

## NEAR-SURFACE CO<sub>2</sub> MONITORING AND ANALYSIS TO DETECT HIDDEN GEOTHERMAL SYSTEMS

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### **ABSTRACT**

“Hidden” geothermal systems are systems devoid of obvious surface hydrothermal manifestations. Emissions of moderate-to-low solubility gases may be one of the primary near-surface signals from these systems. We investigate the potential for CO<sub>2</sub> detection and monitoring below and above ground in the near-surface environment as an approach to exploration targeting hidden geothermal systems. We focus on CO<sub>2</sub> because it is the dominant noncondensable gas species in most geothermal systems and has moderate solubility in water. We carried out numerical simulations of a CO<sub>2</sub> migration scenario to calculate the magnitude of expected fluxes and concentrations. Our results show that CO<sub>2</sub> concentrations can reach high levels in the shallow subsurface even for relatively low geothermal source CO<sub>2</sub> fluxes. However, once CO<sub>2</sub> seeps out of the ground into the atmospheric surface layer, winds are effective at dispersing CO<sub>2</sub> seepage. In natural ecological systems in the absence of geothermal gas emissions, near-surface CO<sub>2</sub> fluxes and concentrations are predominantly controlled by CO<sub>2</sub> uptake by photosynthesis, production by root respiration, microbial decomposition of soil/subsoil organic matter, groundwater degassing, and exchange with the atmosphere. Available technologies for monitoring CO<sub>2</sub> in the near-surface environment include the infrared gas analyzer, the accumulation chamber method, the eddy covariance method, hyperspectral imaging, and light detection and ranging.

To meet the challenge of detecting potentially small-magnitude geothermal CO<sub>2</sub> emissions within the natural background variability of CO<sub>2</sub>, we propose an approach that integrates available detection and monitoring techniques with statistical analysis and modeling strategies. The proposed monitoring plan initially focuses on rapid, economical, reliable measurements of CO<sub>2</sub> subsurface concentrations and surface fluxes and statistical analysis of the collected data. Based on this analysis, areas with a high

probability of containing geothermal CO<sub>2</sub> anomalies can be further sampled and analyzed using more expensive chemical and isotopic methods. Integrated analysis of all measurements will determine definitively if CO<sub>2</sub> derived from a deep geothermal source is present, and if so, the spatial extent of the anomaly. The suitability of further geophysical measurements, installation of deep wells, and geochemical analyses of deep fluids can then be determined based on the results of the near surface CO<sub>2</sub> monitoring program.

### **INTRODUCTION**

Worldwide, most commercial geothermal projects have been developed in or near areas of surface manifestations (e.g., hot springs, geysers, fumaroles). Also, the majority of hydrothermal systems with obvious surface expressions in the U.S. have been explored to determine their development potential. Discovery of new geothermal systems will therefore require exploration of areas where the resources are either hidden or lie at greater depths than presently known reservoirs. As a result, research must be geared toward the development of novel exploration techniques to locate these less-obvious geothermal systems.

We define “hidden” geothermal systems as those with no apparent surface features. Emissions of moderate-to-low solubility gases (e.g., CO<sub>2</sub>, He, CH<sub>4</sub>) may be one of the primary near-surface signals from these systems. Therefore, the detection of anomalous gas emissions related to hidden geothermal systems may be an important tool to discover new resources (Klusman et al., 2000). We focus our study on the detection and monitoring of CO<sub>2</sub> in the near-surface environment as an approach to discover hidden geothermal systems because (1) CO<sub>2</sub> is the major noncondensable gas present in geothermal systems (e.g., Ellis and Mahon, 1977), (2) due to its moderate solubility in water, CO<sub>2</sub> from volcanic-hydrothermal

*Table 1. Measured soil CO<sub>2</sub> fluxes and concentrations at selected locations.*

Site	Maximum CO <sub>2</sub> flux (g m <sup>-2</sup> d <sup>-1</sup> )	Average CO <sub>2</sub> flux (g m <sup>-2</sup> d <sup>-1</sup> )	Maximum soil CO <sub>2</sub> conc. (vol.%)	References
Solfatara crater, Italy	75,000	1520	na	Chiodini et al., 2001; Cardellini et al., 2003
Poggio dell'Ulivo cold degassing area, Italy	22,000	3911	na	Cardellini et al., 2003
Poas volcano, Costa Rica	140	na	16	Williams Jones et al., 2000
Arenal volcano, Costa Rica	291	na	7	Williams Jones et al., 2000
Masaya volcano, Nicaragua	50,000	na	na	Lewicki et al., 2003
Oldoinyo Lengai volcano, Tanzania	1350	166	90	Koepenick et al., 1996
Yellowstone volcanic system, USA	30,000	Travertine areas: 89 Acid sulfate areas: 1200	90	Werner et al., 2000
Dixie Valley Geothermal Field, USA	570	na	na	Bergfeld et al., 2001
Mammoth Mountain, USA	>10,000	1500-2100	90	Gerlach et al., 2001; Sorey et al., 1998
Miyakejima volcano, Japan	18,150	na	na	Hernandez et al., 2001

sources tends to migrate to the near-surface in the gaseous phase in equal or greater proportion than dissolved in groundwater (e.g., Cruz et al., 1999; Favara et al., 2001; Evans et al., 2002), and (3) a broad range of technologies are available to monitor CO<sub>2</sub> in the near-surface environment. Importantly, however, CO<sub>2</sub> is produced in the near surface by a variety of biological processes, and identifying CO<sub>2</sub> from hidden geothermal resources will involve monitoring a system with large variation in fluxes and concentrations arising from natural biologic and hydrologic processes. The detection of anomalous CO<sub>2</sub> will therefore require searching for potential geothermal anomalies, likely of small magnitude, over areas of tens of km<sup>2</sup> or more within the varying background CO<sub>2</sub> fluxes and concentrations. Here, we present integrated measurement, modeling, and analysis strategies to meet this challenge.

### CO<sub>2</sub> IN KNOWN VOLCANIC AND HYDROTHERMAL SYSTEMS

Numerous diffuse CO<sub>2</sub> degassing studies have been conducted in known (i.e., "visible") volcanic and hydrothermal environments, many of which focused on characterizing the magnitude and spatial distribution of CO<sub>2</sub> emissions. Table 1 summarizes the maximum (and average, if applicable) surface CO<sub>2</sub> fluxes and soil CO<sub>2</sub> concentrations measured in selected known systems. As shown, the maximum CO<sub>2</sub> fluxes and concentrations measured varied widely, but could reach up to ~75,000 g m<sup>-2</sup> d<sup>-1</sup> and 90 vol.%, respectively. Both elevated CO<sub>2</sub> fluxes and concentrations were commonly associated with faults, fractures, eruptive fissures, and vents in the study areas. While surface CO<sub>2</sub> emission rates from hidden geothermal systems will likely be lower than

those measured in known volcanic and hydrothermal systems, the preferential pathways for CO<sub>2</sub> flow from depth to the near surface will probably be similar.

### SIMULATIONS OF GEOTHERMAL CO<sub>2</sub> MIGRATION

We conducted numerical simulations to evaluate the magnitudes and spatial distribution of anomalous near-surface CO<sub>2</sub> concentrations and fluxes that might result when CO<sub>2</sub> leaks from a hidden geothermal system at depth. Based on this information, we can then design and evaluate potential monitoring and detection methods.

We use the numerical code T2CA (Oldenburg and Unger, 2004), a research module of TOUGH2 (Pruess et al., 1999). T2CA retains the fundamental porous media flow and transport capabilities of TOUGH2, and models five components (water, brine, CO<sub>2</sub>, a gas tracer, and air) under isothermal or non-isothermal conditions. The main advance in T2CA is the implementation of a simple atmospheric transport and dispersion capability for dilute gases based on the variable-K theory (Arya, 1999). That is, a constant time-averaged logarithmic wind velocity profile is specified for advection, and atmospheric dispersion is modeled as a diffusion process with variable diffusivity as a function of height above the ground surface. In this way, T2CA models coupled subsurface and atmospheric surface layer gas flow and transport.

The geologic framework of the modelled hidden geothermal system is based loosely on an arid Basin and Range Province system like the Dixie Valley (Nevada) geothermal system, only without any surface manifestations. In particular, we consider a

two-dimensional system in which an alluvial fan covers a geothermal anomaly associated with deep range-bounding faults so that it is essentially invisible at the surface (Figure 1). Within this system, we model the upward migration of CO<sub>2</sub> from a small (15 m<sup>2</sup>) region that represents the top of a conductive fault, located near the water table, ~300 m in the horizontal direction from the left boundary. The CO<sub>2</sub> spreads in the heterogeneous system (i.e., the alluvial fan) as it migrates upward until it seeps out at the ground surface. We consider both a homogeneous permeability case, along with five realizations of heterogeneous permeability. The heterogeneous permeability cases are significant because gas migration will tend to follow high-permeability pathways. Here, permeability is characterized by a mean value of 10<sup>-12</sup> m<sup>2</sup>, and varies by four orders of magnitude. There is a 45-m correlation length in the Y-direction (sub-horizontal), and no correlation in the vertical direction, thereby creating a layered structure intended to represent an alluvial fan. We simulated source strength CO<sub>2</sub> fluxes of 5.76, 57.6 and 576 g m<sup>-2</sup> d<sup>-1</sup>. These fluxes were arbitrarily chosen to produce small CO<sub>2</sub> seepage fluxes, and are significantly lower than those measured in known/visible volcanic and hydrothermal systems (e.g., Table 1). We chose to model this low range of values to test the limits of available technologies for near-surface CO<sub>2</sub> detection. For reference, the largest source CO<sub>2</sub> flux we consider is similar to the highest surface CO<sub>2</sub> fluxes measured at Dixie Valley (Table 1). We present results for 200 years of simulation, at which point the gas seepage flux and concentrations are nearly steady.

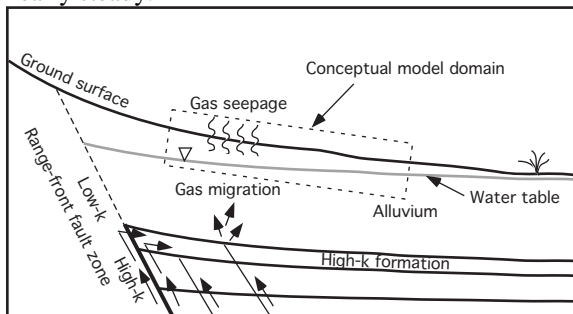


Figure 1. Conceptual model for gas migration from a deep hidden geothermal system. Also shown is the outline (dashed) of the two-dimensional model domain (see Figure 2).

To emphasize the key simulation results relevant to design of a near-surface CO<sub>2</sub> monitoring program, we present coupled CO<sub>2</sub> subsurface migration and surface-layer mixing for one of our five heterogeneous permeability realizations, high source CO<sub>2</sub> flux, and constant wind speeds of 1 and 3 m s<sup>-1</sup> (Figure 2). Figure 2 shows that the gas in the CO<sub>2</sub> plume is essentially pure CO<sub>2</sub> in the subsurface, even though the source CO<sub>2</sub> flux is quite small. Importantly, surface-layer winds are capable of

diluting CO<sub>2</sub> concentrations to very small values above the ground surface. For example, surface-layer CO<sub>2</sub> concentrations only reach maximum values of ~10<sup>-7</sup> mole fraction (0.1 ppmv) for both wind speeds considered. Overall, the high simulated CO<sub>2</sub> concentrations observed at the ground surface and in the subsurface, relative to the atmospheric surface layer, suggest that monitoring of CO<sub>2</sub> in the subsurface or at the ground surface may have greater potential to detect anomalous CO<sub>2</sub> of geothermal origin than above-ground techniques.

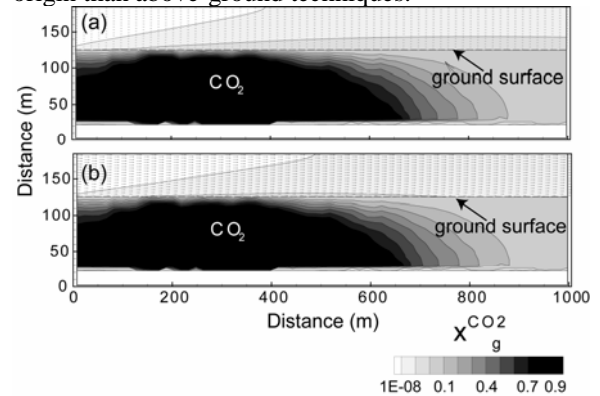


Figure 2. Coupled CO<sub>2</sub> subsurface migration and surface-layer mixing at  $t = 200$  years for one heterogeneous permeability realization, high source CO<sub>2</sub> flux (576 g m<sup>-2</sup> d<sup>-1</sup>), and constant wind speeds of (a) 1 m s<sup>-1</sup> and (b) 3 m s<sup>-1</sup>. CO<sub>2</sub> concentration is in mole fraction.

Figure 3 shows horizontal profiles of CO<sub>2</sub> concentration at 3 m depth and surface CO<sub>2</sub> flux for the low, medium, and high source CO<sub>2</sub> flux and one heterogeneous permeability realization. These profiles all show a similar increase and then decrease in concentration and flux crossing the CO<sub>2</sub> plume. Maximum CO<sub>2</sub> concentrations for the low, medium, and high source strengths are about 2 x 10<sup>-4</sup>, 2 x 10<sup>-5</sup> and 7 x 10<sup>-5</sup> ppmv, respectively, whereas maximum surface CO<sub>2</sub> fluxes are about 4 x 10<sup>-4</sup>, 0.52, and 100 g m<sup>-2</sup> d<sup>-1</sup>, respectively. These profiles also show that the width of the CO<sub>2</sub> plume increases with increasing source strength. If the source area of CO<sub>2</sub> emission were increased (i.e., to simulate more diffuse, rather than focused CO<sub>2</sub> flow), the magnitude of the near-surface CO<sub>2</sub> concentration and flux signals would decrease, while the width of the anomaly would increase. Relative to the homogeneous permeability cases (not shown here), fluxes along the heterogeneous profiles are more spatially variable and maximum observed fluxes may be greater or lower, depending whether high or low permeability was assumed, respectively. Complete results for the five heterogeneous permeability realizations, homogeneous permeability, and three source CO<sub>2</sub> flux values can be found in Lewicki and Oldenburg (2004).

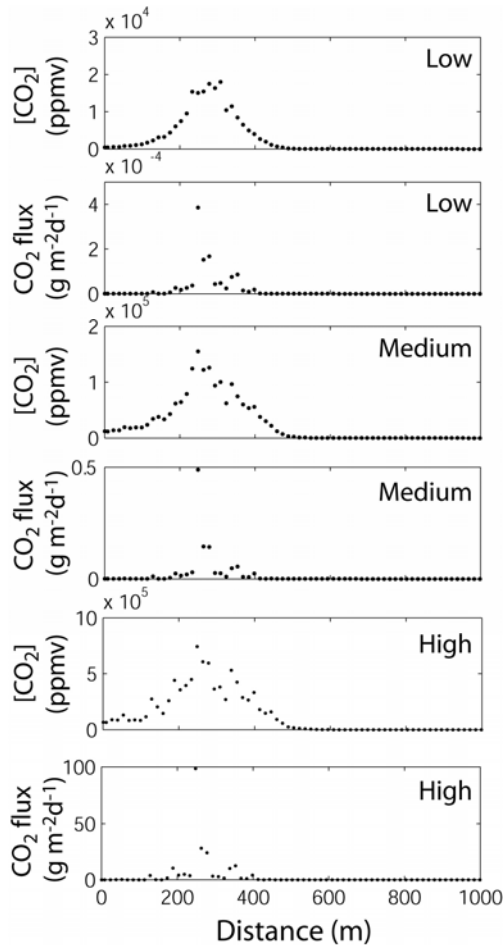


Figure 3. Horizontal profiles of shallow subsurface  $CO_2$  concentration ( $[CO_2]$ , 3 m depth) and surface  $CO_2$  flux for low, medium, and high (5.76, 57.6, and 576  $g\ m^{-2}\ d^{-1}$ , respectively)  $CO_2$  source flux, one heterogeneous permeability realization, and  $t = 200$  years.

### **BACKGROUND $CO_2$**

We define “background”  $CO_2$  as  $CO_2$  derived mainly from the atmosphere and biologically mediated oxidation of organic carbon. Background soil  $CO_2$  fluxes and concentrations are primarily dependent on  $CO_2$  production in the soil by biological processes, flow of  $CO_2$  from biologic/hydrologic sub-soil sources into the soil column, and exchange of  $CO_2$  with the atmosphere by concentration and pressure-driven transport processes (diffusion and advection, respectively).

Biologically produced  $CO_2$  in soils (i.e., soil respiration) is derived from root respiration and oxidative decay of organic matter. While many factors may regulate soil respiration rates, changes in atmospheric and soil temperature and soil moisture

have been shown to strongly influence these rates and related  $CO_2$  concentrations and fluxes.  $CO_2$  that enters soil from sub-soil sources can be derived from groundwater degassing of  $CO_2$  derived from respiration, atmospheric, and carbonate mineral sources. Also, production of  $CO_2$  at sub-soil depths can occur by oxidative decay of relatively young or ancient (peat, lignite, kerogen) organic matter in the vadose zone. Exchange of  $CO_2$  from subsurface sources with the atmosphere can occur by diffusion and/or advection. Diffusive flow depends on the gas production rate and soil temperature, moisture, and properties such as porosity. Advective flow can be driven by changes in atmospheric temperature, pressure, wind, and rainfall.

The chemical and isotopic compositions of gases collected at soil and sub-soil depths provides information on  $CO_2$  production and the source of this  $CO_2$  (Table 2).  $CO_2$  concentration profiles measured with depth in the vadose zone can yield information about  $CO_2$  production. For example, an increase in  $CO_2$  concentration with depth below the soil indicates  $CO_2$  production at sub-soil depths. Production of  $CO_2$  by oxidative decay of organic matter tends to consume  $O_2$  at a similar rate. Also, atmospheric  $O_2$  will diffuse down into the soil and sub-soil as sub-surface  $CO_2$  diffuses to the atmosphere. A flux of geothermal  $CO_2$  would produce elevated  $CO_2$  concentration at depth, relative to the atmosphere, but would not be accompanied by  $O_2$  consumption, although atmospheric  $O_2$  would diffuse down into the soil. Based on these general processes, the  $CO_2$  and  $O_2$  concentration profiles should be different, depending on whether a geothermal flux is present. One might expect groundwater degassing of respiration and atmospheric-derived  $CO_2$  to show similar chemical trends within the vadose zone to degassing of geothermal  $CO_2$ . However, vadose zone  $CO_2$  concentrations produced by groundwater degassing and biological respiration processes have generally been reported to be less than 13 vol.%  $CO_2$  (e.g., Wood and Petraitis, 1984; Amundson and Davidson, 1990; Wood et al., 1993), whereas near-surface  $CO_2$  concentrations associated with geothermal emissions could be much higher. For example, simulated geothermal source  $CO_2$  fluxes of 57.6 to 576  $g\ m^{-2}\ d^{-1}$  produce maximum near-surface  $CO_2$  concentrations of ~20–70 vol.% ( $2 \times 10^5$  to  $7 \times 10^5$  ppmv, Figure 2). Importantly, however, the maximum near-surface  $CO_2$  concentration produced by a source  $CO_2$  flux of 5.76  $g\ m^{-2}\ d^{-1}$  is only predicted to be ~2 vol.% ( $2 \times 10^4$  ppmv, Figure 2), which could be problematic to distinguish from background  $CO_2$  concentrations. Table 2 also shows that the ranges of typical carbon isotopic compositions of geothermal  $CO_2$  are distinct from

Table 2. Chemical and isotopic signatures related to  $CO_2$  derived from different sources.

CO <sub>2</sub> source	$\delta^{13}\text{C}_{\text{CO}_2}$ (‰)	$\Delta^{14}\text{C}_{\text{CO}_2}$ (‰)	Near-surface CO <sub>2</sub> conc.	CO <sub>2</sub> conc. profile with depth	O <sub>2</sub> conc. profile with depth
Atmosphere	-7	70	Low	na	na
Plant root respiration and oxidative decay of young soil organic matter	C <sub>3</sub> : -24 to -38 C <sub>4</sub> : -6 to -19	≥70	Low to moderate	Increasing through soil zone	Decreasing through soil zone
Oxidative decay of ancient organic matter	C <sub>3</sub> : -24 to -38 Aquatic/C <sub>4</sub> : -6 to -19	Highly depleted to absent, depending on age	Low	Potentially increasing through vadose zone	Potentially decreasing through vadose zone
Marine carbonate rocks	Also age dependent 0 ± 4	Absent	Low	Increasing through vadose zone	No effect
Geothermal	-2 to -6	Absent	Moderate to high	Increasing through vadose zone	No effect

Conc., C<sub>3</sub>, and C<sub>4</sub>, refer to concentration, C<sub>3</sub> plants, and C<sub>4</sub> plants, respectively. All near-surface concentrations given are general estimates; they are strongly dependent on the magnitude of the CO<sub>2</sub> flux.

those whose dominant sources are background biological CO<sub>2</sub>. Therefore, analysis of the  $\Delta^{14}\text{C}$  and  $\delta^{13}\text{C}$  compositions of gases collected from the soil and, in particular, from the sub-soil where biologic CO<sub>2</sub> production rates are low can serve as a tool to distinguish CO<sub>2</sub> of geothermal from background origin.

### **INSTRUMENTATION FOR MONITORING CO<sub>2</sub>**

A broad range of technologies is available to measure near-surface CO<sub>2</sub> concentrations and fluxes to detect anomalous CO<sub>2</sub> of geothermal origin. These technologies include (1) the infrared gas analyzer (IRGA) for measurement of concentrations at point locations, (2) the accumulation chamber (AC) method for measuring soil CO<sub>2</sub> fluxes at point locations, (3) the eddy covariance (EC) method for measuring net CO<sub>2</sub> flux over a given area, (4) hyperspectral imaging of vegetative stress resulting from elevated CO<sub>2</sub> concentrations, and (5) light detection and ranging (LIDAR) that can measure CO<sub>2</sub> concentrations over an integrated path in the air column. These techniques differ from one another in terms of the spatial and temporal scale of the measurement, measurement sensitivity and error, and cost. Here, we focus on the relatively low-cost and reliable IRGA, AC, and EC methods for CO<sub>2</sub> concentration and flux measurements.

#### **Infrared Gas Analyzer**

The infrared gas analyzer (IRGA) is an instrument commonly used to measure CO<sub>2</sub> concentration in subsurface or atmospheric air. The measurement is based on CO<sub>2</sub> absorption of infrared radiation within a sample gas cell. Portable IRGAs are available for use in the field and can make single or continuous measurements over time, which may be made within

about one second to minutes, depending on the instrument. IRGAs are available to measure CO<sub>2</sub> concentration over a low range (e.g., 0-1000 ppmv) or over a high range (e.g., 0-100 vol.%). The precision and accuracy can be as good as ± 0.2 ppmv at 350 ppmv and ± 1%, respectively. The cost of equipment may range from \$500 to \$30,000.

Soil or subsoil gas CO<sub>2</sub> concentrations can be rapidly measured at many point locations within a large area using a probe and a portable IRGA. Using this method, a probe is driven down to the depth of interest, gas is pumped from the soil into the IRGA by an internal pump, and CO<sub>2</sub> concentration is measured.

#### **Accumulation Chamber Method**

IRGAs may be coupled with additional instrumentation to obtain surface CO<sub>2</sub> fluxes. For example, the accumulation chamber (AC) method (e.g., Chiodini et al., 1998) is used to measure soil CO<sub>2</sub> flux using an AC and an IRGA. An AC with an open bottom (cm<sup>2</sup> scale) is placed on the soil surface, the contained air is circulated through the AC and the IRGA, and the rate of change of CO<sub>2</sub> concentration in the AC is measured by the IRGA (Figure 4). The CO<sub>2</sub> flux is then calculated as proportional to the rate of change. The accuracy of the AC method was estimated to be -12.5 % due to alteration of gas flow by the AC (Evans et al., 2002); precision is ± 10 % (Chiodini et al., 1998). Each AC measurement is typically made within several minutes by one person, allowing for many measurements to be made over relatively short periods of time under variable terrain conditions. The cost of the portable AC instrumentation typically ranges from \$15,000 to \$25,000.

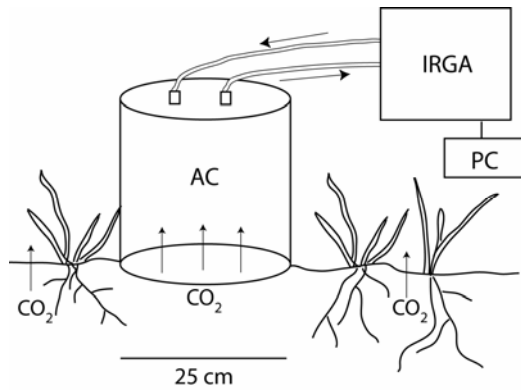


Figure 4. Schematic diagram of an accumulation chamber (AC) measurement system of soil CO<sub>2</sub> flux. The air contained in the AC is circulated through the AC and the infrared gas analyzer (IRGA) and the rate of change of CO<sub>2</sub> concentration in the AC is measured by the IRGA and recorded by the computer (PC).

### Eddy Covariance

Eddy covariance (EC) (Baldocchi, 2003 and references therein) is a technique whereby high-frequency measurements of atmospheric CO<sub>2</sub> concentration at a fixed height above ground are made by an IRGA, along with micrometeorological variables such as wind velocity, temperature, and relative humidity (Figure 5). Integration of these measurements provides a gross conservation of energy and mass over an area of land (the EC footprint) from which the net CO<sub>2</sub> flux is derived. The method essentially involves time averaging the product of the time series of fluctuating CO<sub>2</sub> concentration and vertical wind velocity. Under steady-state conditions and for sufficiently long averaging time, this converges to the ensemble mean flux. The measured vertical CO<sub>2</sub> flux is an integral of the surface flux over the upwind footprint (typically m<sup>2</sup> to km<sup>2</sup>), the size of which scales with the measurement height, and is also dependent on meteorological conditions. One advantage of EC is that it provides a spatially and temporally averaged measurement, potentially providing more representative flux data and allowing for more efficient monitoring strategies than point measurements can provide. A limitation of the EC method is that it assumes a horizontal and homogeneous surface, and violations of this assumption can introduce significant error into the measurement. However, under acceptable terrain and meteorological conditions, estimates of daytime and nighttime error are generally less than 7 and 12%, respectively (e.g., Moore, 1986; Soegaard et al., 2000; Berger et al., 2001). The cost of EC equipment ranges from ~\$15,000 to \$40,000.

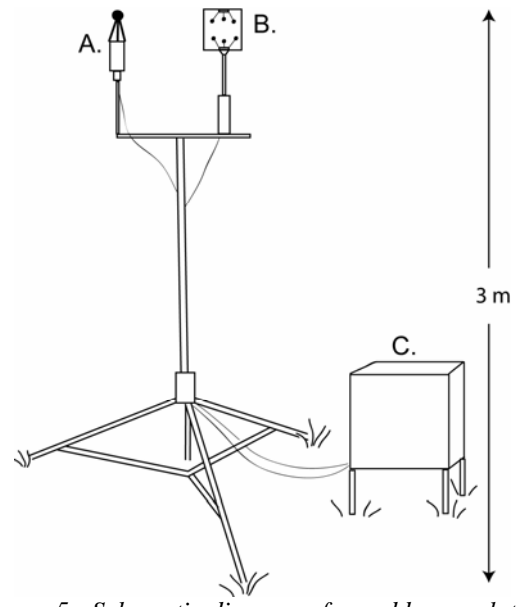


Figure 5. Schematic diagram of an eddy correlation (EC) instrumentation tower to measure surface CO<sub>2</sub> flux. An (A) open-path IRGA, (B) high frequency response sonic anemometer, and (C) box containing power source and datalogger/PC are shown.

### STRATEGIES FOR DETECTION OF GEOTHERMAL CO<sub>2</sub>

To meet the challenge of detecting potentially small-magnitude geothermal CO<sub>2</sub> emissions within the natural background variability of CO<sub>2</sub>, we propose an approach that integrates available detection and monitoring techniques with statistical analysis and modeling strategies. Overall, we advocate a monitoring strategy that initially focuses on rapid, economical, reliable measurements of CO<sub>2</sub> concentrations in the soil and potentially in pre-existing wells/gradient holes within the study area, and surface CO<sub>2</sub> fluxes using the AC method ± EC. Our objective is to minimize the number of these measurements and then focus more time- and cost-intensive methods on “high-probability” anomalies of geothermal origin.

Even small geothermal source CO<sub>2</sub> fluxes are expected to produce high CO<sub>2</sub> concentrations within the vadose zone. As a result, if wells/gradient holes already exist within the area targeted for geothermal exploration, they should be sampled for CO<sub>2</sub> concentration (and additional chemical and isotopic analyses if CO<sub>2</sub> levels are high). Point measurements of soil CO<sub>2</sub> fluxes and concentrations should also be made along grids using the AC method and a portable IRGA, respectively. If the study area satisfies the terrain and vegetation distribution requirements of the EC technique, it should be used to measure net

surface fluxes. Particular attention should be paid to characterizing gas flow along high-permeability pathways, such as faults/fractures. Importantly, the spatial and temporal variability of soil CO<sub>2</sub> fluxes and concentrations should also be quantified within a background area with similar geologic, climatic, and ecosystem characteristics to the area targeted for geothermal exploration. Bayesian statistical analysis of CO<sub>2</sub> concentration and flux measurements in both the area targeted for geothermal exploration and the background study area should be used to identify the presence (or absence) of CO<sub>2</sub> anomalies with high statistical confidence, and estimate the number of measurements required to do this (e.g., Bayes, 1763; Lewicki and Oldenburg, 2004). Also, geostatistical methods should be used to map the spatial distribution of soil CO<sub>2</sub> concentrations and fluxes, and these parameters' autocorrelation and cross-correlation coefficients. These maps can be used to discern spatial patterns that may be indicative of geothermal CO<sub>2</sub> emissions and estimate total CO<sub>2</sub> emission rates from the study areas (e.g., Lewicki et al., in press).

Once CO<sub>2</sub> concentrations and fluxes have been determined with high confidence to be of geothermal origin, more expensive sampling of gas profiles with depth through the vadose zone, and chemical and isotopic analyses could be undertaken. In particular, an increase in CO<sub>2</sub> concentration with depth would indicate deep CO<sub>2</sub> emissions. Also, the carbon-13 and carbon-14 values of subsurface CO<sub>2</sub> should distinguish CO<sub>2</sub> of geothermal from background origin (Table 2). Integrated analysis of all measurements will determine definitively if CO<sub>2</sub> derived from a deep geothermal source is present, and if so, the spatial extent of the anomaly.

## **CONCLUSIONS**

The properties of CO<sub>2</sub>, methods for detection and monitoring of this gas, and the ranges of natural background CO<sub>2</sub> fluxes and concentrations are generally well known. We are able to gain some insight into near-surface CO<sub>2</sub> concentrations and fluxes resulting from CO<sub>2</sub> migration and seepage from hidden geothermal reservoirs using numerical simulation. Nevertheless, detecting small anomalous geothermal CO<sub>2</sub> fluxes and concentrations within natural background CO<sub>2</sub> variations poses a challenge. The exploration strategy that we propose to find geothermal CO<sub>2</sub> involves integrated measurement and statistical analysis to understand the natural background system. Once this understanding is achieved, integrated measurement, modeling, and sampling technologies can be applied toward the characterization of CO<sub>2</sub> within the study area targeted for exploration. If CO<sub>2</sub> concentrations and fluxes are suggestive of the presence of CO<sub>2</sub> derived from a geothermal source, the area should be investigated

further by more cost- and time-intensive vertical profile sampling and isotopic analyses. Integrated analysis of all measured data will determine definitively if CO<sub>2</sub> derived from a deep geothermal source is present, and if so, the spatial extent of the anomaly. The appropriateness of further geophysical measurements, installation of deep wells, and geochemical analyses of deep fluids can then be decided based on the results of the near surface CO<sub>2</sub> monitoring program.

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