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DIFFUSE CO_2 DEGASSING THROUGH SOIL AND GEOTHERMAL EXPLORATION

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ABSTRACT

Measurements of the diffuse flow of CO2 through soil in geothermal fields can be useful for the purpose of delineating fractures or other structures that direct flow of fluids in the geothermal reservoir. These measurements are conveniently carried out with "closed-chamber CO_2 flux meters". Examples are given of the application of this method for siting geothermal wells in two geothermal systems in Iceland. Another example describes how this method can be used to constrain the minimum heat flow from a geothermal reservoir.

1. INTRODUCTION

CO_2 is the most common gas in geothermal fluids. The concentration of this gas in steam vents in geothermal fields commonly ranges from a few tenths of a percent to several percents, although condensation near the surface can result in even higher concentrations. The concentration of CO_2 in geothermal steam is positively correlated to the reservoir temperature and this correlation has been used to establish chemical geothermometers based on the CO_2 concentration in steam (c.f. D'Amore, and Panichi, 1980; Arnórsson and Gunnlaugsson, 1985). These and other gas geothermometers are among the most powerful tools that geochemists apply in geothermal exploration of high enthalpy resources. In recent years some attention has also been paid to measuring the diffuse flow of CO_2 through soil in geothermal fields for the purposes of geothermal exploration (e.g. Chiodini et al., 1998; Lopez et al., 2004; Magaña et al., 2004; Padrón et al., 2004; Fridriksson et al., 2006).

Several methods have been developed to assess CO_2 flux through soil. These include the closed chamber method, eddy covariance method and measurements of concentrations of soil gases. Each of these methods has certain strengths and certain weaknesses but the main advantage of the closed chamber method is simplicity and fast measurements, making it realistic to measure the flux at a few hundred points in one day if the terrain is accessible. The purpose of this paper is to give a short description of the closed chamber method for measurement of CO_2 flux through soil and give examples of applications of this method to geothermal studies.

2. THE CLOSED CHAMBER METHOD

The instrument used for closed chamber measurements of diffuse degassing through soil consists of five components; 1) an inverted circular chamber of known volume and transactional surface area,

2) an infrared (IR) spectrophotometer to measure CO_2 concentration, 3) plastic pipes and a pump that pumps air from the camber to the IR CO_2 detector, 4) an analog-digital (AD) converter, and 5) a palmtop or laptop computer. The chamber is placed, face down, on the ground and the air inside the chamber is pumped continuously in a closed loop, out of the chamber into the IR detector and returned to the chamber again. The concentration of the CO_2 inside the system is measured continuously and the recorded as a function of time by the controlling software. If gas is emitted from the soil its concentration will increase as a function of time. The software allows the user to determine the change of gas concentration within the system in units of ppm/s and taking into account the volume and transactional area of the chamber, as well as air pressure and temperature, the rate of concentration change can be used to compute the flux of gas through the soil in units such as $g/m^2/day$.

The CO_2-flux meters used by LaGeo and ISOR are manufactured by West Systems, Italy. These flux meters are equipped with a LICOR LI-820 single-path, dual wavelength, non-dispersive IR gas analysers. Figure 1 is a schematic diagram of a West Systems flux meter, and Figure 2 is a side view of a chamber. The internal volume of the flux meter is about $2.76\ 10^{-3} m^3$ and its transactional area of the chamber is about $3.1\ 10^{-2}\ m^2$.

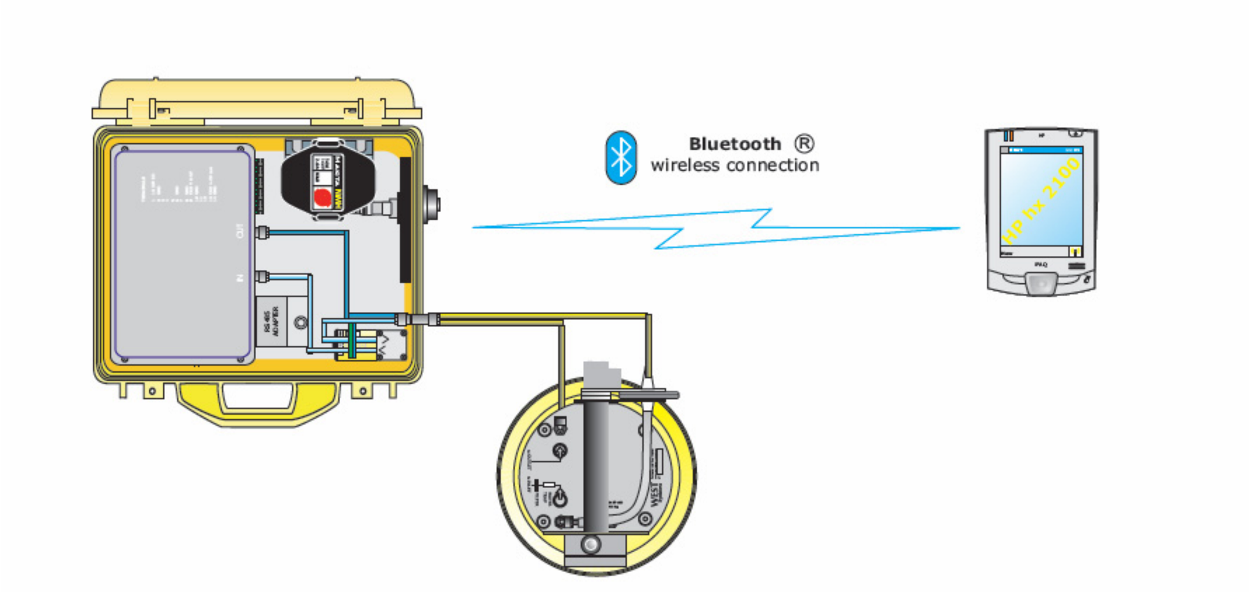

FIGURE 1: CO_2 flux meter from Westsystems (from www.westsystems.com/portable.html)

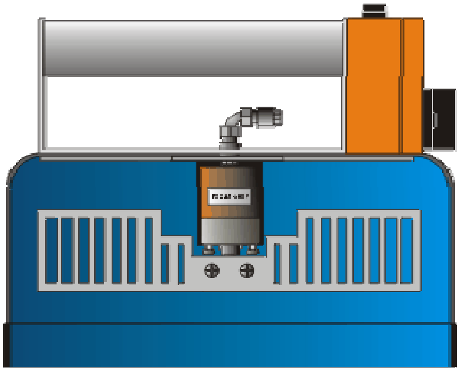

Figure 2: Measurement chamber (www.westsystems.com/portable.html)

The flux measurement is based on the rate of CO_2 increase in the chamber (Figure), the measurement is done for approximately 2 minutes at each location.

Figure 3 shows typical results of a CO_2-soil flux measurement. Initially the CO_2 concentration inside the cell is constant at about 400 to 900 ppm but after approximately 40 seconds the CO_2 concentration starts to increase linearly with time.

2.1 The procedure

The chamber (Figure) is pressed firmly against the ground and loose soil is packed (if necessary) around the outside. This is done to seal the measurement unit and prevent atmosphere from entering the system and affect the measurement. In this step is important not to remove the ground cover before the measurement is carried out. This may cause temporary high CO2 flow rate out of the soil. It is also important to note that if the CO2 flux measurements are to be reliable it is critical that they are only carried out in dry weather as rain water may saturate the soil pores and lead to unrealistically low flux values while the soil is wet and unrealistically high values immediately after it has dried out (Granieri et al., 2003). The CO_2 flux measurements are, therefore, only conducted in dry weather conditions that have prevailed preferably for 2 days.

Another limitation of this method is that it can only be used in areas where the surface material has a homogenous porosity on the scale of the chamber. In other words, this method will work well on organic soil, sand, and even snow but not on fresh lava fields.

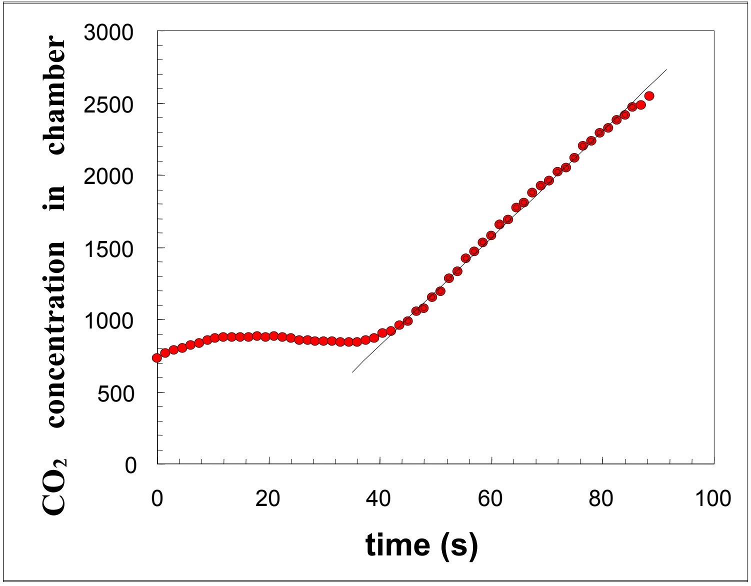

FIGURE 3: Raw data from a soil flux measurement. The slope of the linear part of the curve is a measure of the CO_2 flux through the soil.

The appropriate distance between measurement-points varies but the general rule of thumb is that at least three or four measurements are needed in order to define geothermal soil degassing anomalies. So if the width of the anomalies is of the order of 100 m the grid spacing can be of the order of 25 to 30 m between points. Flux measurements on a grid allow the construction of a diffuse soil degassing maps that have several applications, including great usefulness for geothermal exploration.

3. APPLICATIONS OF DIFFUSE CO_2 FLUX IN GEOTHERMAL STUDIES

The diffuse flux of CO_2 through the soil in geothermal fields can provide important information on the nature of the geothermal system. Open fractures, with respect to fluid flow, are the preferential pathways for CO_2 escaping from a boiling geothermal reservoir. If such a structure is buried in the subsurface it may be located based on mapping of a linear CO_2 flux anomaly on the surface. The total amount of CO_2 escaping from a given geothermal reservoir through the soil provides a possible constraint on the minimum heat output of the system. Furthermore, CO_2 flux studies have been shown to be valuable for environmental studies of geothermal systems. Changes in CO_2 flux have been used to quantify changes in surface activity due to power production (Fridriksson et al., 2010). And finally, it may be illustrative to compare the CO_2 emissions from geothermal power production with flash technology at a given geothermal system to the natural CO_2 emissions from that system. Examples of selected applications of CO_2 flux measurements in geothermal studies are given below.

It must be pointed out that although the examples provided in this paper are success stories they may not necessarily apply to all geothermal fields. Some geothermal systems may not have faults or other structures that connect the geothermal reservoir to the surface and in such a situation one would not expect CO_2 flux anomalies on the surface. Similarly, if a boiling geothermal reservoir is located under a high flow rate ground waters system the CO_2 transported with steam toward the surface may dissolve in the groundwater and be carried with it laterally away from the geothermal reservoir. This process would result in carbonated ground water.

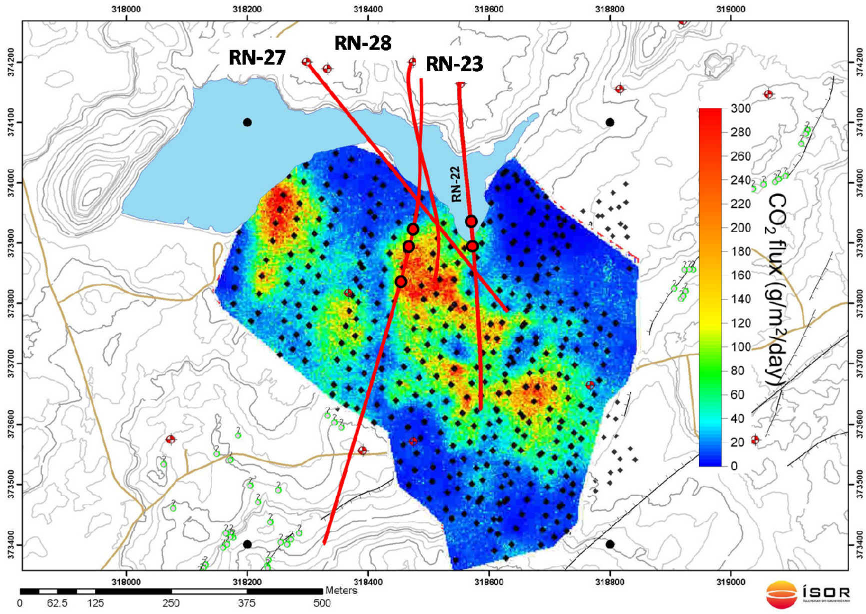

FIGURE 4: Soil diffuse CO_2 degassing anomalies and well tracks in the Reykjanes geothermal field. Major producing aquifers in wells RN-22 and RN-23 are indicated by large circular symbols

3.1 Identification of active fractures with CO_2 flux measurements

CO_2 soil flux has been measured in the Reykjanes and Krafla geothermal fields in Iceland (Fridriksson et al., 2006; Ármannsson et al., 2007). Figures 4 and 5 show the results of soil flux surveys in these areas. In both areas it is evident that the CO_2 soil flux anomalies are well defined and in both cases the shapes of the anomalies coincide with local tectonic directions. In Reykjanes, four wells have been drilled toward the most prominent CO_2 soil flux anomaly. The tracks of these wells are shown in Figure 4. The locations of major producing aquifers in wells RN-23 and RN-22 are indicated by circular symbols on the well tracks. Similarly, well KT-40 in Krafla (Figure 5) was directed towards the CO_2 soil flux anomaly to the southeast.

In both the Reykjanes and Krafla geothermal systems, the wells drilled towards the CO_2 soil flux anomalies are the best producers (in the case of Reykjanes) or among the most promising ones (KT-40 in Krafla) in their respective systems. Figure 6 shows the production curves for all wells that have been tested in Reykjanes in the last 5 years. It illustrates that 4 of the 5 best producers in the system are the four wells drilled into the soil flux anomaly shown in Figure 4. Similarly,

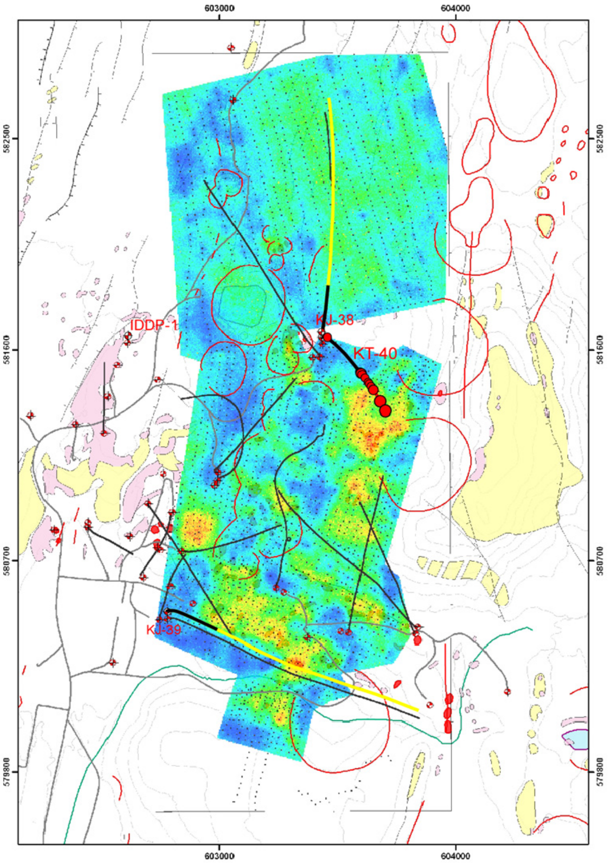

FIGURE 5: Soil diffuse CO_2 degassing anomalies and well tracks in the Krafla geothermal field. Major producing aquifers in well KT-40 are indicated by large circular symbols; see Figure 4 for colour scale

well KT-40 has the highest injectivity observed in any well in the Krafla system. The average injectivity of the last 9 wells drilled before KT-40 is 4.7 l/s/bar but the measured injectivity of KT-40 is 15 l/s/bar.

The good success of the wells drilled towards observed CO_2 soil flux anomalies in Reykjanes and Krafla illustrate that mapping of gas flux anomalies may provide very valuable information on the finer details of the structure of the geothermal systems. This information can be used to guide the directional drilling of production wells in order to maximize their productivity. As such, this method can be a useful tool for detailed exploration in systems that are already developed.

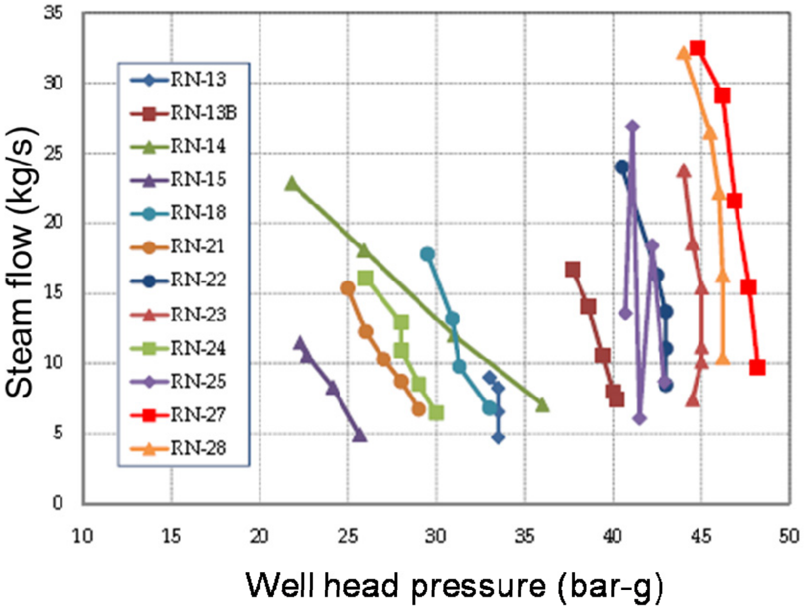

FIGURE 6: Production curves for production wells in the Reykjanes geothermal system, SW-Iceland. Wells RN-22, 23, 27 and 28 are directed towards the CO_2 gas flux anomaly shown on Figure 4

3.2 Constraints on heat flow

Diffuse CO_2 degassing has been used in several areas to place constraints on the minimum heat output from geothermal reservoirs (e.g. Chiodini et al., 2001; Fridriksson et al., 2006). This is based on the assumption that the CO_2 emitted at the surface was released from the geothermal reservoir with steam. In order to do this estimate it is necessary to measure the CO_2 flux over the whole geothermal field and assess the total CO_2 flux. Another critical parameter in this calculation is the CO_2/H_2O ratio in the original steam (or CO_2 concentration). In some cases this ratio can be measured directly in samples from wells and fumaroles but in other cases this may be estimated. In the worst case, the range of CO_2/H_2O ratios in steam from a given field may be estimated. It must be iterated that this will provide a minimum estimate of the total heat output because some of the CO_2 that leaves the reservoir with steam may not reach the surface as some fraction may dissolve in groundwater or precipitate as calcite above the geothermal system.

This method was used to quantify the total heat output from the Reykjanes system in Iceland (Fridriksson et al., 2006). They found that in 2004 the total CO_2 flux from the system was of the order of 13.5 ton/day. The concentration of CO_2 in primary steam in that system was taken to be equal to 3,200 mg/kg and as a result the estimated amount of H_2O in the steam was found to be 4200 ton/day which corresponds to about 130 MWt. The current 100 MWe power plant at Reykjanes, which has been in operation since 2006, extracts about ten times this amount of heat from the system. Although it does not provide a quantitative proof of the estimate of the natural heat flow it is interesting to note that the since the commissioning of the Reykjanes power plant in 2006 pressure has dropped dramatically in the system, or by about 35 bar in 3 years (Fridriksson et al., 2010). This observation is in qualitative agreement with the above, i.e. that the natural heat flow from the system is drastically smaller than the current level of production.

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