Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Soil CO_2 Flux Surveys: A Review of the Technique in Geothermal Exploration

Mark C. Harvey[1] & Colin C. Harvey[2]

[1]School of Environment, University of Auckland, Auckland, New Zealand

[2]GNS Science, Private Bag 2000, Taupo, New Zealand

Keywords: CO2, flux, fumarole, heat, geothermal, hydrothermal, survey, energy, plant, survey, gradient, exploration

ABSTRACT

Portable equipment designed for surveying CO_2 flux in geothermal prospects has been commercially available since the late 1990's. Since that time, much research has been applied to development of the technique. The use of the technique for commercial geothermal exploration is gaining momentum. The technique is relatively low cost, and provides immediate results allowing survey coverage to be adapted in real time. The technique can provide much useful information relevant to geothermal exploration, including contributions to mapping permeable structures, resolving system boundaries, estimation of non-condensable gas (NCG) contents, estimations of heat flow, and refinement of conceptual models. The technique can also be used to establish an environmental baseline for CO_2 emissions prior to development. This paper provides a literature review of over twenty CO_2 flux surveys in geothermal prospects or projects conducted in more than ten countries. The technique has also been successfully developed for monitoring active volcanism which is beyond the scope of this paper.

1. INTRODUCTION

A common model of a magmatic hydrothermal system consists of a convecting cell of fluid. Cool meteoric water exchanges heat with a magmatic body at depth, then rises toward surface through permeable rock formations as a high temperature plume of low density water, steam and gas (mostly CO_2). Water lost from the circulating cell is typically recharged at margins by cool meteoric water (Dempsey, Simmons, Archer, & Rowland, 2012). The quiescent-state heat flow from the system is of particular interest to volcanologists for purposes of volcanic monitoring, and for exploration of hydrothermal energy resources (Hochstein & Sudarman, 2008); magmatic hydrothermal systems are of increasing interest as a low carbon source of base load electricity.

When the CO_2:steam (CO_2:H_2O) mass ratio of the rising plume is known from fumarole measurements, CO_2 flux can be mapped at surface and used as a proxy for heat flow (Brombach, Hunziker, Chiodini, Cardellini, & Marini, 2001; Chiodini et al., 2005; Fridriksson et al., 2006; Hernández et al., 2012; Rissmann et al., 2012). The CO_2:H_2O ratio is measured directly from surface steam vents (fumaroles) located above the rising plume, and CO_2 flow is mapped using portable equipment for making soil CO_2 flux measurements. Accordingly, fumarole chemistry provides complimentary information to CO_2 flux measurements; together these measurements can provide an estimate of heat flow from hydrothermal systems.

In many cases, use of CO_2 flux to determine heat flow will provide a more comprehensive evaluation of sub-surface heat flow than direct measurement of thermal gradients (Fridriksson et al., 2006; Hernández et al., 2012; Hernández et al., 2012). This is because a proportion of up-flowing water and steam (and associated heat) may disperse into near surface aquifers, which flow laterally away from the system following the topographic gradient. Accordingly, the shallow subsurface above such up-flows may retain near-ambient temperature profiles as the heat escapes elsewhere; the sub-surface heat flow is hidden.

CO_2 flux and heat flow does not occur evenly across the entire surface of a geothermal reservoir, but rather from diffuse degassing structures (DDS) that connect surface CO_2 emissions to their source (Chiodini et al., 2001): boiling geothermal reservoirs. DDS constitute drilling targets for geothermal energy exploitation, and can be accurately mapped by CO_2 flux measurements.

This literature review has identified over 20 reported studies of CO_2 gas flux surveys throughout the World, in geothermal prospect areas, or where geothermal power plants already exist. The growth in the use of the technique is evident from the fact that only three of the surveys were reported between 2000 and 2005 (Italy, USA and Greece), while at least 11 surveys were completed between 2010 and 2014. This paper provides a review of reported CO_2 flux surveys undertaken in geothermal systems throughout the World. Some systems that are under exploitation while others are currently undergoing exploration.

2. METHODOLOGY

In volcanic and geothermal settings CO_2 flux measurements are typically made using a West Systems portable soil gas flux meter, (accumulation chamber method). The accumulation method calculates CO_2 flux by placing a 200 mm diameter accumulation chamber on the soil surface and pressing it into the soil to obtain a seal. Gases flowing into the chamber are pumped to an infrared gas analyser. The increase in CO_2 concentration inside the chamber over time is recorded by the instrument. The rate of concentration increase is proportional to flux. Most surveys are conducted in times of dry weather. This because rain can disrupt the diffusion of CO_2 through surface soils and may mask the presence of degassing.

After measurements are made, survey post processing has two key elements. Firstly, the identification of the biological background component of CO_2 flux, so this is not confused with the geothermal signal. This is particularly important in areas where the geothermal reservoir is known or suspected to have a low gas content. There are several approaches to identification of background flux including: (i) the graphical statistical approach (GSA) that partitions separate log-normally distributed populations using cumulative probability plots (Chiodini et al., 1998; Fridriksson et al., 2006), (ii) evaluation of background on the basis of biological ^{13}C isotope signature (Chiodini et al., 2008; Rissmann et al., 2012;), and (iii) taking a background control set of measurements at some distance from areas of visible surface thermal activity, where no magmatic CO_2 flux is expected (Chiodini et al., 2007; Viveiros et al., 2010).

Secondly, geostatistical analysis so that representative flux maps of the survey area can be produced, along with summary statistics and uncertainty for total CO_2 flow, heat flow, mean CO_2 flux and heat flux. Flux maps are generally produced by interpolation of raw data using Sequential Gaussian Simulation (SGS), a stochastic simulation technique that can reproduce the spatial variability of flux (histogram and variogram). SGS will also provide summary statistics with associated uncertainty.

The use of CO_2 flux as a proxy for heat flow is based on the assumption that the rising mixture of CO_2 and H_2O (steam), has the same CO_2:H_2O ratio as high temperature and high flow-rate fumaroles measured at surface; in order to obtain accurate estimates of heat flow from CO_2 flow, there should be high temperature and flow-rate fumaroles, or deep liquid enthalpy wells available for sampling in the area of interest. Heat flow is obtained by multiplying the assumed steam flow by enthalpy of steam less enthalpy of water at ambient temperature (Chiodini et al., 2005).

Heat flow can also be assessed by shallow temperature gradient measurements (Hochstein and Bromley, 2005), in which case associated steam flow can be inferred (assuming most heat derives from condensation of the ascending steam phase). Together with CO_2 flow (from CO_2 flux survey), the CO_2:H_2O ratio of an area can be assessed, which is relevant to geothermal resource evaluation (can be used to estimate the non-condensable gas content of the reservoir)(Brombach et al., 2001, Werner et al., 2004).

Summary data from a variety of CO_2 flux and shallow temperature gradient surveys in are tabulated (Table 1) and summarised below. Table 1 provides key outputs from each survey relevant to geothermal resource evaluation, including i) mapping of faults/structures or system upflow(s), ii) heat flow estimate, and iii) CO_2:H_2O ratio of the area.

3. SURVEYS AT GEOTHERMAL PROSPECTS

One of the earliest published surveys of soil diffuse CO_2 flux in a geothermal area, which utilizes the accumulation chamber technique, was by Chiodini (1996) at the Fossa crater, Vulcano Island (Italy). Italian scientists have been amongst the leaders in the development and application of the technique for both geothermal systems and monitoring of volcanic activity. Since the late 1990's the technique has been applied at volcanic and geothermal areas around the world. The technique is gaining traction in geothermal exploration for its relatively low cost, rapid results, ability to locate drilling targets and quantify heat flow, which is an indicator of resource potential.

Summary data from surveyed geothermal prospects are tabulated (Table 1).

4.1 Nisyros, Greece

At Nisyros a significant heat flow (58MWth) was determined from CO_2 flux measurement, and found to be associated with fumarole areas and Diffuse Degassing Structures (DDS)(Brombach et al., 2001). Heat flow was also evaluated using shallow temperature gradient measurements and found to be in good agreement with the CO_2 flux derived heat flow. The CO2:H2O ratio of the steam phase supplying the thermal area was estimated using CO_2 flux and temperature gradient measurements. This ratio was found to be in good agreement with fumarole gas analysis.

According to Bertani (2012), Nisyros was "under evaluation for geothermal electricity generation both by PPC/Renewables (the Greek electricity company) and foreign investors, but the authorization process (from the Ministry issuing the tender of geothermal leases) is slowing the development".

4.2 Vesuvio, Italy

At Vesuvio a modest heat flow (17MWth) was determined from CO2 flux measurement, and found to be mostly constrained with the inner part of the crater (Frondini et al., 2004). Spatial patterns of CO_2 flux were found to be in good general agreement with spatial patterns of shallow temperature gradient measurements.

According to Carlino et al. (2012), the absence of a large radius hydrothermal system at Vesuvio is consistent with very low temperatures measured in the Trecase deep exploration well lactated ~ 4km from the crater.

4.3 Pantelleria, Italy

CO_2 emissions at Favara are associated with faults, fractures or cracks in the soil, and a modest heat flow (10-12 MWth). Spatial patterns of CO_2 flux were found to be in good general agreement with spatial patterns of shallow temperature gradient measurements. Heat flow was also evaluated using shallow temperature gradient measurements and found to be in good agreement with the CO_2 flux derived heat flow (Graniere et al., 2014).

The geochemistry of the geothermal fluids had previously been evaluated as part of an exploration programme and two wells were drilled in 1993 which recorded temperatures of 260C.

4.4 Hengil, Iceland

Most CO_2 is associated with areas close active thermal manifestations, on the northeast flank of the Hengil central volcano, nearby to the Nesjavellir power plant. The flux is probably associated with a SSW–NNE trend, indicating a structural association Hernández et al (2012). At Hengil a large heat flow (1237 MWth) was determined from CO_2 flux measurements. This large heat flow is consistent with elevated heat flows over a large total survey area (168km^2), and large anomalous area (~30km^2).

The installed electrical capacity at the Nesjavellir geothermal plant is 120 MWe, with a further 300 MWth direct use (Hernández et al., 2012).

4.5 Ohaaki, New Zealand

At Ohaaki West, a significant heat flow (82 MWth) was determined from CO_2 flux measurement, which is over 40% larger than heat flow determined by direct measurement of soil temperature gradients. Large patches of anomalous CO_2 flux coincide with regions of cold, unaltered ground, indicating the separation of the steam phase from CO_2 below the land surface. This suggests CO_2 can be useful for locating “blind” areas of sub-surface thermal activity.

The installed electrical capacity at the Ohaaki geothermal plant is 116 MWe (Rissmann et al. 2012).

4.6 Wairakei, New Zealand

The magnitude of CO_2 flux at Karapiti, Wairakei, is quite low (Werner et al., 2004), consistent with the low gas content of the geothermal reservoir. A total heat flow of (~50 MWth) is derived from CO_2 flux measurements. This value slightly lower than diffuse heat flow determined from shallow temperature gradients (69MWth)(Hochstein and Bromley, 2005).

The CO_2:H_2O ratio of the steam phase supplying the thermal area (from gas analysis of many fumaroles) was compared to the CO_2:H_2O ratio derived from CO_2 flux and temperature gradient measurements, and found to be in reasonable agreement. However, the standard deviation for the CO_2 flux based CO_2:H_2O ratio was greater than for the fumarole based ratio (Werner et al., 2004). In some areas, anomalous CO_2 flux coincides with regions of cold ground, indicating the separation of the steam phase from CO_2 below the land surface.

The installed electrical capacity of the Wairakei geothermal plant is 181 MWe (Sepúlveda et al. 2012).

4.7 Rotorua, New Zealand

Areas of anomalous CO_2 flux correspond closely with known hot fluid upflow areas in Rotorua. Elevated CO_2 flux was observed along inferred faults and structures, lending confidence to their existence (Werner et al., 2006).

Rotorua has an extensive geothermal system that has been exploited in the past for direct use heating purposes.

4.8 Camp Flegrei, Italy

Thermal energy associated with CO_2 flux at Camp Flegrei (138MWth) is the dominant pathway of energy release and an order of magnitude greater than conductive heat loss (Chiodini et al., 2001). However, this is a minimum estimate of the total heat flow at Camp Flegrei. The highest CO_2 flux values overlap with faults and fractures which indicate degassing is strictly related to tectonic structures. Both CO_2 flux and shallow temperature gradients were measured at a small subset of the total DDS area. The mean heat flux derived from CO_2 flux (153W m^{-2}) was found to be in close agreement with the mean heat flux derived from shallow temperature gradients (160 W m^{-2}).

The Camp Flegrei area was previously evaluated for geothermal potential. Four productive exploration wells have been drilled with an estimated potential >10MWe (Granieri et al., 2012).

4.9 El Tizate, San Jacinto, Nicaragua

A CO_2 gas flux and shallow temperature survey was undertaken in 2011 to determine if areas of elevated CO_2 flux and/or elevated shallow (≤1m) subsurface temperature support the presence of mapped faults, and to identify other potential structural features that may be providing anomalous temperature and gas flux (Harvey et al., 2011). Thermal energy associated with CO_2 flux at El Tizate (326 MWth) is associated with previously mapped structures, shallow temperature measurements, and the productive steam field area. In addition, a new major structure was identified by the CO_2 flux survey (Harvey et al., 2011).

The electrical capacity of the San Jacinto geothermal plant is approximately 48 MWe based on 2013 generation (RAM, 2013).

4.10 Rotokawa, New Zealand

Thermal energy derived from CO_2 flux at Rotokawa (317MWth) is associated with deep seated permeability and major normal faults. This value is much larger than the heat flow determined in the same area by direct measurement of soil temperature gradients (73MWth) (Bloomberg et al., 2012). In some areas, anomalous CO_2 flux coincide with regions of cold ground, indicating the separation of the steam phase from CO_2 below the land surface.

The electrical capacity of the Rotokawa geothermal plants (Rotokawa A and Nga Awa Purua) is approximately 174 MWe (Bloomberg et al., 2012).

4.11 Krafla, Iceland

At Krafla there is a positive correlation between CO_2 soil flux emissions and the structural geology of the area; CO_2 flux shows a NE-SW trend that is parallel with the Hveragil fissure. The CO_2 emission from natural sources exceeds emission from the power plant by approximately 3 times (Dereinda and Armannsson, 2010).

The electrical capacity of the Krafla geothermal plant is 60MWe (Dereinda, 2008).

4.12 Ischia, Donna Rachele - Italy

Thermal energy derived from CO_2 flux at Ischia (~40MWth) is associated with hydrothermally altered areas along faults (Chiodini et al., 2004). At Ischia, additional thermal areas were not surveyed, thus the estimated heat flow released from Donna Rachele DDS is probably only small fraction of the total thermal energy released.

Ischia was previously explored for geothermal potential. One exploration well found 225C at 1151m (Carlino et al., 2012).

4.13 Reykjanes, Iceland

Thermal energy derived from CO_2 flux at Reykjanes (130MWth) is concentrated along strike slip faults in the area. At Reykjanes, CO_2 flux is considered a more reliable proxy for heat loss than soil temperatures (Fridrikkson et al., 2006). This is because anomalous CO_2 flux coincides with regions of cold ground, indicating the separation of the steam phase from CO_2 below the land surface.

The electrical capacity of the Reykjanes geothermal plant is 100MWe (Fridrikkson et al., 2010).

4.14 Ngatamaraiki, New Zealand

Hanson et al. (2014) emphasise the importance of utilizing diffuse CO_2 flux and high spatial density δ13C of CO2 surveys to identify blind geothermal resource targets in low CO_2 flux systems. The current electrical capacity of the Ngatamaraiki geothermal plant is 82MWe.

4.15 Platanares, Honduras

Barberi et al. (2013) report that CO_2 soil flux investigations provided very useful data for underground permeability assessment. In particular, CO_2 flux anomalies are elongated about NW–SE, parallel to the main tectonic lineaments of Platanares.

The most recent geothermal investigations at Platanares occurred after 2005 by ELCOSA (Electricidad de Cortes, S.R.L.), a private Honduran company.

4.16 Azacualpa, Honduras

Barberi et al. (2013) report that CO_2 soil flux investigations provided very useful data for underground permeability assessment. In particular, a wide zone of anomalous CO_2 degassing was interpreted to derive from a geothermal reservoir. CO_2 flux anomalies are associated with thermal manifestations and the form of the anomalies suggests that CO_2 is emitted from NW–SE trending fractures, and possibly also from N–S or NNE–SSW fractures.

The most recent geothermal investigations at Azacualpa occurred after 2005 by ELCOSA (Electricidad de Cortes, S.R.L.), a private Honduran company.

4.17 Berlin, El Salvador

No CO_2 flow of geothermal origin was interpreted at Berlin (Renderos, 2009). There is no information on the seasonal conditions under which the survey was undertaken. The electrical capacity of the Berlin geothermal plant is 109 MWe (Renderos, 2009).

4.18 Dixie Valley, USA

CO_2 flux measurements were undertaken at Dixie Valley by Bergfeld (2001). The most anomalous CO_2 flux values occurred at sites along traces of the Stillwater fault zone. The magnitude of CO_2 flux was found to be closely related to the rate of boiling of the geothermal reservoir.

The electrical capacity of the Dixie Valley geothermal plant is 62 MWe (Renderos, 2009).

4.19 Vanuatu

A CO_2 flux survey was undertaken on Vanuatu (Harvey and Alexander, 2010). No detailed published data are currently available. Results showed the technique has potential to locate permeable structures. At this location the technique was limited by the limited survey size.

Takara (Efate) has been investigated previously using surface based geoscientific methods, including geology, geochemistry and geophysics. A development is planned by Geodynamics to be progressed in two stages (4 MWe for 8 MWe in total).

4.20 Longonot (Kenya)

A CO_2 flux survey was undertaken at Longonot, Kenya (Alexander et al., 2011). No detailed published data are currently available.

Several detailed geoscientific studies have been undertaken at Longonot to determine the resource potential. AGIL is currently developing a large scale geothermal project at Longonot. The exploration permit allows for a plant capable generating 140 MWe or the maximum economically available (Alexander et al., 2011).

4.21 Indonesia

Two confidential CO_2 flux surveys have been undertaken at separate geothermal prospect areas in Indonesia. No published data are currently available.

4.22 Latera, Italy

Soil CO_2 flux at Latera Caldera is associated with an NE-SW band coinciding with a structural high of fractured Mesozoic limestones)(Chiodini, 2007). Thermal energy derived from CO_2 flux is 239MWth. Four geothermal wells drilled into the structural high are productive, which indicates a clear relationship between the geothermal reservoir and surface CO_2 flux.

Wells located to the west and east of the main production area are planned to serve as reinjection wells; these wells are all drilled in zones with no anomalous CO_2 flux has been found. The wells area hot but dry (no permeability)(Chiodini, 2007).

The Latera geothermal plant has an installed electrical capacity of 26 MWe, but does not currently operate for environmental reasons related to H_2S emission (Chiodini, 2007).

5. CONCLUSIONS

CO_2 flux survey results were compiled for a variety of geothermal systems throughout the World. Many survey's provided an estimate of heat flow based on CO_2 flux. In addition most surveys were able to verify the location of structures, and map the associated CO_2 emissions. In some studies (i.e. San Jacinto), new previously unidentified faults were identified on the basis of mapped CO_2 flux, and system boundaries were identified.

Perhaps most compelling evidence supporting the use of CO_2 flux for geothermal exploration is the overlap between the areas anomalous CO_2 flux and the productive steamfield (Latera, Krafla, Reykjanes, Ohaaki, Rotokawa and San Jacinto).

At Nisyros and Wairakei (Karapiti), the CO_2:H_2O ratio of the steam phase supplying the thermal area was estimated using CO_2 flux and shallow temperature gradient measurements, and found to be in good agreement with fumarole gas analysis. CO_2:H_2O ratio is an important component of resource evaluation, as geothermal reservoirs with high CO_2:H_2O are more prone to calcite scaling (bores and pipes)(Satman et al., 1999), and plant design may require additional gas extraction measures (Gunerhan, 1999).

At Krafla, the CO_2 emission from natural sources exceeds the emission from the power plant by approximately 3 times. This finding has relevance for developments that are subject carbon emission regulations; it would be prudent to quantify background CO_2 emissions (prior to fluid production), as part of an environmental baseline study. For example, a survey of geothermal plant CO_2 emissions reported a measurable decrease natural CO_2 flux (Lardarello field, Italy) as a result of geothermal power development (Bertani and Thain, 2002).

Measurement of CO_2 flux in geothermal prospects has proven to be a useful technique in the tool kit for the exploration geologist/geochemist during the early stages of geothermal exploration. The technique is relatively low cost (requires a single operator carrying a small back), and provides results in real time allowing for dynamic adaptation of the survey design in response to results. The surveys described in this study have provided useful results at large (>100km^2) and small scales (<0.1km^2).

Table 1: Compilation of Soil Diffuse CO_2 Flux Surveys in Prospect/Development Areas

Study Area	Project Status	CO_2 Flux Associated with Structure/Upflow	Heat Flow estimate based on CO2 flux (MWth)	NCG estimate based on CO_2 flux and Shallow Temp Gradient	Reference
Nisyros, Greece	Under evaluation	yes	58	yes	Bertani (2012), Chiodini et al. (2005)
Vesuvio, Italy	Previously evaluated c1980. One deep exploration well found low temperatures	yes	17	no	Carlino et al.(2012), Chiodini et al. (2005)
Pantelleria, Italy	Previously evaluated. One deep well found 260 °C at 1000m	yes	10 to 12	no	Granieri et al. (2012), Chiodini et al.(2005)
Hengil, Iceland	One of Iceland's largest high-temperature geothermal areas with two active geothermal power plants: Nesjavellir and Hellisheidi		1237	no	Hernández et al. (2012)
Ohaaki, New Zealand	116MWe geothermal power plant	yes	127	yes	Rissmann et al. (2012), Rissmann (2010)
Wairakei, New Zealand	181MWe geothermal power plant	yes	40	yes	Sepúlveda et al. (2012), Werner et al. (2004)
Rotorua, New Zealand	Protected with some direct use	yes	none	no	Werner et al., (2006)
Camp Fleigrei, Italy	Previously evaluated. 4 productive exploration wells with estimated potential >10MWe.		138	no	Granieri et al. (2012), Chiodini et al.(2001)
El Tizate, San Jacinto, Nicaragua	48 MWe geothermal power plant	yes	410	no	Harvey et al. (2012), Harvey et al. (2014)
Rotokawa, New Zealand	174MWe geothermal power plant	yes	317	no	Bloomberg et al. (2012)
Krafla, Iceland	60MWe geothermal power plant	yes	268	no	Dereinda, F. H. (2008), Harvey et al. (2014)
Ischia, Donna Rachele	Previously evaluated. Exploration well found 225C 1151m	yes	40	no	Carlino et al.(2012)
Reykjanes, Iceland	100MWe geothermal power plant	yes	130	no	Fridrikkson et al. (2006), Fridrikkson et al. (2010)
Ngatamaraiki, New Zealand	82MWe geothermal power plant	yes	Unknown	Unknown	Hanson (2013)
Platanares, Honduras	Exploration	no	Unknown	no	Barberi et al. (2013)
Azacualpa, Honduras	Exploration	no	Unknown	no	Barberi et al. (2013)
Berlin, El Salvador	109 MWe geothermal plant	no	Unknown	no	Renderos (2009)
Dixie Valley, USA	62 MWe geothermal plant	yes	Unknown	no	Bergfeld et al. (2001)
Vanuatu	Exploration	no	Unknown	no	Harvey and Alexander (2010)
Longonot, Kenya	Exploration	Confidential	Unknown	Confidential	Alexander and Ussher (2011)
Two Indonesian Prospects	Confidential	Confidential	Confidential	Confidential	Since 2010
Latera, Italy	24MWe geothermal plant	yes	239MWth	no	Chiodini et al., (2007)

REFERENCES

Alexander, K. B., Ussher, G., & Merz, S. K. (2011). Geothermal Resource Assessment for Mt. Longonot, Central Rift Valley, Kenya. *Geothermal Resources Council Transactions*, *35*, 1147-1154.

Barberi, F., Carapezza, M. L., Cioni, R., Lelli, M., Menichini, M., Ranaldi, M., & Tarchini, L. (2013). New geochemical investigations in Platanares and Azacualpa geothermal sites (Honduras). *Journal of Volcanology and Geothermal Research*, *257*, 113-134.

Bergfeld, D., Goff, F., & Janik, C. J. (2001). Elevated carbon dioxide flux at the Dixie Valley geothermal field, Nevada; relations between surface phenomena and the geothermal reservoir. *Chemical Geology*, *177*(1), 43-66.

Bertani, R. (2012). Geothermal power generation in the World 2005–2010 update report. *Geothermics*, *41*, 1-29.

Bertani, R., Thain, I. (2002). Geothermal power generating plant CO2 emission survey. IGA News 49, 1–3.

Bloomberg, S., Rissmann, C., Mazot, A., Oze, C., Horton, T., Gravley, D., Pawson, J. (2012). Soil gas flux exploration at the Rotokawa geothermal field and White Island, New Zealand. *PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering.*

Brombach, T., J. C. Hunziker, G. Chiodini, C. Cardellini, and L. Marini (2001), Soil diffuse degassing and thermal energy fluxes from the southern Lakki plain, Nisyros (Greece), *Geophys. Res. Lett., 28*, 69-72.

Carlino, S., Somma, R., Troise, C., & De Natale, G. (2012). The geothermal exploration of Campanian volcanoes: Historical review and future development. *Renewable and Sustainable Energy Reviews*, *16*(1), 1004-1030.

Chiodini, G., Cioni, R., Guidi, M., Raco, B., & Marini, L. (1998). Soil CO2 flux measurements in volcanic and geothermal areas. *Applied Geochemistry, 13*(5), 543-552.

Chiodini, G., Frondini, F., Cardellini, C., Granieri, D., Marini, L., & Ventura, G. (2001). CO2 degassing and energy release at Solfatara volcano, Campi Flegrei, Italy. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *106*(B8), 16213-16221.

Chiodini, G., R. Avino, T. Brombach, S. Caliro, C. Cardellini, S. De Vita, F. Frondini, D. Granirei, E. Marotta, and G. Ventura (2004), Fumarolic and diffuse soil degassing west of Mount Epomeo, Ischia, Italy, *J. Volcanol. Geotherm. Res., 133*, 291-309.

Chiodini, G., Granieri, D., Avino, R., Caliro, S., Costa, A., & Werner, C. (2005). Carbon dioxide diffuse degassing and estimation of heat release from volcanic and hydrothermal systems. *Journal of Geophysical Research: Solid Earth (1978–2012), 110*(B8).

Chiodini, G., Baldini, A., Barberi, F., Carapezza, M. L., Cardellini, C., Frondini, F.,& Ranaldi, M. (2007). Carbon dioxide degassing at Latera caldera (Italy): Evidence of geothermal reservoir and evaluation of its potential energy. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *112*(B12).

Dempsey, D., Simmons, S., Archer, R., & Rowland, J. (2012). Delineation of catchment zones of geothermal systems in large-scale rifted settings. *Journal of Geophysical Research: Solid Earth (1978–2012), 117*(B10)

Dereinda, F. H. (2008), CO2 Emissions from the Krafla Geothermal Area, Iceland. Dereinda, F. H. (2008), CO2 Emissions from the Krafla Geothermal Area, Iceland. United Nations University, Reports 2008, Number 15.

Dereinda, F.H and Ármannsson, H. (2010). CO2 Emissions from the Krafla Geothermal Area, Iceland. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010 (Ed. R Horne), 7 pp.

Fridriksson, T., B. R. Kristjánsson, H. Ármannsson, E. Margrétardóttir, S. Ólafsdóttir, and G. Chiodini (2006), CO2 emissions and heat flow through soil, fumaroles, and steam heated mud pools at the Reykjanes geothermal area, SW Iceland, *Appl. Geochem., 21*, 1551-1569

Fridriksson, T., Oladottir, A. A., Jonsson, P., Eyjolfsdottir, E. I., & Orkugardur, G. (2010). The response of the Reykjanes geothermal system to 100 MWe power production: fluid chemistry and surface activity. In *Proceedings of the World Geothermal Congress*.

Granieri, D., Chiodini, G., Avino, R., & Caliro, S. (2014). Carbon dioxide emission and heat release estimation for Pantelleria Island (Sicily, Italy). *Journal of Volcanology and Geothermal Research*, *275*, 22-33.

Gunerhan, G. G. (1999). An upstream reboiler design for removal of non-condensable gases from geothermal steam for Kizildere geothermal power plant, Turkey. *Geothermics*, *28*(6), 739-757.

Hanson, M, (2013) Identifying geothermal activity in low CO_2 flux geothermal systems. Abstract. Paper No. 387-13, GSA Annual meeting. 27-30 Oct 2013, Denver, Colorado, USA.

Harvey, M.; Alexander, K., (2011). Soil CO2 flux surveys for geothermal exploration; lessons learned. Geoscience Society of New Zealand Miscellaneous Publication 129: 123

Harvey, M.C., Rowland, J.V., Rissmann, C.F.W., Bloomberg, S., and Hernández, P.A. (2015). CO_2 Derived Heat Flux: a New Metric for the Evaluation of Geothermal System Prospectivity. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015 (Abstract Accepted).

Hernández, P. A., N. M. Pérez, T. Fridriksson, J. Egbert, E. Ilyinskaya, A. Thárhallsson, G. Ívarsson, G. Gíslason, I. Gunnarsson, and B. Jónsson (2012), Diffuse volcanic degassing and thermal energy release from Hengill volcanic system, Iceland, *Bulletin of volcanology, 74*, 2435-2448.

Hochstein, M. P., & Bromley, C. J. (2005). Measurement of heat flux from steaming ground. *Geothermics*, *34*(2), 131-158.

RAM (2014) 2013 year end results. http://ram-power.com/news-media/ram-power-announces-2013-year-end-results

Renderos, R. E. (2009). Carbon dioxide fixation by calcite and diffusive degassing in the southern region of the Berlín Geothermal system, El Salvador. Unived Nations University Geothermal Training Programme.

Rissmann, C. F. (2010). Using Surface Methods to Understand the Ohaaki Hydrothermal Field, New Zealand. PhD Thesis, University of Canterbury.

Rissmann, C., B. Christenson, C. Werner, M. Leybourne, J. Cole, and D. Gravley (2012), Surface heat flow and CO2 emissions within the Ohaaki hydrothermal field, Taupo Volcanic Zone, New Zealand*, Appl. Geochem., 27*, 223-239.

Satman, A., Ugur, Z., & Onur, M. (1999). The effect of calcite deposition on geothermal well inflow performance. *Geothermics*, *28*(3), 425-444.

Sepúlveda, F., Rosenberg, M. D., Rowland, J. V., & Simmons, S. F. (2012). Kriging predictions of drill-hole stratigraphy and temperature data from the Wairakei geothermal field, New Zealand: Implications for conceptual modeling. *Geothermics*, *42*, 13-31.

Truesdell, A.H., 1976: Summary of Section III. Geochemical Techniques in Exploration. Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, pp. 53–79.

Viveiros, F., Cardellini, C., Ferreira, T., Caliro, S., Chiodini, G., & Silva, C. (2010). Soil CO2 emissions at Furnas volcano, São Miguel Island, Azores archipelago: Volcano monitoring perspectives, geomorphologic studies, and land use planning application. *Journal of Geophysical Research: Solid Earth (1978–2012), 115*(B12).

Werner, C., Hochstein, M.P., and Bromley, C.J. (2004). CO2-flux of steaming ground at Karapiti, Wairakei. Proceedings 26th NZ Geothermal Workshop.

Werner, C., & Cardellini, C. (2006). Comparison of carbon dioxide emissions with fluid upflow, chemistry, and geologic structures at the Rotorua geothermal system, New Zealand. *Geothermics, 35*(3), 221-238.

White, D. 1986: Subsurface waters of different origins. In: Ólafsson, J. and Ólafsson, M. (editors) *Fifth International Symposium on Water-Rock Interaction. Extended abstracts.* International Association of Geochemistry and Cosmochemistry, Orkustofnun, Reykjavík, 629-632.