

This paper summarizes results from CO_2 flux studies conducted in a variety of geothermal systems world-wide. Results show general relationships between the intensity of soil CO_2 flux, and characteristics of the underlying reservoir. In general, the magnitude of soil diffuse CO_2 flux at the surface can be related to topography and reservoir temperature. This general relationship can be explained by the following sequence of processes. Firstly, surface topography directs surface and subsurface recharge; all else being equal, geothermal systems located in lower elevation areas receive a greater lateral inflow of recharge. Conversely, higher elevation systems receive less recharge, and this raises reservoir temperature; higher elevation systems are generally hotter for the same reason engines run hotter when they are low on coolant. Accordingly, topography influences reservoir temperature. Secondly, temperature controls the concentration of CO_2 in the reservoir via temperature-dependent mineral-water equilibrium. Thirdly, reservoir CO_2 content controls the magnitude of soil diffuse CO_2 flux at the surface. The relationship between reservoir CO_2 content and temperature is the basis for a new CO_2 flux-based geothermometer for geothermal exploration. These findings have implications for the development of hydrothermal electricity, currently slowed by the economic risks of exploration. We emphasize recharge as an important factor in the science of geothermal exploration, and the utility of the CO_2 flux survey technique for geothermal resource evaluation.

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). Rising CO_2 intercepts a hydrothermal reservoir and undergoes geochemical reactions (**Figure 1**); the reservoir is a sink for CO_2 (CO_2 rising from beneath is captured as calcite), and a source of CO_2 (released to the surface by boiling). Water discharged from the system 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 non-marine systems, recharge is of meteoric origin.

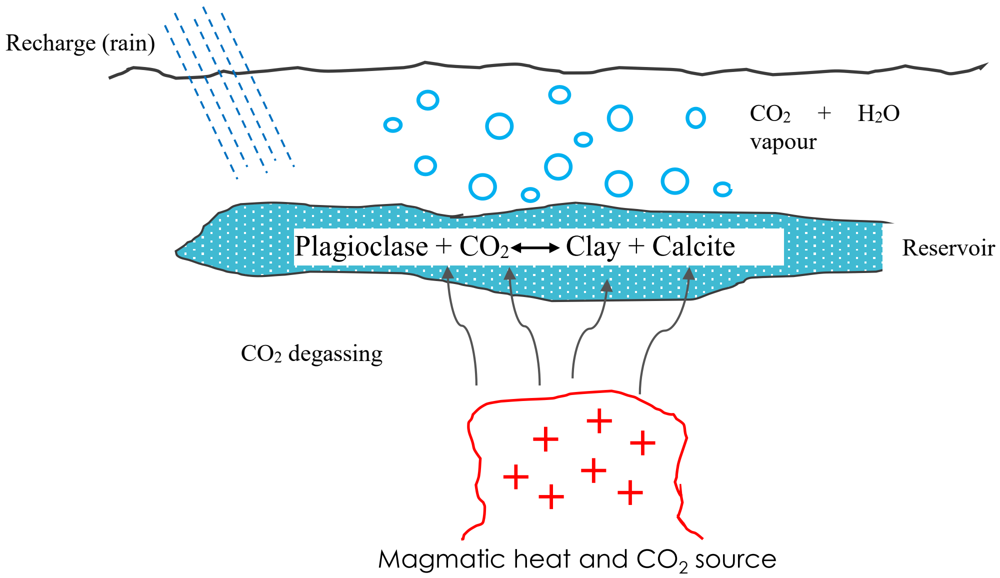

Figure 1 Simple meteoric recharged hydrothermal system conceptual model. CO_2 originates from the magmatic heat source (intrusive), then rises toward the surface before encountering a hydrothermal reservoir. Note: the flow of CO_2 from the intrusive may not be not the same as that measured at the surface; the reservoir is a source or sink for CO_2.

CO_2 flux surveys in geothermal and volcanic areas have been increasing in number since equipment became commercially available in the late 1990's. Accordingly, the past 15-20 years can be regarded as the pioneer phase of geothermal CO_2 flux exploration, with a small but growing body of literature. Understandably, most early studies have made "stand-alone" interpretations relating solely to the area under investigation (e.g. fault permeability, heat flow, CO_2 flow) (e.g. *Chiodini et al.*, 1996; *Werner et al.*, 2000; *Fridriksson et al.*, 2006), with only limited comparison to other systems; there simply were not enough published studies for comparison.

The lack of comparative studies leaves fundamental unanswered questions, which are addressed by this paper. For example, when we compare the intensity of CO_2 flux for a variety geothermal system, do we observe a systematic relationship to topography, and water recharge mechanisms? Alternatively, when we examine a variety of well understood (i.e. drilled) geothermal systems do we see a relationship between surface CO_2 flux intensity, reservoir gas content and temperature? This paper summarizes recent investigations into the controls over CO_2 flux intensity in thermal areas, which have improved the predictive power of CO_2 flux to reveal the nature of the deep reservoir in undrilled geothermal systems.

2. SURFACE CO_2 FLUX AND RECHARGE TO THE RESERVOIR

Here we summarize the findings of *Harvey et al.* (2015), which determined that variations in surface fluxes of CO_2 and heat, measured in a range of hydrothermal systems, may be explained by the specific hydrological settings of the systems (**Figure 2**). Previous studies had observed that heat fluxes, for a variety of similar systems in the Taupo Volcanic Zone (TVZ), fall within a single order-of-magnitude (e.g. *Weir,* 2009). Further, that this range is restricted relative to the much wider range of permeabilities known to exist in reservoir host rocks (permeabilities extend over several orders of magnitude); if permeability were the primary control over system heat output, then heat fluxes would also be expected to span several orders of magnitude, but this was not observed (*Weir,* 2009).

Heat flows from geothermal systems in the TVZ were compared in previous studies (*Weir,* 2009; *Dempsey et al.,* 2012), and shown to be proportional to rainfall catchment areas estimated from modelling. These studies did not consider surface topography/watershed basins but acknowledged this will have a strong effect. For example, surface topography will affect the direction and magnitude of surface and subsurface recharge; all else being equal, geothermal systems located in lower elevation areas, or those located nearby a body of water, would receive a greater lateral inflow of recharge than systems located beneath a topographic high (e.g. volcanic cone)(**Figure 2**). It follows that systems located in a basin, or topographic depression, should receive a greater flow of water, which is the medium of convective heat flow. All else being equal, a greater flow of water would also result in a lower reservoir temperature, which affects surface CO_2 flux (Section 3).

This concept is nicely illustrated in the TVZ, where it is apparent the majority of systems are located on the Waikato River (9 out of 13)(**Figure 3**). The Waikato River constitutes the primary hydrological drainage and topographic low for the TVZ. Another example that illustrates this concept, is the generally low power density (electrical capacity per unit area of reservoir) observed for vapour dominated reservoirs. The low power density of the Geysers (USA), and Lardarello (Italy), relative to other geothermal electric plants, was noted previously and attributed to restricted recharge (Allis, 2000). Generation at these, and most other geothermal power plants (both vapour and liquid dominated), is now typically supported by artificial recharge (reinjection) of fluids into the margins of the productive reservoir (*Stefansson*, 1997; *Kaya et al.*, 2007).

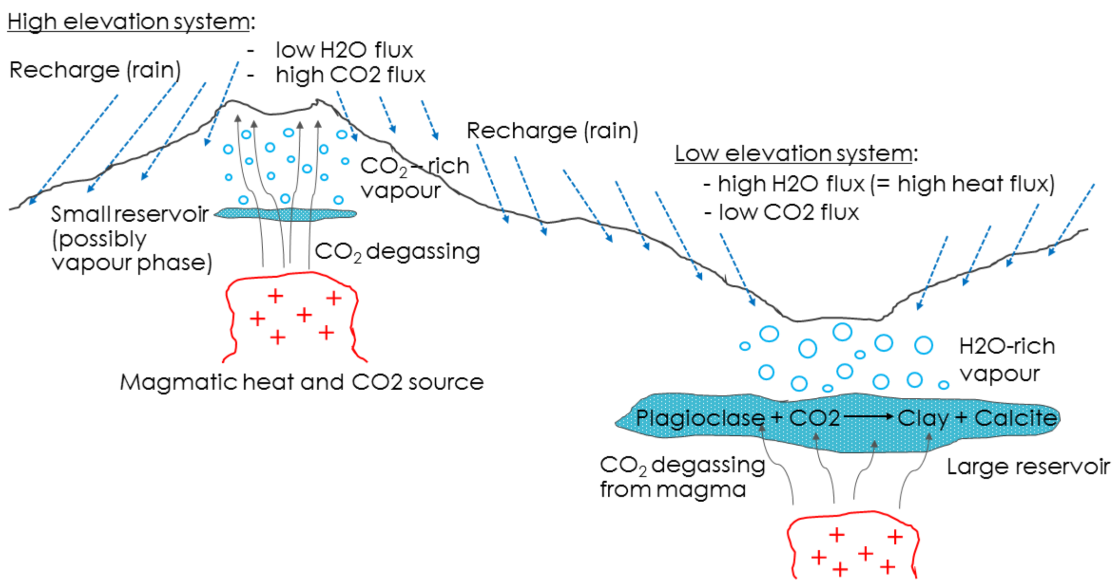

Figure 2 Surface fluxes of CO_2 and H_2O may be explained by the hydrological setting of the system. In the above example, topography controls recharge (note: lower-elevation reservoir is much larger), which controls surface flux of H_2O and CO_2.

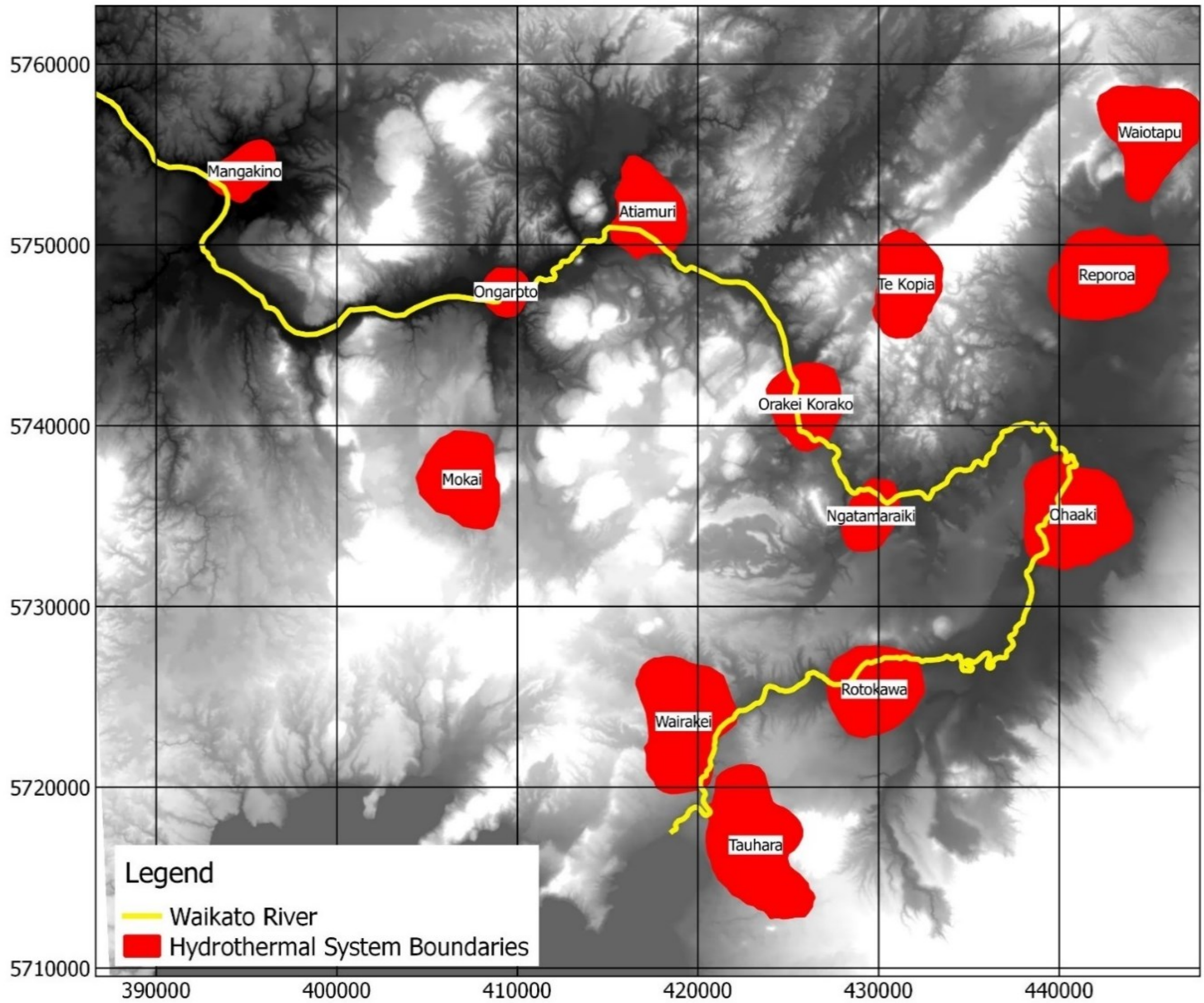

Figure 3 Location of hydrothermal fields (red areas) in the Taupo Volcanic Zone overlaid on a satellite digital terrain model (WGS84). Darker shading indicates lower elevation topography. Field boundaries are based on shallow electrical resistivity data (Bibby *et al.*, 1995).

A review of 53 geothermal fields worldwide study gave a mean power capacity of 16.2 MW electric km^{-2} (*Wilmarth and Stimac,* 2014). By assuming a typical conversion efficiency of 10% from thermal energy to electric (*Ghoniem,* 2011; *Zarrouk and Moon,* 2014), 16.2 MW electric km^{-2} gives 162 MW km^{-2}. This heat flux is comparable to the mean heat flux for meteoric supplied hydrothermal systems determined by surface CO_2 flux measurements in areas of thermal ground (198 MW km^{-2}) (*Harvey et al*., 2015). It is worth noting these values are of the same order-of-magnitude as the global average solar heat flux captured by the Earth's surface water (solar evaporation = 80 MW km^{-2})(*Trenberth et al.,* 2009). Because the system is in a steady state, this energy is subsequently released as the evaporated moisture condenses (rain).

The energy flux associated with a phase change in water (i.e. liquid to vapour, or vice versa) is related to a change in the specific enthalpy of the fluid. This allows heat flux (e.g. MW km^{-2}) and water flux (e.g. tons km^{-2} day^{-1}) to be used interchangeably. It is important to note that such enthalpy changes are quite insensitive to temperature. For example, the change in enthalpy associated with steam (100°C) condensation to liquid water (12°C) in hydrothermal areas (2624 kJ kg^{-1}), is very close to the value associated with the evaporation of Earth's surface waters (~2260 kJ kg^{-1}). Therefore, the mean heat flux for natural-state meteorically supplied geothermal systems (198 MW km^{-2}) may be constrained by the available incoming solar energy flux, the ultimate power source that drives the Earth's hydrological cycle.

3. CO_2 FLUX AND RESERVOIR TEMPERATURE

Here we summarize the findings of *Harvey et al.* (2017), which explored the relationship between heat flux, CO_2 flux, and deep reservoir temperature for eight hydrothermal systems, located in New Zealand (6), Iceland (1) and Argentina (1). In that study, a new geothermometer for geothermal exploration ($T_{CO2\ Flux}$) was proposed based on soil diffuse CO_2 flux and shallow temperature measurements, which may be generally applied in areas of steam heated ground. Full details of the geothermometer, including assumptions for usage, and tabulated summary of geothermometer results for a variety of geothermal systems is provided in *Harvey et al.* (2017) and *Harvey et al.* (2019).

Temperature estimates derived from $T_{CO2\ Flux}$ were compared to reservoir temperatures (measured and inferred) from the eight areas. $T_{CO2\ Flux}$ temperatures were found to be close to the known (or inferred) reservoir temperatures for all eight systems. It is proposed that $T_{CO2\ Flux}$ provides a temperature estimate that is not subject to problems of limited sample size, one of the main limitations of water and gas geothermometers.

$T_{CO2\ Flux}$ results from some systems (Wairakei, Ohaaki, Rotokawa) indicated thermal areas receive vapour from separate aquifers. The areas of maximum $T_{CO2\ Flux}$ at Wairakei and Rotokawa occur at the location of upflows (as shown in existing conceptual models). At White Island, powerful magmatic CO_2 flows would be expected to penetrate or bypass the acidic liquid reservoir, especially during non-equilibrium eruptive events. Such a physical process would invalidate the $T_{CO2\ Flux}$ geothermometer, which assumes temperature dependent water mineral equilibrium in neutral pH reservoir fluids.

Harvey et al. (2015) showed the intensity of surface CO_2 degassing is related to recharge but did not provide the precise mechanism through which deep recharge could influence surface CO_2 flux (Section 2). *Harvey et al.* (2017) proposed the mechanism, that recharge has an influence on the temperature of hydrothermal reservoirs. This provides the missing link between recharge and soil CO_2 flux; reservoir temperature controls the concentration of CO_2 in the reservoir via mineral-water equilibrium, which in turn controls the magnitude of soil diffuse CO_2 flux at the surface (**Figure 2**).

The relationship between reservoir temperature and recharge is intuitive if one considers the following analogy. Here, a hydrothermal system is represented by a gasoline engine in which the engine block (reservoir rock) exchanges heat with a circulating coolant (reservoir water). A thermostat regulates temperature by regulating the flow of coolant through the block. In doing so, the coolant's temperature is also modified. A radiator with a puncture, or blown head gasket (hot spring), allows water to escape the system. If fluid is not added to the radiator (recharged) with sufficiently regularity, the block will dry, and result in a higher system temperature.

4.0 CONCLUSIONS

Variations in CO_2 flux and reservoir temperature may be explained by topographic and hydrological factors. Recharge availability, often related to topography, exerts a strong control over the location of hydrothermal systems. Natural state heat flux for meteorically supplied geothermal systems may be constrained by the available incoming solar energy flux, the ultimate power source that drives the Earth's hydrological cycle.

Recharge also has an influence on the temperature of hydrothermal reservoirs; higher recharge flux lowers reservoir temperature, a system analogous to water-cooled gasoline engines. Thus, recharge influences reservoir temperature, which controls the concentration of reservoir CO_2 via temperature-dependant mineral-water equilibrium. This in turn controls the magnitude of soil diffuse CO_2 flux at the surface, which is the basis for a new CO_2 flux-based geothermometer for geothermal exploration.

These findings have implications for the development of hydrothermal electricity, currently slowed by the economic risks of exploration. We emphasize recharge as an important factor in the science of geothermal exploration, and the utility of the CO_2 flux survey technique as an easily applied geothermometer.

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