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Gases and emanations at the geosphere-atmosphere interface and their relevance for geothermal system analysis

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ABSTRACT

The composition of soil gas and degassing rates at Earth's surface provide insights into the characteristics of volcanic-geothermal systems and represent an image of processes at depth and on its way to the surface. The different techniques of soil gas measurements are useful both for fundamental and applied research, such as fault zone analysis, geothermal exploration, hazard assessment and monitoring.

Based on area-wide field surveys in different geothermal settings we aim to develop a geothermal gas fingerprint with focus on overall soil gas composition and spatial variability. This requires the compilation of a substantial and representative database. We will to introduce our concept for a comprehensive, area-wide and systematic understanding of gases and emanations at the geosphere-atmosphere interface taking the entire geothermal system into consideration. Only a systematic approach will pave the way for a holistic system characterization, allowing the transferability of results to a spatial dimension for further correlation with data from other scientific disciplines (e.g., geophysics, structural geology, remote sensing). Therefore, key parameters, sampling techniques, data processing and interpretation, and the necessity of interdisciplinary approaches will be described.

1. INTRODUCTION

Soil gas surveys determine gas fluxes and soil gas concentrations at the interface from geosphere to atmosphere. Gases in volcanic soils can be of different origins, e.g., magma degassing, radiogenic production in the crust, alteration of rocks, or biological activity. Several processes dominate the final concentration of these gases (e.g., mixing, contamination, chemical reactions, solubility in groundwater, etc.). The transport of gases within the geosphere is influenced by the source of the gas and the existence of preferential pathways for degassing or zones of increased permeability. Gas emissions at the surface of volcanic-geothermal areas are governed by diffusive and advective mechanisms. Diffusion is described by Fick's law, whereas advection is described by Darcy's law. On the other hand, the mechanism of advective transport linked to changes of temperature (i.e., transport of gases in geothermal areas) is defined as convective transport. The transport of gases in a geological environment is a combination of both processes.

Degassing processes are only visible to some extent as active surface manifestations, e.g., steaming ground, fumaroles, bubbling hot springs and mud pools, whereas a large contribution is based on invisible diffuse degassing processes. The analysis of soil degassing has been of interest for monitoring volcanic activity already for a long time (Baubron et al., 1990; Allard et al., 1991; Chiodini et al., 1996; Gerlach et al., 2001; Salazar et al., 2001; Hernández et al., 2001a and b, 2003, 2006, 2012, 2017; Padrón et al., 2003, 2012; Burton et al., 2013; Pérez et al., 2013). Most common gas is CO_2, accompanied by other rare gases, e.g., He, H_2, and ^{222}Rn (Allard, 1992). Considering the two types of volcanic gas release (visible and non-visible), Notsu et al. (2006) proposed a five-stage evolutionary model for the release of volcanic gases. According to this model, diffuse degassing begins to increase already as soon as magma rises into the shallow subsurface - still before plume degassing shows obvious signs of volcanic reactivation.

Our motivation is to gain a comprehensive regional understanding of gases and emanations in the uppermost soil atmosphere affected by the deep subsurface. Soil gas composition and gas flux often represents an image of what is happening at depth and on its way to the surface. Such information are useful in fundamental and applied research, e.g., fault zone analysis, volcanic-geothermal system analysis, and monitoring. We focus on the development of a geothermal fingerprint analysis for exploration, based on gas signatures at the surface. Our goal is to develop a systematic approach to understand the origin of detected anomalies, which will enable a holistic system characterization by trend analyses, classifications, and other statistical methods. In a second step, this concept will be transferred to a spatial dimension. Most important is the identification of key parameter and methods. Therefore, multiple case studies are necessary in different geothermal systems. Only a comprehensive database from various geothermal systems will enable the development of transferable and system-specific exploration approaches.

1.1 Soil gas analysis

Since the early 1980s, analyses of gas transfer processes at the soil-air interface of volcanic systems became more important (Reimer et al., 1979; McCarthy and Reimer, 1986; Hinkle, 1994; Sorey et al., 1998; Salazar et al., 2001). Soil gas surveys have been used extensively for different purposes, e.g., study of seismically active faults (e.g., Reimer, 1980, 1985), detection of buried mineral deposits (McCarthy and Reimer, 1986), detection of structures with enhanced permeability for deep gas migration and preferential pathways for degassing in volcanic systems (Hernández et al., 2004; Padrón et al., 2012; 2013), or volcanic monitoring (Arpa et al., 2013; Padrón et al., 2013b). Soil gas surveys have become a powerful tool in geothermal exploration (Bertrami et al., 1990; Finlayson 1992; Voltattorni et al., 2010). Many diffuse degassing studies have revealed that mapping relative soil gas enrichments and fluxes can help to detect permeability structures such as major fault zones (Fridriksson et al., 2006; Chiodini et al., 2007; Hernández et al., 2012; Barberi et al., 2013; Padilla et al., 2013; Hanson et al., 2014; Jolie et al., 2015, 2016; Padrón et al., 2015).

Nowadays, different sampling techniques, installations and analytical methods exist. Depending on the objective of the investigation, different techniques should be considered. In the last decades, the development of theoretical models and analytical instrumentation for soil gas measurements have contributed greatly to provide multi-disciplinary monitoring techniques, both as portable systems and permanent stations for continuous measuring. Soil gas sampling is a cost-effective and easy-to-use sampling technique. Usually, surface flux measurements are performed by flux chambers (Parkinson, 1981; Chiodini et al., 1998). Several flux chambers and portable fluxmeters have been designed in the last years. Different volatile compounds can be measured by surface flux instrumentation (i.e., CO_2, H_2S, SO_2, CH_4, NOx, etc.). On the other hand, soil gas samples are usually collected at different depths with the aim to study the spatial variation of concentrations in soils. Hinkle (1994) studied the optimum sampling depth to avoid major atmospheric/meteorological effects. It was also concluded that measured soil gas concentrations at one site are comparable within a few days without large changes of atmospheric conditions. The two most common techniques for soil gas analysis are gas chromatography and mass spectrometry (McCarthy and Reimer, 1986).

1.2 Range of application

Soil gas measurements are performed in different scientific disciplines for a wide range of applications. The main fields of application are fundamental research (volcanology, structural geology, climatology), monitoring (volcano, geothermal well integrity, environment, mining), hazard analysis (volcanic, hydrothermal eruptions, natural radionuclides) and geological exploration (mineral prospection, geothermal system analysis).

Quantitative and area-wide analysis of degassing processes at Earth's surface helps to discriminate and categorize areas with high and low gas flux/soil gas concentrations. Areas of increased degassing can be indicative for degassing processes from magmatic intrusions (Hernández et al., 2012). In general, soil gas anomalies indicate permeable sectors, where fluids from deep sources find its way to the surface (geothermal upflow). Such zones are key target areas for geothermal production wells (Fig. 1).

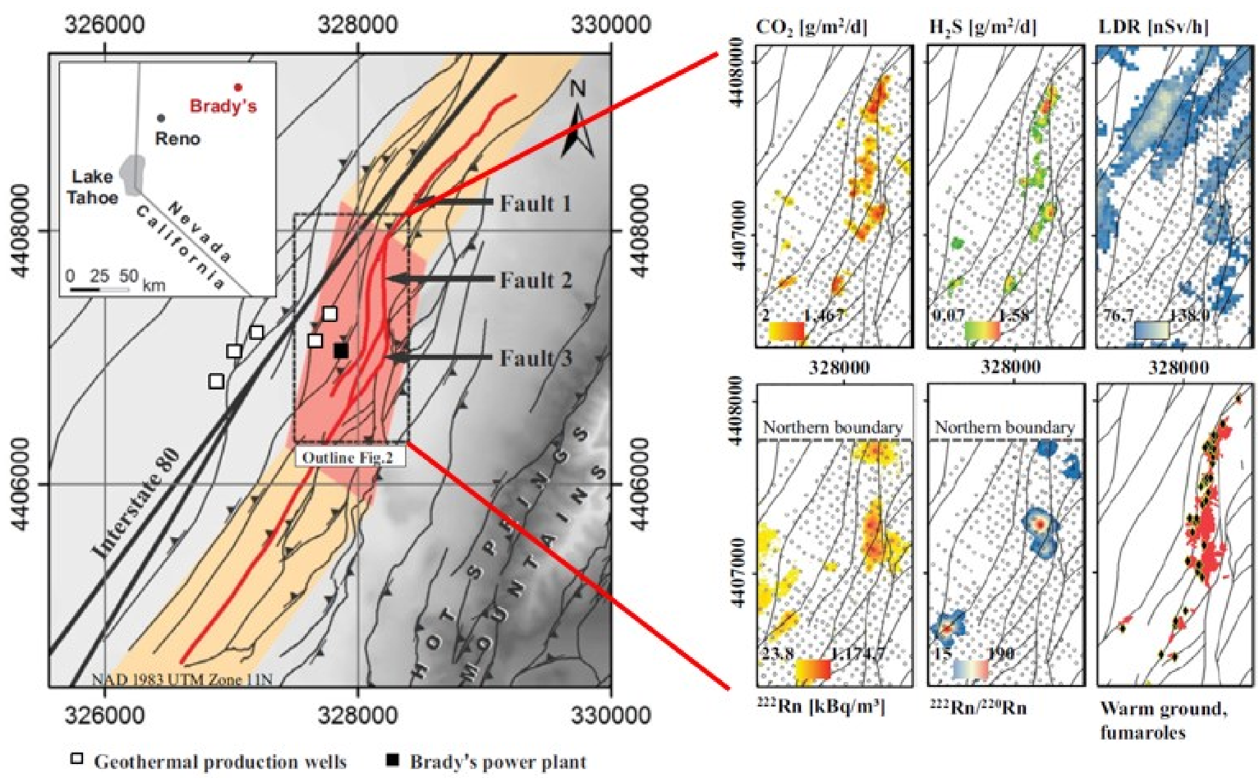

Figure 1: Soil gas anomalies along the Brady's fault zone and its structural step-over (modified after Jolie et al., 2016). The step-over is characterized by maximum gas emissions indicating increased structural permeability, whereas gas emissions decrease to the NE and SW along the fault zone. The step-over is the target zone for production wells of the Brady's geothermal power plant.

In many field studies it could be proven that the pattern of degassing anomalies reproduce the orientation and internal setup of permeable fault structures (e.g., segmented faults, fault step-over and intersections). Such information can be useful for an improved understanding of favorable structural settings for upwelling geothermal fluids (Faulds and Hinz, 2015). Studies have also shown that hidden structures can be detected, provided that fluid circulation exists at depth (Lewicki and Oldenburg, 2004).

The holistic analysis of soil gas data by statistical methods enables a characterization of the geothermal system at a regional scale and gives indications for a classification of the expected geothermal resource. By the analysis of $^{3}He/^{4}He$ or $^{222}Rn/^{220}Rn$ depth indications can be obtained (deep vs. shallow). The development of a systematic geothermal fingerprint analysis based on gas signatures at the geosphere-atmosphere interface will be a useful goal for the future of geothermal exploration and monitoring. However, full capability of soil gas analytics can only be achieved by an integration with other geoscientific disciplines.

2. PARAMETER AND METHODS

2.1 Overview of parameters

Water vapor as the main volcanic gas usually exceeds 60% of the total molar content, followed by CO_2, which is usually present between 10% and 40% of the total molar content (Giggenbach, 1996). The rest of the components (SO_2, H_2S, HCl, HF, He, etc.) is usually present at much lower concentrations. The chemical composition of the gases coming from geothermal or volcanic systems depends on the type of magma. Below, some geochemical characteristics of the most common volcanic/hydrothermal gases are described.

2.1.1 Carbon dioxide:

Its low solubility in silicate melts at low and moderate pressures (Stolper and Holloway, 1988; Pan et al., 1991) make it a good tracer to detect subsurface magma degassing. However, it is important to note that CO_2 can also be produced in the subsurface by a variety of biological processes and can be affected by different processes on its way through the geosphere. CO_2 can be produced as well by oxidation of other species such as CO and CH_4 that migrate from depth through fractures to the surface. In geothermal areas, the CO_2 at the geosphere-atmosphere interface is generally the result of a gas mixture from magmatic and biogenic reservoirs, diluted with atmospheric gas. Several studies could demonstrate that changes in CO_2 efflux and/or concentrations provide important information about subsurface magma movement. CO_2 flux may increase extraordinarily before volcanic eruptions (Hernández et al., 2001a). The study of isotopic composition of C is commonly studied to discriminate the different sources of CO_2.

2.1.2 Sulfur species:

H_2S is the dominant sulfur species at hydrothermal conditions and in low temperature fumaroles, where the emissions originate from the deep hydrothermal system (Giggenbach, 1980). On the other hand, SO_2 is the dominant sulfur species in high temperature volcanic gas emissions at atmospheric pressure. Recently, some studies on H_2S emissions from volcanic areas have been performed (Carapezza et al., 2012; Hernández et al., 2012; Voltaggio and Spadoni, 2009).

2.1.3 Hydrogen:

H_2 is one of the best geochemical indicators of magmatic processes operating in magmatic systems at depth, because of its chemical and physical characteristics such as low weight and low solubility in groundwater and hydrothermal fluids. Moreover, H_2 is considered one of the most abundant trace species in volcano-hydrothermal systems and a key participant in many redox reactions occurring in the hydrothermal reservoir gas (Giggenbach, 1987; Chiodini and Marini, 1998).

2.1.4 Helium:

Helium is an excellent geochemical tracer. It is chemically inert, radioactively stable, non-biogenic, highly mobile and relatively insoluble in water (Reimer, 1980; Ozima and Podosek, 2002; Fu et al., 2005). There are two naturally occurring isotopes of helium (^{4}He and ^{3}He). Radioactive decay of ^{238}U, ^{235}U and ^{232}Th is the main source of ^{4}He, while ^{3}He is considered a primordial gas that is released by mantle degassing to the atmosphere (Graham, 2002).

2.1.5 Radon and Thoron:

^{222}Rn (Radon) and ^{220}Rn (Thoron) are two radioactive isotopes with a half-life of 3.8 days and 54.4 seconds, respectively. In volcanic/geothermal systems, the interpretation of soil ^{222}Rn data is still subject of current research and scientific discussions due to the variety of factors that affect the source and transport of this gas. Some studies proved that variations in soil ^{222}Rn can be produced by magma injections, crustal micro-fracturing and changes in rock permeability due to the opening of gas conduits and fissures (Hernández et al., 2004; Semprini and Kruger, 1984; Whitehead, 1984). Variations in ^{222}Rn activity in soils can be used to map fault zones and permeability structures (Padilla et al., 2013). As a result of their different half-lives, $^{222}Rn/^{220}Rn$ ratio is used to distinguish between gases released from shallow and deep zones. However, a low $^{222}Rn/^{220}Rn$ ratio can be also found in areas with fast soil gas transport mechanism (Giammanco et al., 2007).

2.1.6 Argon isotopes:

Argon isotopes can provide useful information related to the magmatic contribution of endogenous gases. $^{40}Ar/^{36}Ar$ ratios in gases derived from mantle is high compared to the atmospheric value (Graham, 2002).

2.1.7 Mercury vapor:

The geochemical prospection of volatile elements such as mercury vapor (Hg^{0}) in soils has been used as a very useful tool for the detection of anomalous zones of heat flow and areas with higher permeability where fluids ascent towards the surface (Varekamp and Buseck, 1983;

1984; Padrón et al., 2003). Magma degassing is one of the main sources of production of mercury vapor in geothermal areas and it is one of the main constituents of volcanic gases (Varekamp and Buseck, 1984). Increased mercury concentration can be a marker for palaeo-geothermal systems.

2.2 Analytical overview and tools

In the following, a selection of equipment for soil gas analysis will be presented, which can be used in geothermal exploration (see also Fig. 2). In addition to the methods described below, remote sensing technologies (e.g., hyperspectral imaging) can also be applied for measuring gas concentrations above the ground, surface temperatures, alteration zones, etc.

2.2.1 Fluxmeter/ Accumulation chamber technique

Measurements of diffuse CO_2, H_2S and CH_4 efflux can be performed in-situ according to the accumulation chamber method (Parkinson, 1981; Chiodini et al., 1998). This methodology uses portables fluxmeters for single soil gas measurements as well as automated geochemical stations for continuous soil gas monitoring. The use of long-term installations for the measurement of CO_2 flux provides extremely useful information on temporal/seasonal variations, in addition to snapshot flux surveys. Measurement procedure consists of placing a chamber of known dimensions on the ground, forcing the gas to circulate within a closed loop between the chamber and the analyzer. The increase of CO_2 concentration in the chamber as a function of time is recorded, allowing the calculation of CO_2 efflux at each measuring site. Different types of CO_2 analyzer are available. Usually nondispersive infrared carbon dioxide analyzer CO_2 analyzers are installed. H_2S and CH_4 efflux measurements are performed by electrochemical sensors. The measurement range and accuracy is variable, depending on the model and calibration of the analyzer.

2.2.2 Tunable diode laser

The tunable diode laser spectroscopy (TDLS) allows the measurement of the gas mixing ratio based on the absorption of infrared radiation by the target gas. The TDL system consists of a Tunable Diode Laser light source and an infrared transmitter/receiver unit (transceiver) to measure CO_2 mixing ratios over linear paths of up to hundreds of meters. A laser emitted from the transceiver propagates through the atmosphere to a retro-reflector array and returns to the transceiver where it is focused onto a photodiode detector. These two signals are converted into electrical waveforms. A computer inside the transceiver processes these waveforms to determine the concentration of CO_2 (ppmv) (Trottier et al., 2009). TDL gas analyzers are able to detect a variety of gases including CO_2, H_2O, H_2S, O_2, NOx, CH_4, etc. It is a portable tool that has been used for monitoring CO_2 degassing in volcanic areas where usually very high concentrations of CO_2 are observed (Mazot and Christenson, 2012).

2.2.3 Alpha spectroscopy

Radon (^{222}Rn) and Thoron (^{220}Rn) activity concentrations in soil gas samples can be determined by high-resolution alpha spectroscopy of the deposited decay products. The ^{222}Rn activity concentration is obtained from the radiometric in-situ measurement of its short living daughter product ^{218}Po, and the ^{220}Rn activity concentration from the radiometric measurement of the short living daughter product ^{216}Po, both emitting alpha radiation at nuclide specific energies. The number of the detected ^{218}Po and ^{216}Po ions per time unit is proportional to the radon, respectively thoron activity concentration in the measurement chamber (Jolie et al., 2012). Increased radon ^{222}Rn activity concentration can be correlated with deep fracture zones. Portable Radon-Thoron-Monitors allow flexible applications in the field.

2.2.4 Gamma spectroscopy

Gamma radiation measurements are performed with sodium iodide scintillators (NaJ(TI)) coupled with photomultiplier to increase signal strength. Scintillation detectors convert radiation energy into light, which is converted again into electrical signals. The device is capable of recording the complete gamma spectrum from 0-2,850 keV, and allows the identification of the spectral peaks of up to 28 nuclides (e.g., ^{214}Bi, ^{208}Tl, ^{40}K; Jolie et al., 2012).

2.2.5 Quadrupole Mass Spectrometry (QMS)

Quadrupole Mass Spectrometers can be used for chemical and isotopic composition analysis. The quadrupole mass filter consists of four parallel rods arranged in a defined geometry with opposite electrical potential. Ions forming through electron bombardment in the ion source are separated by the mass/charge ratio in the rod system and a mass spectrum is obtained by monitoring the ions passing through the quadrupole filter. Special interest has been addressed to the analysis of He and Ar isotopes (Padrón et al., 2012). Usually, soil gases samples are collected at 40-100 cm depth using metallic probes as described by Hinkle and Kilburn (1979). The samples are stored in glass vials with rubber stoppers. Before sampling the metal probe needs to be flushed to avoid contamination with ambient air.

2.2.6 Micro Gas Chromatography (µGC)

Micro gas chromatrography is a common technique used in analytical chemistry. The analysis of Ne, H_2, O_2, N_2, etc. is performed with a Thermal Conductivity Detector (TDC), equipped with a 20 m length Molsieve 5Å column and pure Ar as carrier gas. The concentrations of CO_2 and CH_4 can be determined using a Poraplot-Q column of 10 m length, a TDC detector and pure He/Ar as carrier gas.

2.2.7 Isotopic Ratio Mass Spectrometer (IRMS)

Carbon isotopic analysis of the soil gas CO_2 ($\delta^{13}C$-CO_2) are usually analyzed by isotopic ratio mass spectrometry (IRMS). The $^{13}C/^{12}C$ ratio is given as $\delta^{13}C$-CO_2 values with respect to VPBD standard with an uncertainty of ±0.1‰. The isotopic signature of carbon gives information on origin/source of CO_2.

2.2.8 Eddy Covariance

The eddy covariance method is based on the turbulent transport theory in the atmosphere and quantifies vertical turbulent fluxes within atmospheric boundary layers. Fluxes are calculated from high-speed measurements of vertical wind speed and gas concentrations. High-speed and high-precision instruments are crucial for the measurement of small changes in the downdraft and updraft air parcels to accurately determine flux values. Anderson and Farrar (2001) applied this technique in an area of high volcanogenic emissions at Mammoth Mountain, California (USA).

2.2.9 Mercury vapor analyzers

Mercury measurements are used for the identification of geothermal upflow zones. Different analytical techniques are available, e.g., gold film based systems or atomic absorption spectroscopy (AAS). In the presence of Hg vapor, thin gold films undergo an increase in electrical resistivity, proportional to the mass of the compound in the sample, whereas AAS uses absorption effects by mercury atoms when UV light passes through optical measuring cells.

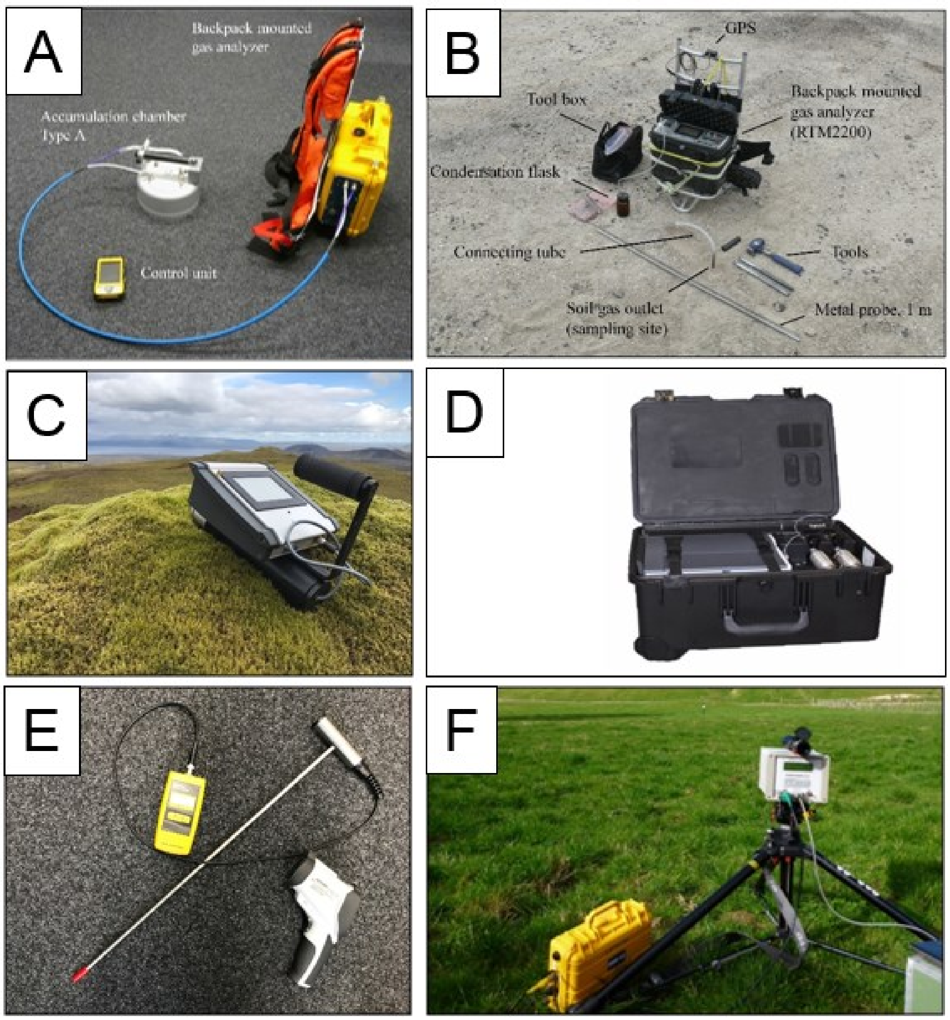

Figure 2: Examples of portable equipment for in-situ measurements. A: CO_2 fluxmeter; B: Alpha-Spectroscope; C: Gamma-Spectroscope; D: Micro Gas Chromatograph; E: Soil temperature probes and Infrared sensors; F: Tunable diode laser.

2.3 Sampling strategy

Table 1 summarizes different options of sampling procedures. Depending on the applied technology, analyses are performed in the laboratory or in-situ. The parameters of the applied grid (i.e., spacing, orientation) are selected according to the scientific question and the expected characteristics of the geothermal system (e.g., high or low flux values/gas concentrations, shape/size/orientation of expected anomalies). A sensitivity analysis based on the observed and expected anomalies helps to identify the optimum grid. For correlation purposes it is recommended to perform all in-situ measurements and sample collections at the same site.

Table 2: Overview of sampling/measuring concepts.

Sampling position		
Shallow depth	Earth's surface	
	On ground	Above ground
• Irregular point measurements (e.g., along road, hiking trails) of gas concentration/flux • Regular grid of gas concentration/flux measurements • Profile measurements of gas concentration/flux at selected points	• Irregular point measurements of gas flux • Regular grid of gas flux measurements	• Continuous/Integrated measurements along profiles (e.g., roving, fixed-distance) • Eddy Covariance Tower (area-wide) • Drones/aircraft (area-wide) • Satellite (area-wide)

3. DATA PROCESSING

The standard procedure for data treatment involves a statistical analysis of the datasets. The probability plot technique is usually applied to assess whether the log-transformed data originate from mixed polymodal distributions (Sinclair, 1974). This technique is based on the recognition of inflection points along S-type curves produced by plotting cumulative percentile data on a log-normal scale. Inflection points allow the distinction of different modes/populations. A second step includes the visualization of the data on a map showing the sampling site locations with graduated symbols according to the measured values. Assuming a sufficiently high data density, an interpolation can be performed. Interpolated maps of the spatial distribution can be computed using sequential Gaussian simulation (sGs), e.g., provided by the sgsim program (Deutsch and Journel, 1998; Cardellini et al., 2003a). In the last decade sGs has been widely applied in studies of soil degassing processes in volcanic and non-volcanic systems (Cardellini et al., 2003b; Frondini et al., 2004; Fridriksson et al., 2006; Chiodini et al., 2008; Carapezza et al., 2009; Mazot et al., 2011). The sGs procedure allows interpolating the measured variables for unsampled sites and assessing the uncertainty of the total diffuse emissions estimated for the entire study area. The simulation is conditional and sequential, i.e., the variable is simulated at each unsampled location by random sampling of a Gaussian conditional cumulative distribution function (Cardellini et al., 2003a). The procedure of the sGs program is composed by the following steps: 1) Normal score transformation of the original data to transform the data into a normal population, 2) Experimental variogram computation of the normal score of the transformed data, 3) Assignment of variogram model to the experimental variogram, 4) Sequential Gaussian simulation of N equiprobable realizations and 5) Back-transformation of the normal score data into simulated values of the original variable. Based on the results of the statistical analysis background values can be excluded from interpolated maps, enabling the analysis of anomaly pattern.

3.1 Chemical ratios of soil gases

The molar ratio between an endogenous gas (e.g., He or H_2) and a typical atmospheric component (e.g., Ne or Ar) can be useful to discriminate areas with anomalous emissions and estimate the contribution of deep-seated gases. Following molar ratios are frequently used: He/Ar, He/Ne, H_2/Ar, He/CO_2, $N_2/^{36}Ar$, N_2/He, etc. The $^{222}Rn/^{220}Rn$ ratio can be calculated to distinguish between gases released from shallow and deep zones.

3.2 Binary and ternary plots

A large number of binary plots (e.g., CO_2-O_2) and ternary plots (e.g., He-Ar-N_2) can be used to obtain information on the source of emitted gases in a spatial context. Based on this technique, it is possible to approximate the existence of mixtures due to different geothermal reservoirs or compartments.

Table 2: Examples of binary and ternary plots for geothermal system analysis.

Examples of binary plots	Examples of ternary plots
• $[CO_2]$ vs. $[O_2]$ • CO_2 efflux vs. $[CO_2]$ • Soil T vs. $[CO_2]$ • Soil T vs. ΔHe • ^{222}Rn vs. ^{220}Rn • $[CO_2]$ vs. ΔHe • ΔHe vs. $1/[CO_2]$ • CO_2 efflux vs. $\delta^{13}C(CO_2)$ • $CO_2/^3He$ vs. $\delta^{13}C(CO_2)$ • $\delta^{13}C(CO_2)$ vs. 1/[He] • $(^{40}Ar/^{36}Ar)$ vs. $(N_2/^{36}Ar)$ • $\delta^{13}C(CO_2)$ vs. $1/[CO_2]$ • $\delta^{13}C(CO_2)$ vs. $^{222}Rn/^{220}Rn$ • $N_2/^{36}Ar$ vs. $\delta^{15}N$	• N_2-CO_2-O_2 • He-Ar-N_2 • N_2-CO_2-CH_4 • He-N_2-CO_2 • He-^{222}Rn-CO_2

3.3 Multidisciplinarity

The key for a successful interpretation of degassing anomalies - related to processes in the deep subsurface - is the quantitative analysis of the spatial correlation of soil gas data with datasets from other scientific disciplines (Jolie et al., 2018). Useful correlations are meaningful with geological cross sections, structural-geological maps, 3D fault stress models (i.e., slip and dilation tendencies), seismic data, volcanic events, hydrogeological data, and others (Table 3).

Table 3: Selection of studies performed in volcanic-geothermal environments with different scientific objectives.

Reference	Objective
Bertrami et al., 1990	Soil gas surveys in volcanic areas in Central Italy to locate permeable zones in buried carbonate reservoirs and to locate the presence of possible gaseous haloes linked to active geothermal systems.
Finlayson, 1992	Soil gas survey conducted over a large part of the Rotorua geothermal field (New Zealand) to determine gas distribution patterns over the field.
Padrón et al., 2003	Concentrations of soil gases and the CO_2 efflux in the Ahuachapán geothermal field (El Salvador) with the aim to correlate anomalies of soil gases and permeability zones/faults.
Voltattorni et al., 2010	Geochemical soil gas survey to locate permeable zones in buried reservoirs in the southern Gulf of California.
Rodríguez et al., 2015b	Joint geochemistry and magnetotelluric survey in a mining area located in Southern Tenerife (Canary Islands, Spain).
Rodríguez et al., 2015a	Soil gas geochemistry studies focused on He and H_2 in different mining area in Tenerife and Gran Canaria (Canary Islands, Spain).
Jolie et al., 2016b	Communicating geothermal reservoirs in the Taupo Volcanic Zone, New Zealand.
Jolie et al., 2016a	Identification and assessment of a structural step-over as target area for geothermal production wells, based on joint soil gas studies and 3D fault stress modeling.
Fridriksson et al., 2016	Soil gas geochemistry and diffuse CO_2 flux survey in the Reykjanes geothermal field (Iceland).

4. DISCUSSION

Soil gas surveys become more important in geothermal exploration and monitoring. This development is due to great developments and improvements in sampling and analytical techniques, which often allow in-situ data reading without necessary sampling for laboratory analysis. Small and light equipment reduces logistical efforts and is easy to operate even in difficult terrain.

For the further development, it needs to be defined how fracture permeability can be quantified based on soil gas data. Large efforts are currently focusing on an optimization of area-wide sampling grids to reduce the time for data collection in the field. We are working as well on the development of systematic and optimized standard approaches, integrating different analytical techniques for soil gas measurements into multi-parameter measurements. The aim is to create a standardized workflow, which provides comparable results for future field studies. Interdisciplinary approaches have to be developed and improved by integrating soil gas surveys with remote sensing, geophysics, 3D fault stress modeling, and others techniques. Data integration will pave the way for a comprehensive understanding of the nature of encountered soil gas anomalies.

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