Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Origin of Radon Anomalies along Geological Structures and Degassing Pathways of the Geothermal System of Acoculco, Puebla (Mexico)

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Keywords: Geothermal energy, Geothermal prospection, Gas geochemistry, Radioanalytical techniques, Renewable energy

ABSTRACT

The identification and development of “hidden” or “blind” geothermal systems (sometimes referred as hot-dry rock systems) are still recognized as geoscientific challenges to be achieved for the geothermal industry. The prospection of “blind” or “hidden” geothermal systems involves complex geochemical tasks because there are no available surface thermal manifestations (fluids) to be analyzed which make difficult to identify and delineate the dry hot-rock reservoir and the primary heat source.

Natural Earth degassing has been a matter of investigation in a large number of geothermal prospection studies. Among these studies, soil-gas radon surveys have been suggested as a suitable geochemical tool for an effective detection of “hidden” or “blind” geothermal systems, specially, to locate permeable pathways above potential geothermal resources in areas with no surface thermal manifestations.

The opportunity to explore “hidden” or “blind” geothermal systems in Mexico appeared with new geochemical studies carried out in the Geothermal System of Acoculco (GSA), Puebla. The GSA has been proposed as a potential hot-dry rock system based on a promissory high-temperature source of ~300 °C, and an early exploration programme carried out by the Comisión Federal de Electricidad (CFE) of Mexico. Previous geological and geochemical studies have reported the presence of anomalous areas of active argillic alteration and cold-gas emissions with ambient surface temperatures. The lack of typical thermal manifestations (e.g., hot springs, fumaroles, geysers or boiling mud pots), the low permeability of rock, and the geochemical footprint of cold-gas emissions found in Acoculco have been referred in similarity with geothermal areas known as *Kaipohans*, which have been proposed to describe the type of anomalous manifestations discovered in this place.

Based on the possible existence of a promissory “hidden” or “blind” system in Acoculco, measurements of radon in soil-gas and water-gas emissions for nearly three years of geochemical monitoring (2016-2018) were carried out. Spatial and temporal variability surveys of soil-gas radon concentrations were carried out to identify strong radon anomalies which were used to detect possible geological structures (buried faults or fractures) and degassing paths existing in the GSA. The characterization of soil-gas radon emissions, the production sources and the main transport mechanisms were also analysed. Results of a geochemical monitoring programme and the measurement methodology are briefly outlined in this work.

1. INTRODUCTION

The utilization of geothermal resources, as an inexhaustible renewable energy source, keeps growing for the generation of electricity and other direct uses (Moya *et al.,* 2018). Technical, environmental, financial, social, and regulatory barriers have been overcome in the exploitation of the conventional hydrothermal systems (Bertani, 2016). Notwithstanding this progress, still exist some scientific challenges to be achieved for the identification “blind” or “hidden” geothermal systems, sometimes referred as hot-dry rock or enhanced geothermal systems (Dobson *et al.,* 2016). Large prospecting opportunities for discovering “blind” or “hidden” geothermal systems are perceived in presence of a low percentage of the accessible geothermal resources discovered to date (Forson *et al.,* 2014).

One of the key goals of the geothermal prospection is to identify and apply new and improved methodologies that may reduce both the risks and costs associated with discovering and developing geothermal resources (Dobson, 2016). The prospection of “blind” or “hidden” geothermal systems involves complex scientific tasks because there are no visible superficial thermal manifestations to be analyzed which make difficult to identify and delimit the hot reservoir or the primary heat source (Simmons *et al.,* 2005). The prospection challenge becomes even greater when the energy potential of these systems, preliminary associated with deep high-temperature sources, requires to be confirmed for future detailed exploration and exploitation projects.

The opportunity to explore a “blind” or “hidden” geothermal system in Mexico have appeared with new geochemical surveys carried out in the Geothermal System of Acoculco (GSA), Puebla (Fig. 1), one of which will be reported in this work. The GSA was proposed as a potential hot-dry rock system based on a promissory high-temperature source of ~300 °C (preliminary inferred from bottomhole temperatures logged in two exploration wells), and an early exploration programme carried out by the Federal Commission for Electricity of Mexico (in Spanish: “Comisión Federal de Electricidad”, CFE): see Lorenzo Pulido *et al.* (2011). Previous geological and geochemical studies carried out in this caldera report the presence of anomalous areas of active argillic alteration and diffuse cold-gas emission with superficial temperatures close to ambient (e.g., López-Hernández *et al.,* 2009; Canet *et al.,* 2015a, 2015b).

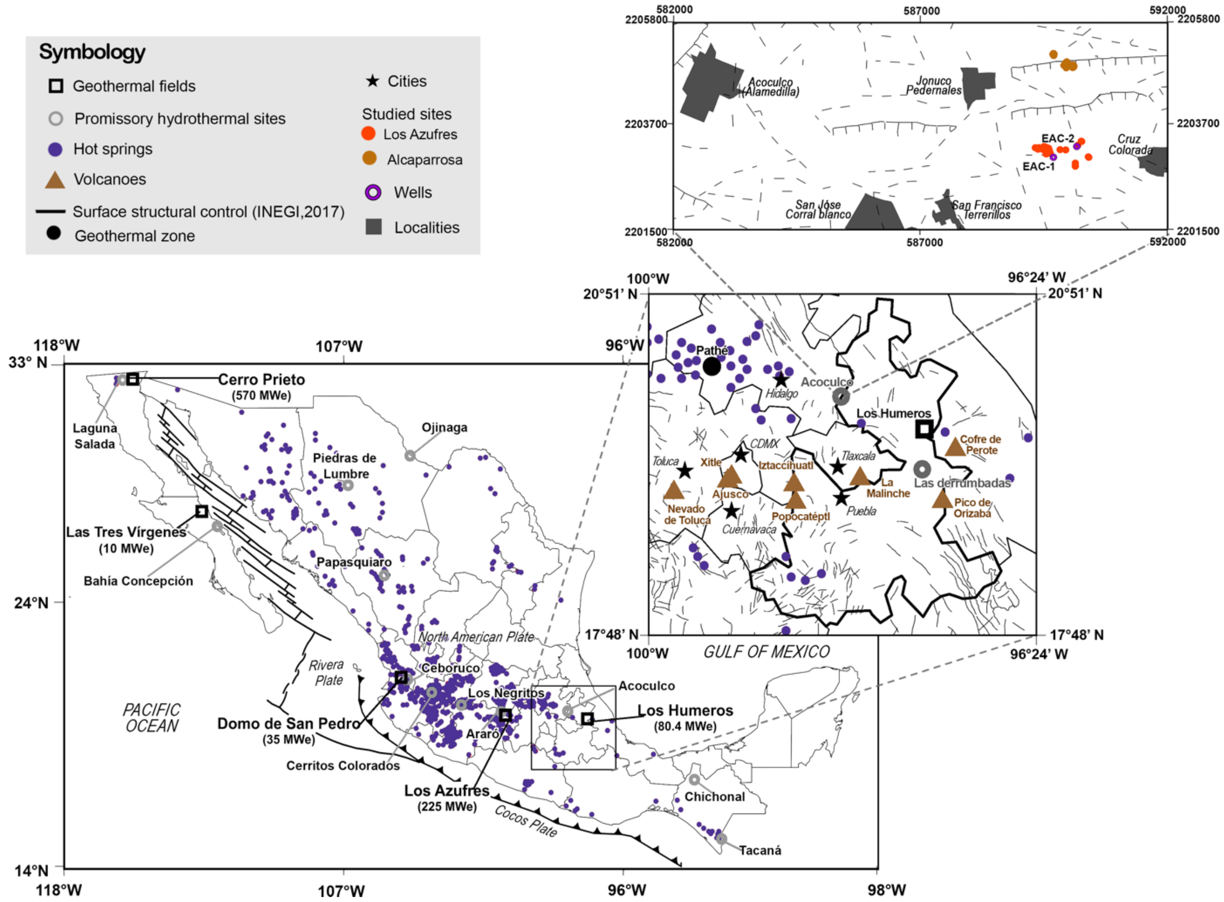

Figure 1: Location of promissory geothermal sites of Mexico, and zoom out projections of the Acoculco geothermal system.

The lack of typical thermal manifestations (e.g., hot springs, fumaroles, geysers or boiling mud pots), the low permeability of rock, and the geochemical footprint of cold-gas emissions found in Acoculco (especially those found in Los Azufres and Alcaparrosa zones) have been referred in similarity with some geothermal areas known as *Kaipohans* (Bogie *et al.,* 1987), which have been adopted to describe the anomalous manifestations discovered in this place (López-Hernández *et al.,* 2009; Peiffer *et al.,* 2014).

To propose a comprehensive conceptual model of the GSA, a new innovative and integral prospection programme was proposed within the research framework of the Mexican Centre for Innovation in Geothermal Energy (in Spanish: "*Centro Mexicano de Innovación en Energía Geotérmica*", CeMIE-Geo: Romo Jones *et al.,* 2017), from where the present research study is derived. This prospecting programme precisely lies, not only in obtaining a knowledge on the subsurface temperatures, the geochemical signatures (chemical and isotopic) of the existing geofluids, or the spatial/temporal distributions of some geochemical tracers, but also to obtain a mapping of the geological structure (faults and fractures), including the rock permeability, and the degassing pathways to transport magmatic gases (CO_2, radon, He, among others) towards the surface.

Natural Earth degassing has been a matter of investigation in previous geothermal prospection studies. Soil-gas radon surveys have been suggested as a geochemical tool for the detection of the "hidden" or "blind" geothermal systems, specially, to delineate gas flow pathways above potential geothermal resources in areas with no surface thermal manifestations (e.g., Voltattorni *et al.,* 2010). Among these tracers, radon gas is capable to be detected in very low concentrations with high sensitivity techniques (Gingrich, 1984). The soil-gas radon method is a cheap, accurate and easy mapping method suggested to detect permeable zones in a geothermal field (Haerudin *et al.,* 2013). The study of soil-gas radon from depth to shallow horizons, including the transport mechanisms, the soil characterization, and their spatial and temporal distributions have a strong influence on their production sources, and potential migration pathways (Gal *et al.,* 2018). Radon emanation has been also proposed as a natural tracer or proxy indicator for the prospection and monitoring of geothermal systems (e.g., Kruger *et al.,* 1977; D'Amore *et al.,* 1978; Whitehead, 1980; Semprini and Kruger, 1984; Andrews *et al.,* 1986; Balcazar *et al.,* 1991; Santoyo *et al.,* 1991; Tavera *et al.,* 1999; Barragán et al., 2008; Richon *et al.,* 2011; Haerudin *et al.,* 2013; Koike *et al.,* 2014; Jolie *et al.,* 2015, 2016; Wang *et al.,* 2017; among other studies).

Based on the possible existence of a new promissory "hidden" or "blind" hot-dry rock system located in the Geothermal System of Acoculco, Puebla (México), measurements of radon in soil-gas emissions for nearly three years of geochemical monitoring (2016-2018) were successfully carried out. Spatial and temporal variability surveys of soil-gas radon concentrations were conducted to identify strong radon anomalies which are currently studied to detect possible degassing paths and geological structures (buried faults or fractures) existing in the most active gas emission zones of Los Azufres and Alcaparrosa within the GSA. The characterization of soil-gas radon emissions, and the production sources have been briefly mentioned in the present work.

2. PHYSICOCHEMICAL AND TRANSPORT PROPERTIES OF RADON GAS

Radon is a radioactive, colourless, odourless, tasteless noble gas with low reactivity (Tanner, 1964). It is very abundant in the Earth mantle. The radioactive decay of ^{238}U and ^{232}Th which are universally found in rock-forming minerals, soils and groundwaters produce gas radon. ^{222}Rn (radon) and ^{220}Rn (thoron) isotopes are continuously produced from the parent α-decay of the ^{226}Ra and ^{224}Ra existing in rocks and minerals, respectively. ^{222}Rn has a short half-life of approx. 3.823 d whereas ^{220}Rn has a shorter half-life of c. 55.83 s (Baskaran, 2016). The half-life of ^{222}Rn is roughly 6,000 times longer than that of ^{220}Rn, which means that the number of atoms of ^{222}Rn is the most important parameter for studying the physical conditions in geothermal systems (Koike *et al.,* 2014). Because ^{222}Rn has a longer half-life than ^{220}Rn, it may be detected at extremely low concentration. The half-life of ^{222}Rn (hereafter referred to as radon) limits its migration by diffusion in soils, so that the radon that is usually measured at the ground surface cannot be released from a deep origin, unless there exist advective driving mechanisms (Muga *et al.,* 2017). The migration of radon over large distances is sustained by advective models by using a carrier gas (e.g., CO_2 or CH_4) or groundwater (Ioannides *et al.,* 2003). The transport of ^{220}Rn is limited to a few centimetres either by diffusive or convective-advective mechanisms due to its shorter half-life.

The physicochemical and transport properties of radon actually constitute the basis of geochemical mapping methods used in some Earth Science studies (e.g., geothermal, hydrocarbon and mineral-uranium prospection, volcanic and earthquake prediction, among others). As radon transport follows preferential permeable pathways formed by zones of enhanced permeability, faults, and fractures, the measurement of soil-gas radon provides a potential mapping method for the detection of degassing pathways, and the delineation of permeable structures and buried faults (e.g., Baskaran, 2016).

3. GEOLOGICAL SETTING AND HIDROTHERMAL ALTERATION

The complex caldera of Acoculco (ACC) belongs to the eastern portion of the Mexican Volcanic Belt (MVB, Fig. 1), and is located in the eastern portion of the Mexico basin. This volcano-tectonic basin is delimited by the Querétaro-Taxco Fault System and the Cofre de Perote-Pico de Orizaba volcanic chain, which is associated to the Sierra de Las Cruces, Sierra Nevada, La Malinche, and Cofre de Perote-Pico de Orizaba volcanic ranges. According to Vázquez-Sánchez and Jaimes-Palomares (1989), three fault major systems dominate the Mexico basin: (i) a NE-SW system of Eocene-late Oligocene age; (ii) a NW-SE trending fault system; and (iii) an E-W fault that produced Plio-Quaternary graben structures.

Within this tectonic scenario, the Apan-Tezontepec volcanic field located at the northeast of the Mexico basin, consists of right-stepping variably dipping NE-SW normal faults. García-Palomo *et al.* (2018) identified five main faults known as Axaxalpa, Apan-Tlaloc, Texcoco, Tizayuca, and Tolcayuca. The Apan-Tlaloc Fault System is a major discontinuity that divides the region into two contrasting areas with different structural and volcanic styles: (i) the western area which is depicted by a horst-graben geometry with widespread Quaternary monogenetic volcanism, and scattered outcrops of Miocene and Pliocene rocks; and (ii) the eastern area which is dominated by tilted horst with a domino-like geometry with widespread Miocene and Pliocene rocks, scattered Quaternary monogenetic volcanoes and the ACC. Interpretation of gravity data suggests that this structural geometry continues into the basement (García-Palomo *et al.,* 2018), composed of Cretaceous limestones exposed in several localities and the lithological column of some wells drilled in the Mexico basin (López-Hernández and Castillo-Hernández, 1997).

The ACC overlies the intersection of two fault regional systems: (i) the NE oriented Apan-Tlaloc Fault System suggested to represent the continuation towards the NE of the Tenochtitlan shear zone (De Cserna *et al.,* 1987); and (ii) the NW oriented Tulancingo-Tlaxco Fault System which represents the SE limit of the Mexican geological province of the Basin and Range (Aguirre-Díaz *et al*., 2005).

The origin of the MVB volcanism is primarily attributed to the subduction of the Cocos Plate beneath the North American Plate (Kostoglodov and Bandy, 1995). Nevertheless, an extensional deformation has been recorded in the NE-SW regional faults in the Apan-Acoculco region (García-Palomo *et al.,* 2018), which has been active since the early Pliocene. These authors proposed that the extension in the eastern part of the TMVB and along the NE-SW faults is produced by the oblique subduction of the Cocos plate beneath southern Mexico. This structural setting, with faults producing tilted horst blocks, allowed the extrusion of calc-alkaline magmas and the emplacement of monogenetic volcanism in the Apan-Tezontepec Volcanic Field and the formation of the ACC. The geological data available for this region were reported by López-Hernández *et al.* (2009); Garcia-Palomo *et al.* (2018); Sosa-Ceballos *et al.* (2018); and Avellán *et al.,* 2019. According to radiometric ages of K-Ar and ^{40}Ar-^{39}Ar measured in representative rock samples (López-Hernández & Martínez, 1996), the volcanic rocks in the ACC were formed by the following three volcanic episodes (Fig. 2):

(i) The first episode (between 3.0 and 2.7 Ma) that produced the Las Minas rhyodacites, the Alcholoya ignimbrite, the Acaxochitlan dacites (3.0±0.3 Ma; K-Ar age), lava fluxes of basaltic composition, and the Tulancingo rhyolitic to dacitic domes that were accompanied by short pyroclastic fluxes (2.7±0.1 Ma; ^{40}Ar-^{39}Ar age),

(ii) The second episode (between 1.7 and 0.24 Ma) that produced the Acoculco rhyolites (1.7±0.4 to 1.36±0.04 Ma; K-Ar ages), the Cruz Colorada dacite, the Cuauteloluco basalts, and the Acoculco rhyolitic ignimbrite (1.4±0.2 Ma, K-Ar age), which was responsible for the caldera collapse. The circular fault system was reactivated with the eruption of the Piedras Encimadas rhyolitic ignimbrite (1.3±0.2 Ma; ^{40}Ar-^{39}Ar age) at the El Rincon region. Subsequently, a dacitic dome was formed and basaltic fluxes covered the Piedras Encimadas ignimbrites. The volcanic activity of Acoculco ended with the La Paila formation made of scoria cones and basaltic fluxes (0.24±0.04 Ma, K-Ar age), and

(iii) The third episode is related to a monogenetic volcanism in the Tezontepec-Apan regional volcanic field. Around the GCA, the volcanic products from Acoculco were interspersed with the basalts from Apan and Tecocomulco of 1.8-2.0 Ma (López-Hernández and Martínez, 1996; Nelson, 1997). This monogenetic volcanic province is characterized by hundreds of scoria cones and andesitic-basaltic lavas (De Cserna *et al.,* 1987; García-Palomo *et al.,* 2002). The basalts from La Paila, mentioned above, were probably genetically related to this regional volcanism.

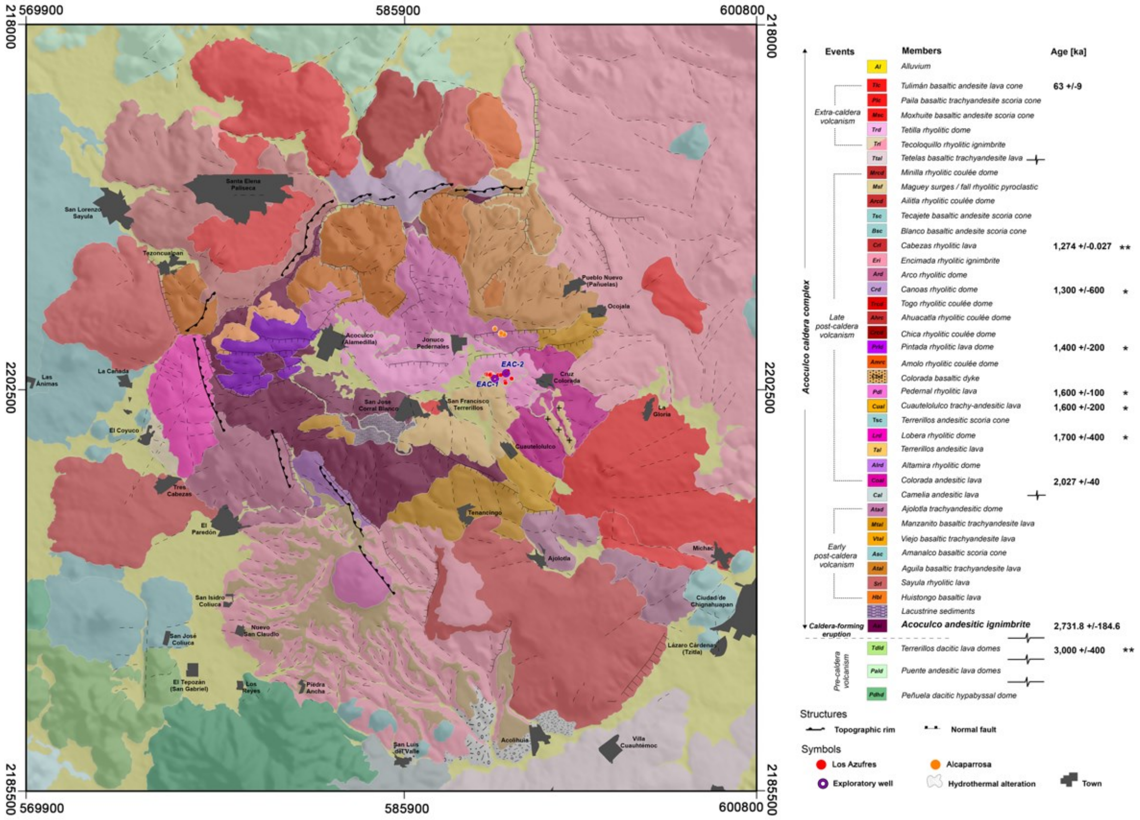

Figure 2: Main geological structures of the Acoculco geothermal system, and location of the anomalous soil-gas emissions zone of Los Azufres and Alcaparrosa (original source: modified after Sosa-Ceballos et al., 2018; and Avellán et al., 2019).

Sosa-Ceballos *et al.* (2018) investigated the origin of magmas tapped during the eruptive history of the ACC, and the magmatic processes that modified these magmas. According to these authors, after the caldera collapse (2.7 Ma), the local stress field was modified and allowed the ascent of peralkaline magmas, generated by partial melting of a metasomatized mantle genetically unrelated to the calcalkaline magmas, through new plumbing systems. Such magmas mixed with calc-alkaline magmas and formed the post-caldera volcanism. Influx of new magma is considered as the probable primary heat source that maintains the active magmatic system.

Hydrothermal Alteration Processes

Silicic alteration is the most widespread type of alteration that undergone the superficial rocks in the ACC (Canet et al. 2015a). This alteration occurs as a pervasive replacement of the pyroclastic deposits by an assemblage of opal, tridimite, and anatase, developed under temperature conditions below ~150 °C, and near-neutral pH. Advanced argillic alteration has a much more restricted distribution in Acoculco, occurring principally nearby active cold-gas emissions. This type of alteration is also expressed by secondary mineral assemblages rich in kaolinite and sulphates (alunite and ammoniojarosite), and it could be the consequence of a steam-heated overprint in the geothermal system. The ubiquitous hydrothermal alteration found in the central part of the ACC has motivated to several geothermal exploration programmes to be subsequently carried out. During early drilling programs carried out by the CFE, two exploratory wells were drilled in 1995 and 2008: EAC-1 and EAC-2, respectively (Lorenzo-Pulido et al., 2011). Some observations found in the EAC-1 well, indicated that the whole volcanic sequence shows an intense hydrothermal alteration, where the most abundant alteration minerals are: quartz, amorphous silica, calcite, pyrite, biotite, epidote, chlorite, illite, smectite, caolinite, and hematite (López-Hernández and Martínez, 1996).

Thermal History

A thermal profile observed from analysis of fluid inclusions, and homogenization temperatures suggests that a convection heat transfer process occurred in the past in the ACC through the upper ~1400 m of the geothermal system (Canet et al., 2015b). The bottomhole temperature measured in the EAC-1 well attained 307 °C, which implies an anomalous geothermal gradient of ~150 °C/km. Bottomhole temperature logs collected from the two exploratory wells show a conductive heat transfer regime under high geothermal gradient (López-Hernández et al., 2009; Lorenzo-Pulido et al., 2011). According to these authors, Acoculco may be a case of self-sealed geothermal system where the main faults and fractures were filled by precipitation of alteration minerals which produced a decrease in rock permeability (resulting in a ~500 m-thick lithocap) that disabled the convective regime of the system. However, the sealing of fractures has indicated that fractures can be opened and sealed several times in active hydrothermal systems (Cox et al., 2011).

A thermal secondary effect was reflected in a decrease in the local geothermal gradient. The changes in petrophysical and heat transport properties marked the ACC as a potential active hot-dry rock geothermal system. This system is strongly characterized by the presence of a superficial extended argillic alteration, sulphate cold springs with low pH's, and cold soil-gas emissions (CO_2, H_2S, radon, among others), which all together provide the features of a "blind" or "hidden" system similar to the well-known Kaipohans (López-Hernández et al., 2009; Peiffer et al., 2014; Avellán et al., 2017; García-Palomo et al., 2018).

3. WORK METHODOLOGY

To carry out the geochemical monitoring programme of radon in the GSA, a work methodology was developed. A schematic flow diagram showing the field work methodology used is presented in Fig. 3. The work methodology involved three major phases:

(i) Geologic-structural reconnaissance analysis to select potential sites for the radon monitoring programme;

(ii) Selection of analytical methods for the measurement of radon concentration; and

(iii) Evaluation of the spatial variability of radon concentration.

3.1 Geologic-Structural Reconnaissance: Selection of Potential Geothermal Areas

A geologic-structural reconnaissance analysis was carried out as a fundamental pre-field task for the radon monitoring. After analysing some previous studies of geologic-structural and geophysical models of the GSA (García-Palomo et al., 2018; Avellán et al., 2019), an inventory of potential geothermal areas located in the GSA was created, including sampling and measurement sites that were selected for delimitating the radon gas surveys. The inventory considered the existing anomalous hydrothermal alteration zones, the cold-gas emission sites, and the fault and fracture systems that have been inferred from previous geological studies (Fig. 3).

Figure 3: Drone picture of the main gas emission sites located in Los Azufres zone of the GSA.

3.2 Selection of Analytical Methods for the Measurement of Radon Concentration

To monitor the radon concentrations emanated from the natural emission sites, a standardized detection method based on alpha spectrometry was selected, calibrated and applied for the spatial and temporal variability surveys. The method was related to batch long-term measurements carried out by using an alpha-scintillation counting system (portable radiation monitor Pylon AB6A).

Portable radiation monitor: Pylon AB6A (hereinafter referred as AB6A monitor)

The AB6A monitor uses active scintillation 600A detectors (also known as ZnS Lucas scintillation cells) which enable a collection of α-particles in a sample to be determined (Lucas, 1957). As a collection procedure, a grab sampling method was used for transferring radon samples from the gas emission sites into the cell. The collection of the grab gas sample required to place the cell under a vacuum, and then releasing to draw the gas sample into the cell. The 600A Lucas cell is a sealed metal cylinder that has two Swagelok pneumatic connectors at one end and a transparent quartz window at the other end. The two Swagelok connectors allow the cells to collect a grab sample (Fig. 4). Although the scintillation cells are sensitive to Radon (^{222}Rn), Thoron (^{220}Rn), and Actinon (^{219}Rn) isotopes, the use of the grab sampling method enabled the isotope with the longer half-life (^{222}Rn) to be measured with accuracy. The AB6A monitor system was periodically calibrated for evaluating the detection sensitivity and the net counting efficiency. Lucas type-cell detectors were calibrated using two source standards of ^{226}Ra at the manufacturer's lab. Before the grab sample collection and measurement, the radon background concentration existing in each Lucas cell was first determined using the AB6A counting system.

Grab gas sample collection

All the gas samples were filtered through a 0.8 μm particulate filter to ensure that a pure sample was drawn into the cell. To avoid a damage in the scintillation cells due to water condensation, a drying column of silica gel was coupled between filter and cell for removing the sample humidity. The grab gas sampling was used to measure a gas sample that is collected at a specific instance in time which is used to calculate the radon concentration at the time of sampling. Due to the nature of radon decay, the grab sample was measured after 3.5 hours of the collection to allow the sample to reach equilibrium. The radon concentration existing at each gas sample was measured following the same steps for determining the background in each Lucas cell.

Radon measurement.

The scintillation detection cells containing a gas sample were coupled into the AB6A counting monitor through a photomultiplier tube (PMT). When radon decays, it produces alpha particles that strike the scintillation material (ZnS, silver activated zinc sulphide scintillator) inside the cell. The alpha particle became a helium atom and the sulphide de-excited by emitting photons or light pulses. The photon of light was detected, converted to an electrical pulse, and amplified by the PMT, which was driven by a high voltage signal (~175 H.V. units) to obtain an optimum detection and amplification. The pulses from the PMT were sent to the interface board electronics for further amplification, waveform shaping, discrimination, and, if appropriate (pulses that are above a minimum noise threshold), and finally, these light pulses were counting to be converted in radon concentration units (Bq/m^3 or pCi/L).

Figure 4: Gas sampling collection system used for the radon monitoring by using the Lucas tube 600A.

3.3 Evaluation of the spatial variability of radon

The aim of this study was to identify the radon concentration gradients existing in the GSA, particularly, those zones containing the higher radon emanation as a strong signal to highlight geothermal anomalies, degassing pathways and permeable geologic structures. To carry out the spatial variability survey, Los Azufres (LA) and Alcaparrosa (AP) zones of the GSA were selected as main gas emission sites (i.e., the most suitable sampling and measurement sites), which were strategically located close to some potential geological faults.

4. RESULTS

Before to carry out the analysis of all the measurements of radon carried out in the two zones of the GSA, the geochemical database BD222RN_GSA was created. The database was created with the concentration gradients of radon measured during the exploration campaigns carried out in Los Azufres (AZ) and Alcaparrosa (AP) zones (period 2015-2018). Table 1 summarises the basic statistics of the radon measurements.

Table 1. Descriptive statistics of radon concentration measurements in soil-gas emission zones of the geothermal system of Acoculco, Puebla (in Bq/m^3 units).

Zone	Mean	SD	Median	n	Min	Max	Q1	Q3
Los Azufres (AZ)	32,656	31,530	27,761	157	<200	135,401	1,870	53,493
Alcaparrosa (AP)	20,805	15,972	22,719	81	121	56,872	2,974	31,389

Spatial variability of radon.

The spatial variability of the radon concentration gradients measured was analysed by using Kriging interpolation maps, which were generated using the defined sampling mesh in the main areas that showed a greater emanation of this gas (i.e., Los Azufres y Alcaparrosa). These interpolation maps are shown in Figs. 5 and 6, respectively. The spatial distribution of radon concentration at Los Azufres (AZ) and Alcaparrosa (AP) was plotted for identifying the location of the major radon anomalies (Figs. 5 and 6). As seen in both figures (5 and 6), anomalous radon concentration values were measured in AZ and AP zones. For the Los Azufres (AZ), the radon concentrations range from 10,000 to 120,000 Bq/m^3, whereas for the Alcaparrosa, the concentration gradients were smaller, and varied from 4,000 to 56,000 Bq/m^3.

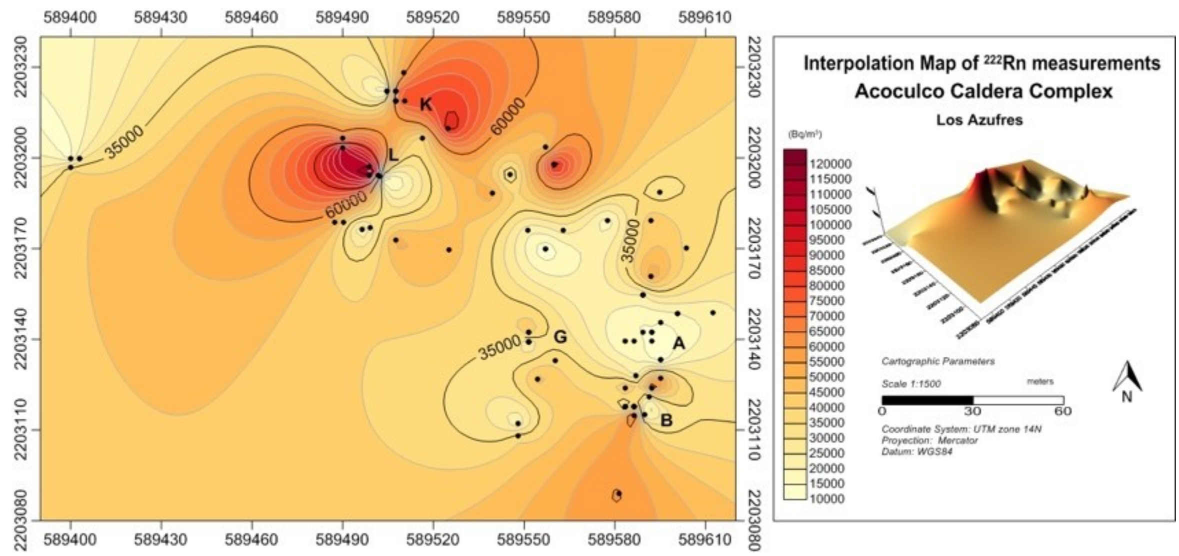

Figure 5: Map of the radon concentration gradients measured in five gas emission sites of the zone of Los Azufres of the geothermal system of Acoculco (A-B, G, and K-L).

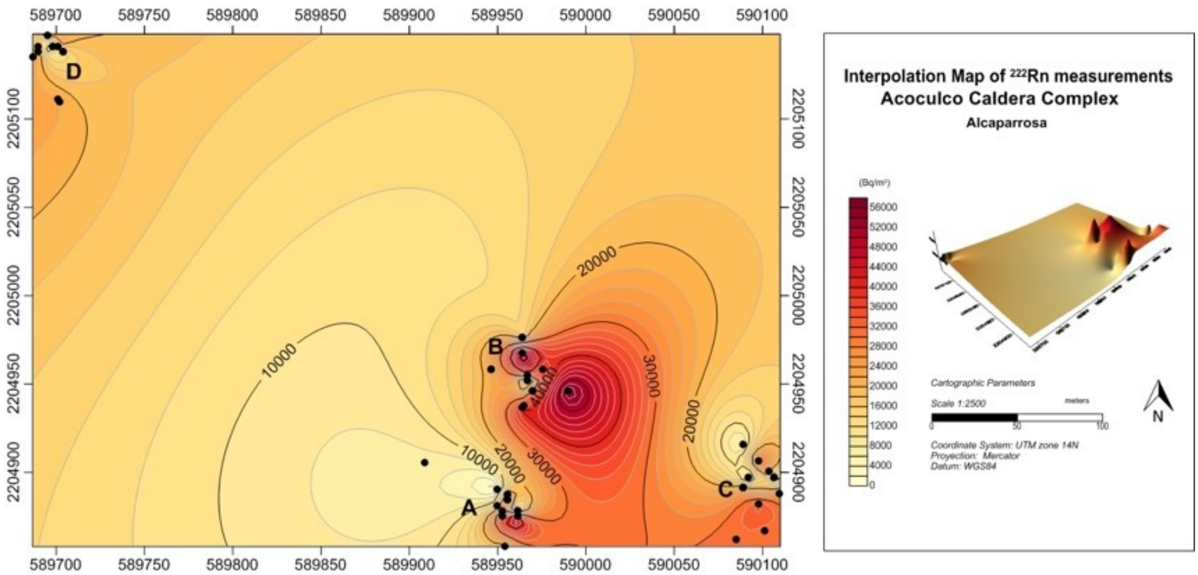

Figure 6: Map of the radon concentration gradients measured in four gas emission sites of the zone of Alcaparrosa of the geothermal system of Acoculco (A-D).

To confirm that the gas emissions collected from both sites (AZ and AP) show a magmatic and deep origin, stable isotope of $\delta^{13}C$ were measured in some samples, together with some soil-gas fluxes CO_2. Such geochemical evidences are shown in Fig. 6.

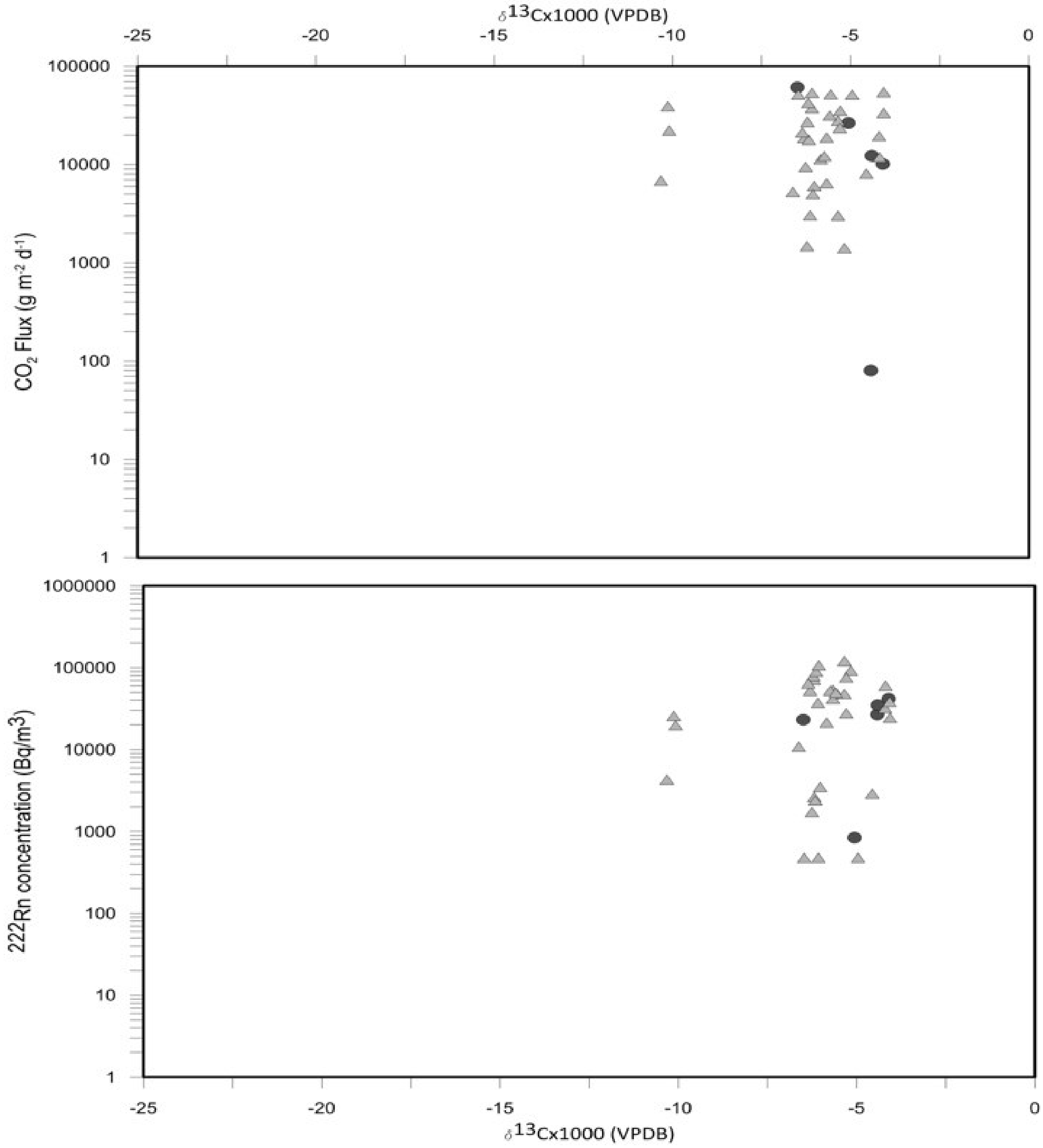

Figure 6: Variability of the radon gas concentrations and the soil-gas (CO_2) fluxes with some selected $\delta^{13}C$ measurements recorded at the AZ and AP zones of the geothermal system of Acoculco.

4. CONCLUSIONS

Radon (^{222}Rn) anomalies were measured in high concentration levels in the vicinity of active micro-fractures or small faults from upward migration measurements of the hidden geothermal system of Acoculco (GSA). A up-fault gas flow hypothesis is preliminary proposed for these gas emission sites, which likely proceed from either active normal fault zones or a system of micro-fractures of the GSA. In agreement with some previous field studies, anomalous high radon concentrations were measured near some mapped faults. However, soil gas samples collected from 1 m depth show that some of the radon anomalies along faults may reflect local changes in some soil types. The distribution of radon concentration found in two zones of GSA (LA and AP) may be explained by means of complex diffusion-advection flow patterns. Radon diffusion processes may not govern alone all of the observed patterns in the measurement data. In fact, in some specific locations of AZ and AP, which were located along a path of possible faults, the radon concentrations are most likely transported by an advective flow of subsurface gases (mainly by CO_2 as a carrier gas), which suggests a channelized gas flow in segments of such faults.

Numerous works have been previously reported on radon anomalies at concentrations significantly higher than background levels alongside active faults. Such a geochemical evidence proposes that these anomalies may provide reliable information about the location of faults and microfractures, and the spatial distribution of fluid flow within fault zones; however, the actual mechanism responsible for the observed radon anomalies is still unclear.

By considering the assumption that the concentrations of radon are the result of gas flow associated with a secondary permeability in fault zones, field soil-gas surveys of radon are widely accepted as an effective geochemical tool to map buried or blind faults not detected during mapping of the surface geology. The strong radon anomalies found in the GSA are explained by a deep magmatic origin, which was confirmed by the values of the $\delta^{13}C$ determined in both sites (-7 to -4 o/oo $\delta^{13}C$). In this way, these radon anomalies may not be explained by other possible sources, such as the production of radon in near-surface soils. Although, exist some previous evidences reported in older publications which suggest that fault-related anomalies may be produced by increased radium decay in soils (Tanner, 1978).

The high radon concentrations observed in the GSA could be closely associated with a micro-fractured zone, and very probably, with a deep high heat flux. The spatial pattern of the soil-gas (CO_2) fluxes and the radon concentration distribution suggest a structural control on gas degassing, in particular, along and near the fault floors.

A comprehensive geochemical study of radon and other deep gases (CO_2 and CH_4) is still under process to elucidate the main mechanisms of transport that exhibit the radon gas (^{222}Rn) anomalies along buried or blind faults of the caldera of Acoculco (particularly in the zones of AZ and AP). In both zones, no evidence of geothermal activity was observed because the GSA is considered as a hidden geothermal system.

ACKNOWLEDGEMENTS

This work was funded by the P09 CeMIE-Geo research project (207032 CONACyT-SENER). The first author also wants to thank to the Physics and Mathematics Department of the Universidad Iberoamericana (Mexico) for the support in a sabbatical leave program carried out on 2018-19.

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