Exploration of deep-seated geothermal reservoirs in the Canary Islands by means of soil CO_2 degassing surveys

Fátima Rodríguez[1], Nemesio M. Pérez[1,2,3], Gladys V. Melián[1,2,3], Eleazar Padrón[1,2,3], Pedro A. Hernández[1,2,3], María Asensio-Ramos[1], Germán D. Padilla[1,2], José Barrancos[1,2] and Luca D'Auria[1,2]

(1) Instituto Volcanológico de Canarias (INVOLCAN), 38320 San Cristobal de La Laguna, Tenerife, Canary Islands, Spain
(2) Instituto Tecnológico y de Energías Renovables (ITER), 38600 Granadilla de Abona, Tenerife, Canary Islands, Spain
(3) Agencia Insular de la Energía de Tenerife (AIET), 38600 Granadilla de Abona, Tenerife, Canary Islands, Spain

Photography: Alba Martín Lorenzo

Geothermal potential in Spain

- Spain has been one of the last European countries where is geothermal energy started; this explains why our country is behind most EU nations in practically all areas of the sector. Nevertheless, there are expectations for a future development on shallow geothermal as well as for power generation, given the existing potential and resources.

At present, there is no geothermal power generation in Spain, despite the good potential in the Canary islands.

COUNTRY	Installed in 2010	Energy in 2010	Installed in 2015	Energy in 2015	Forecast for 2020	Increase since 2010			
	MWe	GWh	MWe	GWh	MWe	MWe	GWh	Capacity %	Energy %
PHILIPPINES	1,904	10,311	1,870	9,646	2,500	-34	-665	-2%	-6%
POLAND					1				
PORTUGAL	29	175	29	196	60		21		12%
ROMANIA			0,1	0,4	5	0,1	0,4		
RUSSIA	82	441	82	441	190				
SLOVAKIA					5				
SPAIN					40				
SWITZERLAND					3				
TAIWAN			0,1		1	0,1			
THAILAND	0.3	2.0	0,3	1,2	1				
TURKEY	91	490	397	3,127	600	306	2,637	336%	539%
UK					15				
USA	3,098	16,603	3,450	16,600	5,600	352		11%	
TOTAL	**10,897**	**67,246**	**12,635**	**73,549**	**21,443**				

Ruggero Bertani (2015)

Geothermal potential in Spain

RECURSOS GEOTÉRMICOS SONEROS		CUALQUIER EMPLAZAMIENTO
Sistemas asociados a sedimentos profundos	Baja temperatura en cuencas zenozoicas y otros almacenes sedimentarios profundos	**Cuenca del Tajo:** Madrid **Cuenca del Duero:** León, Burgos y Valladolid **Área Prebética e ibérica:** Albacete y Cuenca **Cuenca del Guadalquivir**
	Baja y/o media temperatura en zonas intramontañosas y volcánicas	**Galicia:** zonas de Orense y Pontevedra **Depresiones catalanas:** Vallés, Penedés, La Selva, Ampurdán, Olot **Depresiones internas de las Cordilleras Béticas:** Granada, Guadix, Baza, Cartagena, Mula, Almería, Mallorca **Pirineo oriental:** zona de Jaca-Sabiñanigo **Canarias:** isla de Gran Canaria
Sistemas geotérmicos estimulados	Asociados a basamento granítico cubierto por una cobertera suficientemente potente de sedimentos	
	Granitos térmicamente activos asociados a sistemas de fracturación profunda	
Recursos de alta temperatura		**Islas Canarias:** Tenerife, Lanzarote y La Palma

Distribution of resources by technologies in Spain, IGME. Manual de Geotermia de Canarias (GOBCAN)

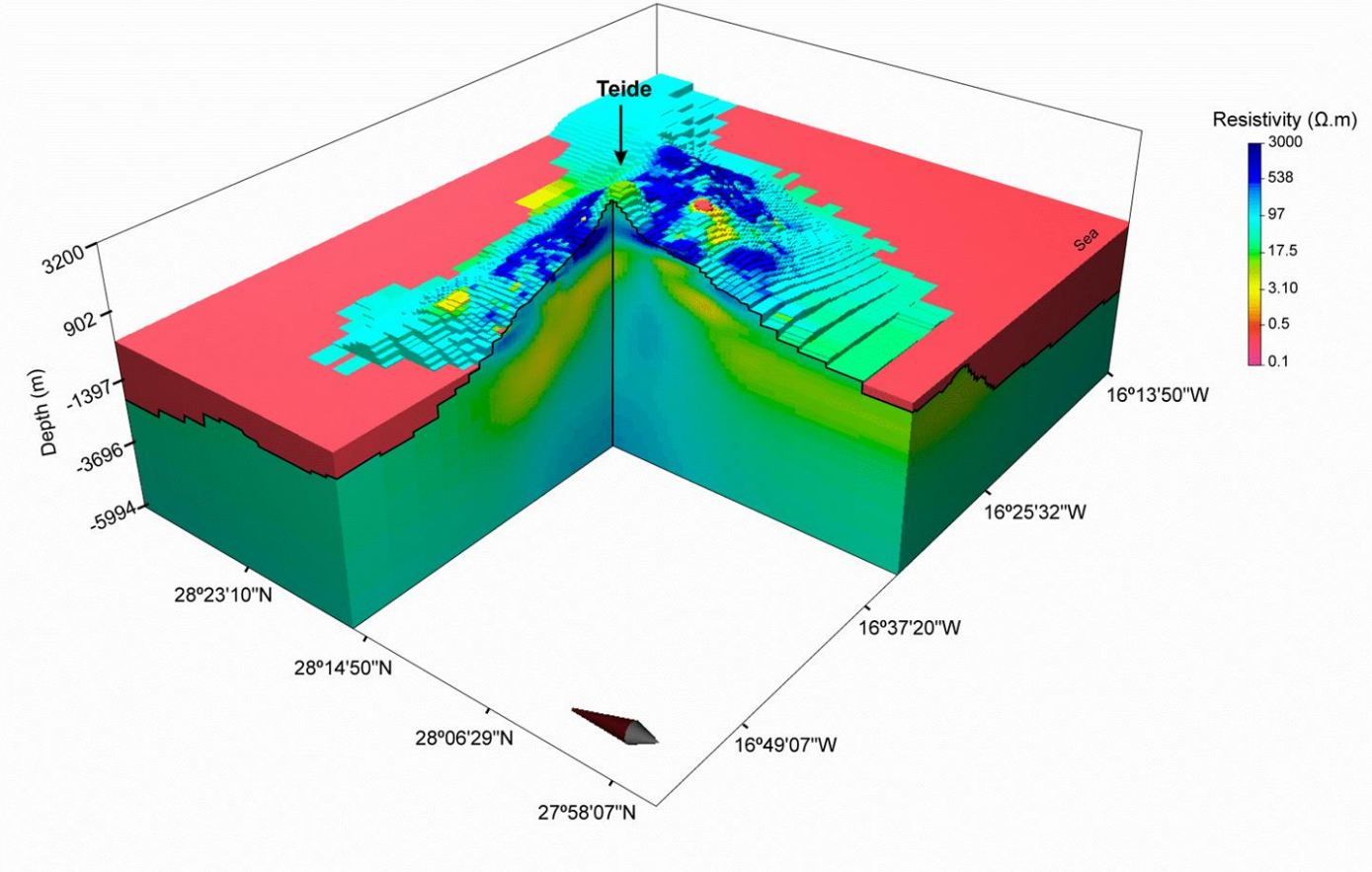
Main Assumptions

- The Canary Islands have great geothermal potential as a consequence of their active volcanism.
- The Canary Islands have an important and stable energy demand supported by the consumption of the resident and tourism populations.
- The energy isolation of the islands makes it a very unique market with average electricity prices close to 200 €/MWh . Geothermal energy can provide stability to the grid, contribute to the reduction of fossil fuels and emissions and reduce the average price of energy.
- The Canary Island's future energy goes through the development of high enthalpy geothermal energy.

Situation of geothermal studies in the Canary Islands

- The Canary Islands were widely studied by the Spanish Geological Survey (IGME) between 1970 – 1980. As a result of these exploratory studies, one exploratory drilling in Tenerife and two in Gran Canaria were performed with unsatisfactory results.
- Stoppage of research from 1994 to 2006.
- A renewed interest in geothermal energy is emerging for the generation of electricity on a global scale as renewable energy on Earth, but this interest in the Canary Islands requires the necessary and sufficient support from public and/or private entities so that geothermal energy contributes to strengthen the mix energy in the Canary Islands.

Geophysical methods for geothermal exploration (Magnetotelluric, MT)



A 3-D resistivity model showed a geoelectrical distribution typical of a high-temperature geothermal system with a low resistivity layer, interpreted as an impermeable clay cap located roughly at 1,500 meters depth.

(Piña-Varas et al 2014)

Geochemical methods for geothermal exploration (Diffuse degassing surveys)

- Soil gas surveys in the **southern volcanic-rift** of Tenerife provided useful information about the mechanisms of **uprising of deep-seated gases** and helped finding **vertical permeability** structures that favour leakage of endogenous gases from the volcano-geothermal system.

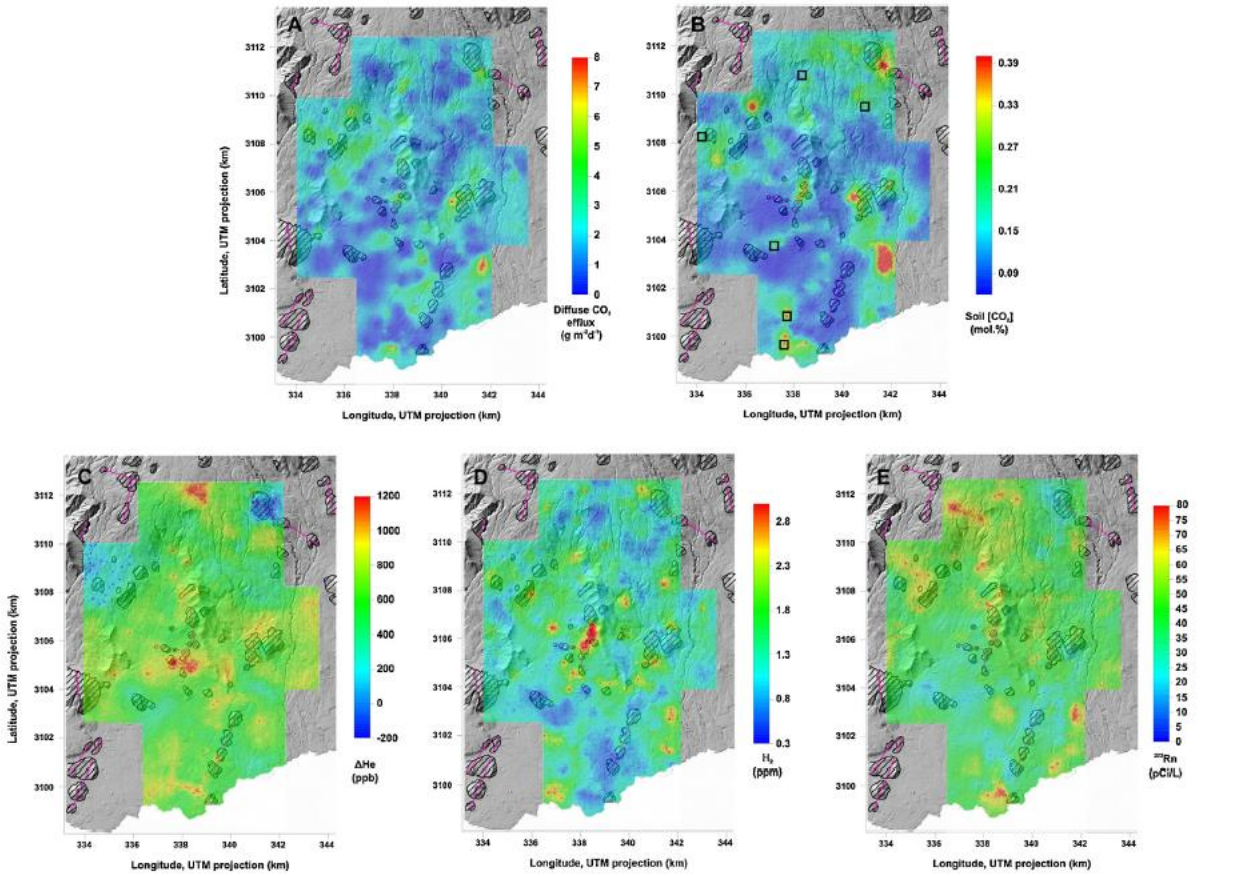


Fig. 6. Spatial distributions of diffuse CO_2 efflux (A), soil CO_2 concentration (B), ΔHe (C), H_2 concentration (D) and ^{222}Rn values (E), based on 100 equiprobable sequential Gaussian simulations. Open squares in (B) indicate the location of samples showing a significant contribution of deep seated CO_2 in Fig. 3B. The location of eruptive fissures (pink lines) and vents (hatched areas) is also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

(Rodríguez et al 2015 a)

Geothermal Exploration Research in Tenerife

Combination of geochemical and geophysical methods for geothermal exploration

- The **inverse correlation between the thickness of the detected clay alteration cap and enrichments of non-reactive gases as He**, suggests the presence of permeability discontinuities in the study area since the uprising of volcano-geothermal gases towards the surface is less hindered where lower thickness of the clay alteration cap is present.

(Rodríguez et al 2015 a)

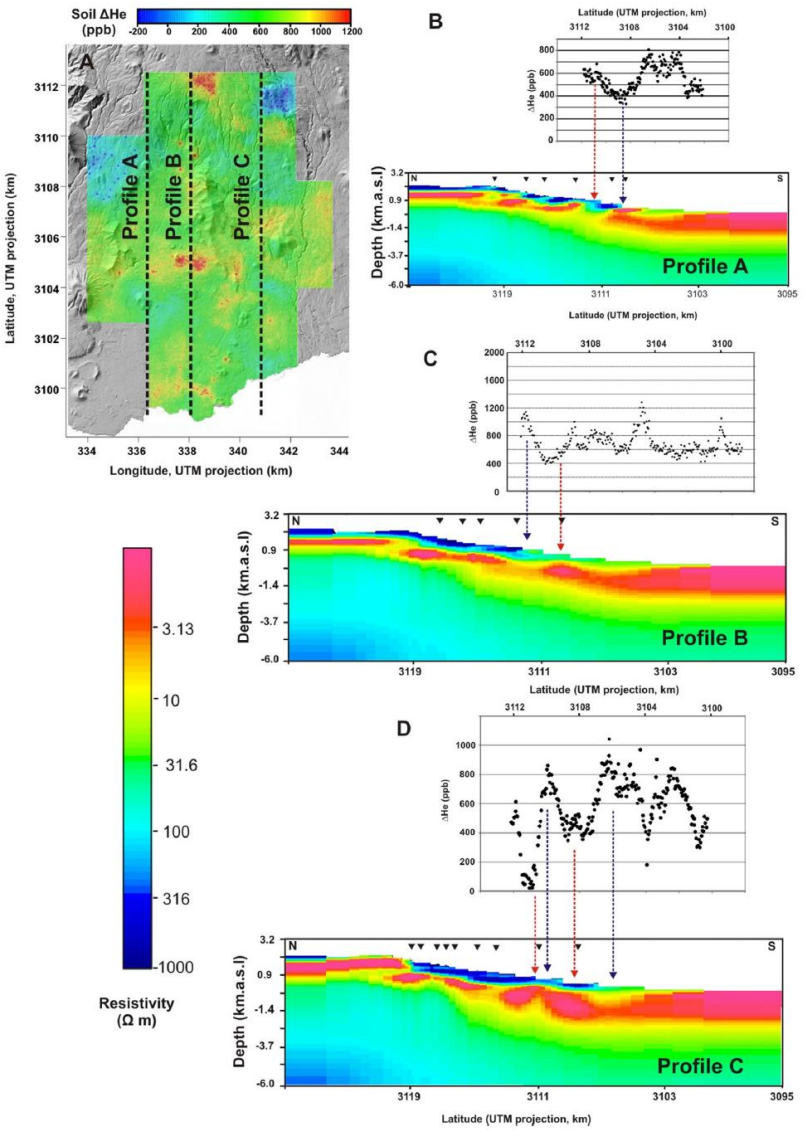
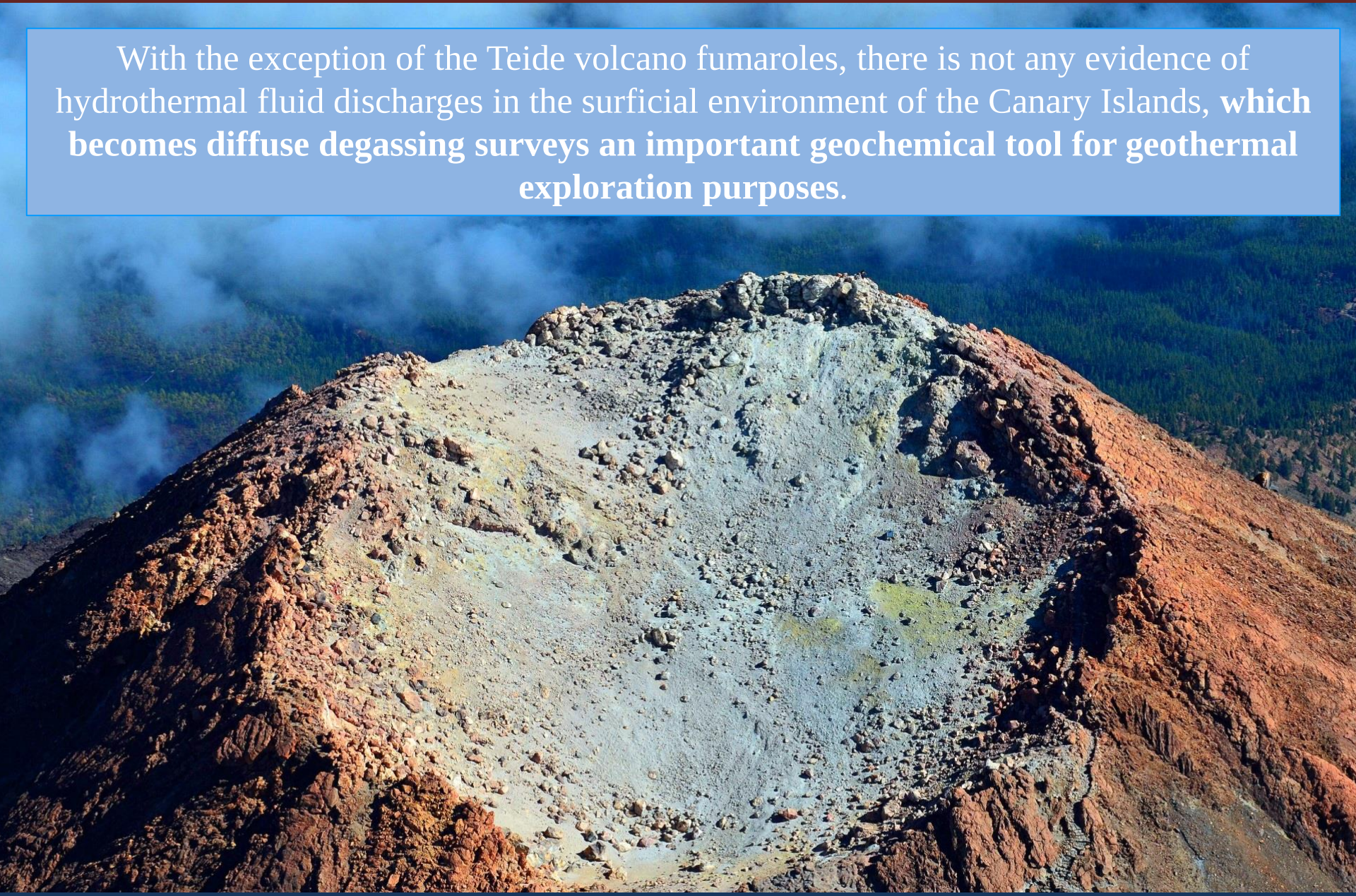


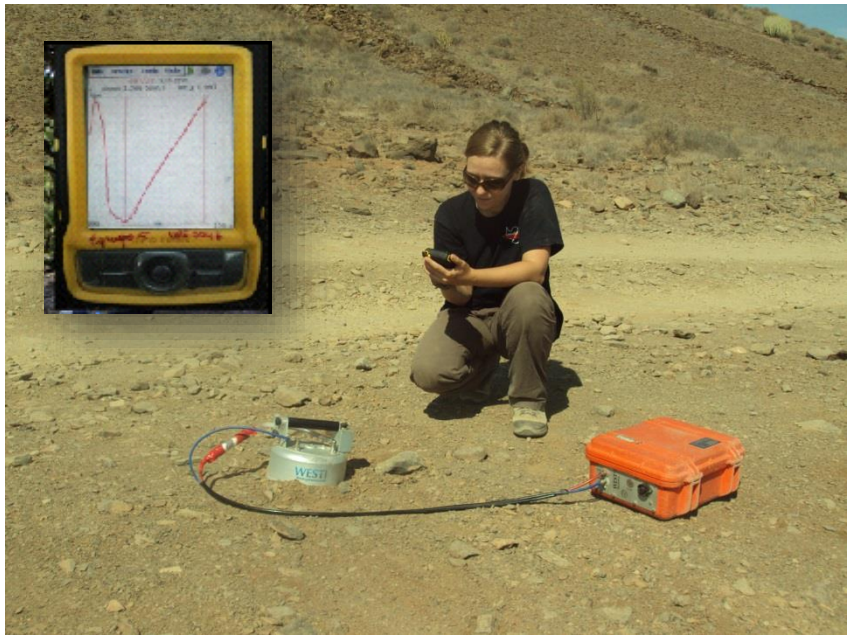
Fig. 9. (A) ΔHe map showing the location of the N–S resistivity cross-section corresponding to three N–S profiles. (B), (C) and (D) depict values of soil ΔHe and results of the final 3-D resistivity model along A, B and C vertical N–S cross-sections respectively. Blue and red dashed arrows indicate observed positive and negative correlation between highest values of ΔHe and clay cap discontinuities and lowest values of ΔHe and the thicker clay cap, respectively. Inverse black triangles show the location of MT sites within each profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

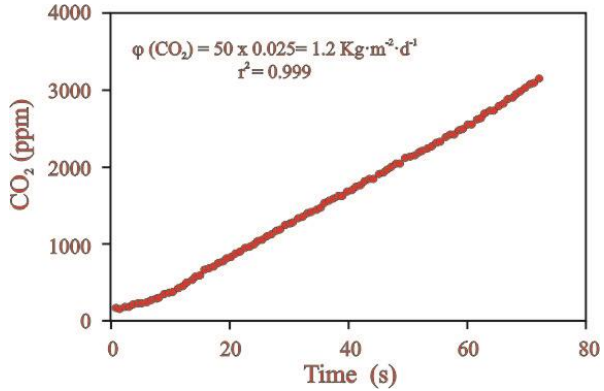
Why diffuse degassing surveys?

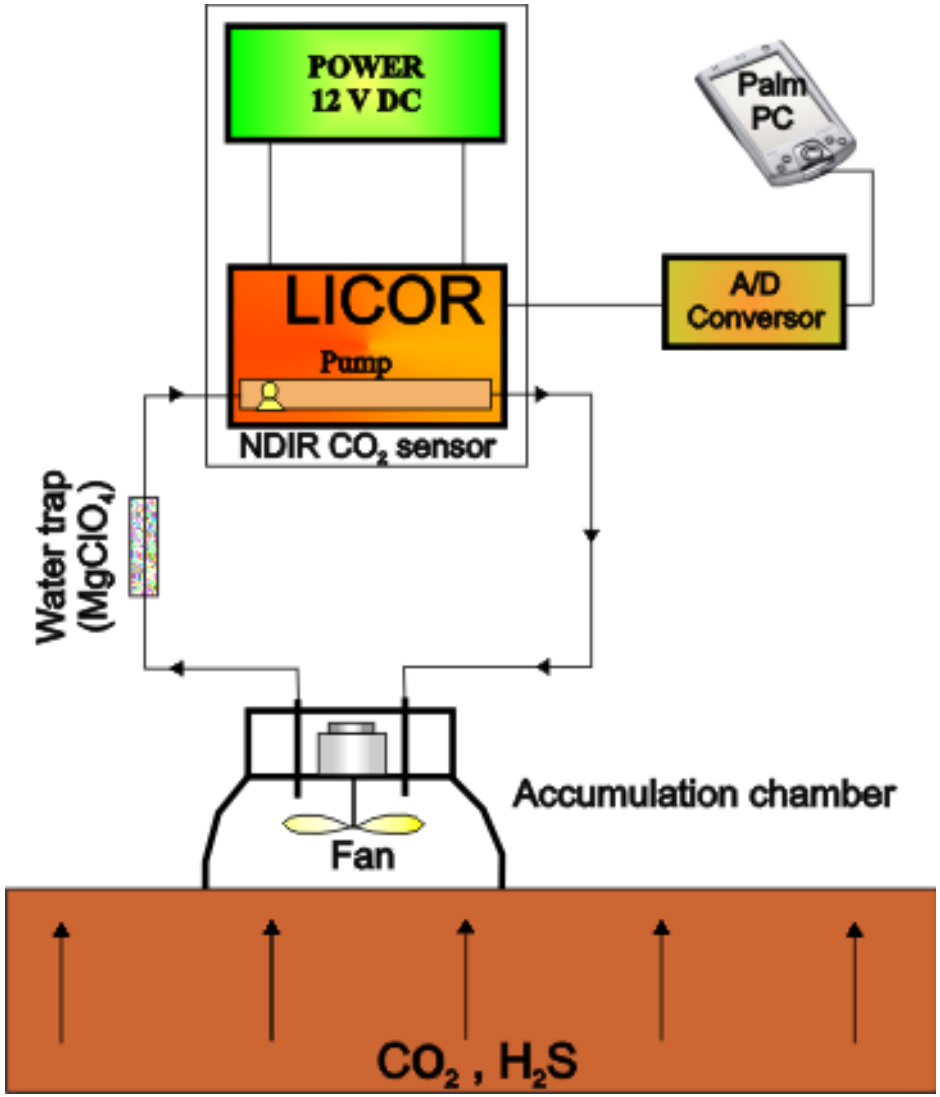
With the exception of the Teide volcano fumaroles, there is not any evidence of hydrothermal fluid discharges in the surficial environment of the Canary Islands, **which becomes diffuse degassing surveys an important geochemical tool for geothermal exploration purposes**.



Methodology: In-situ CO_2 efflux measurements







(Parkinson 1981; Chiodini et al 1998)

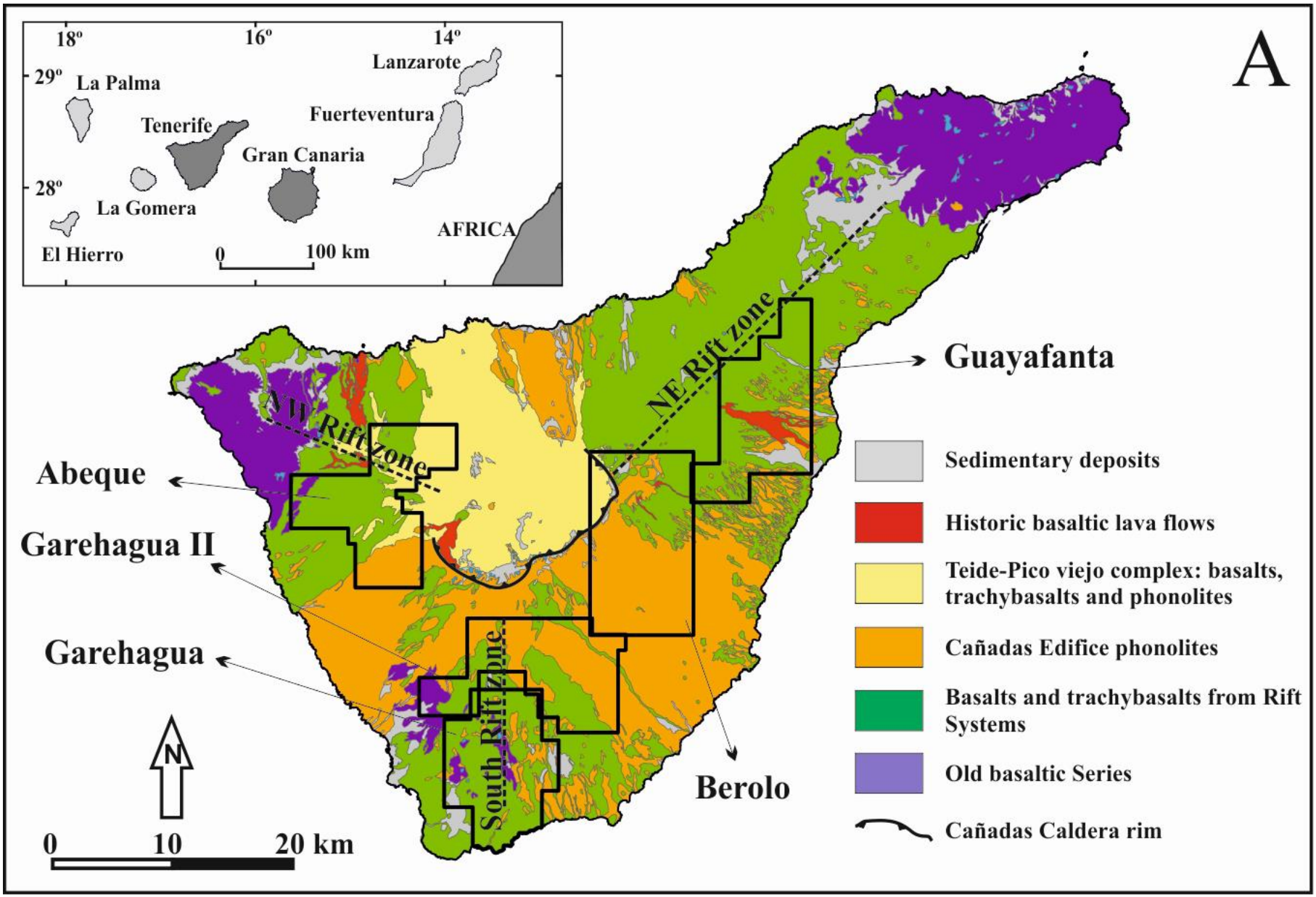
Methodology:
Soil gas sampling for chemical & isotopic analysis

Soil gas sampling at 40 cm depth for later analysis in laboratory by means:

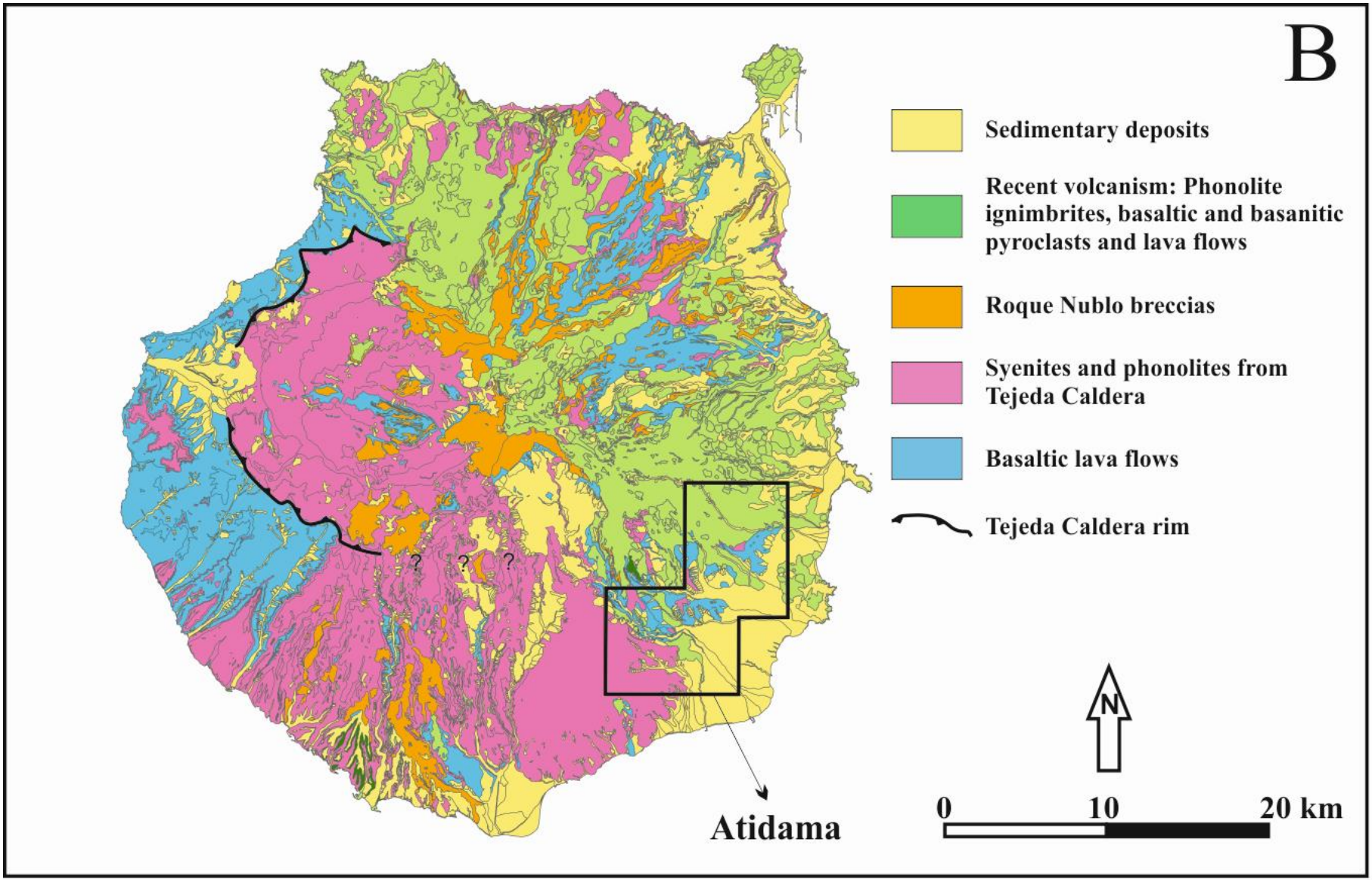
- Micro-gas chromatography (H_2, O_2, N_2, CO_2 & Ne)
- Quadrupole mass spectrometry (He, Ar isotopes)
- Isotopic ratio mass spectrometry ($\delta^{13}C$-CO_2)

(IRMS) – Thermo Finnigan MAT 253

The Oceanic volcanic island of Tenerife

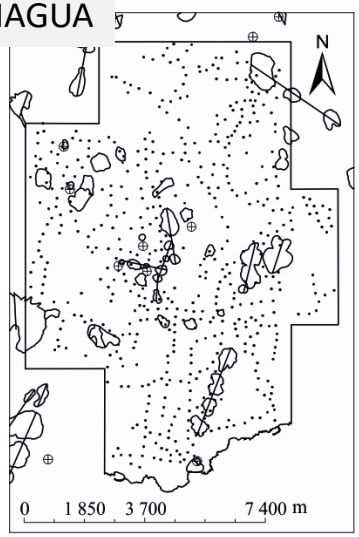


The Oceanic volcanic island of Gran Canaria

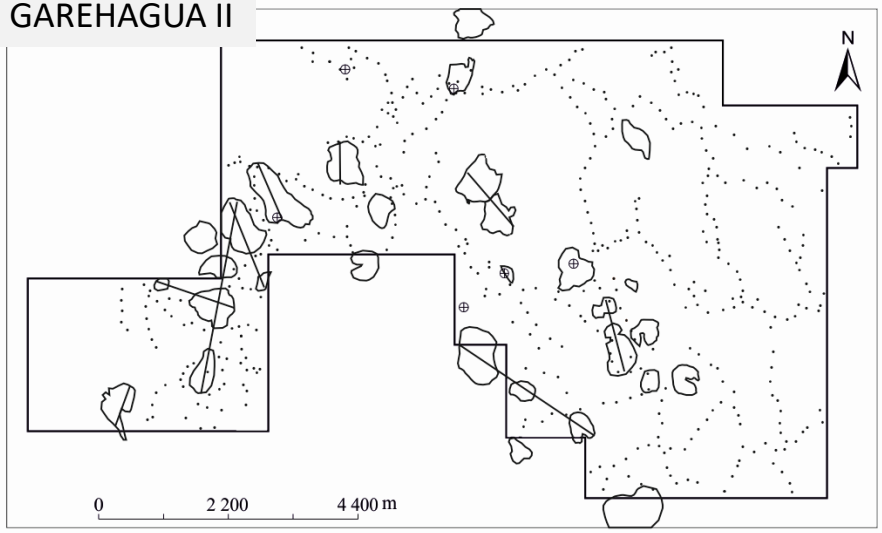


Volcano-structural maps and sample sites location

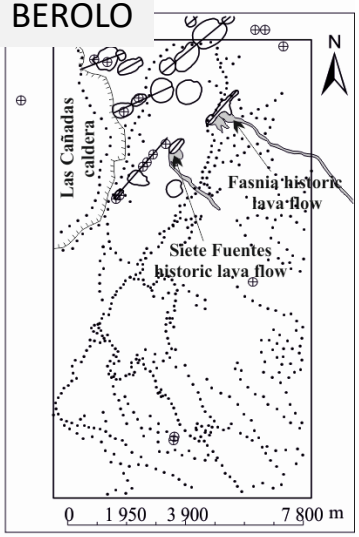
GAREHAGUA



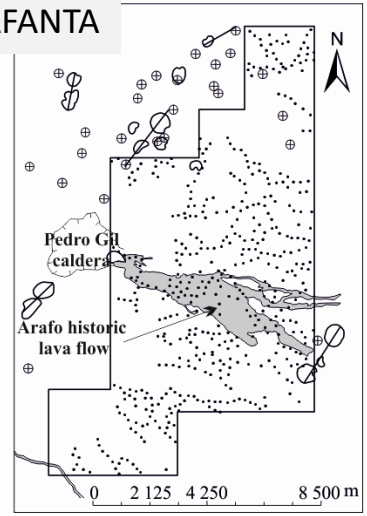
GAREHAGUA II



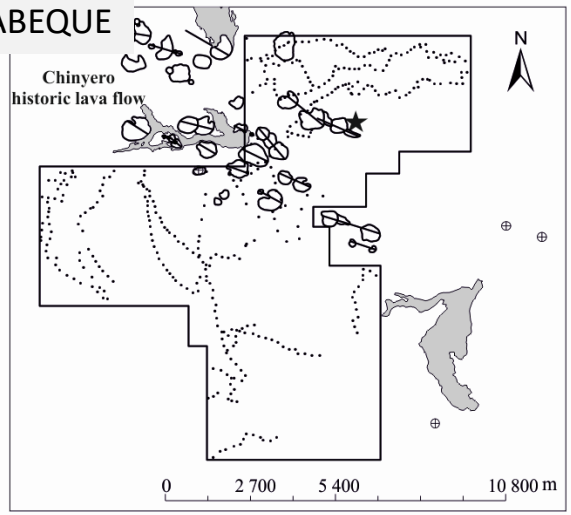
BEROLO



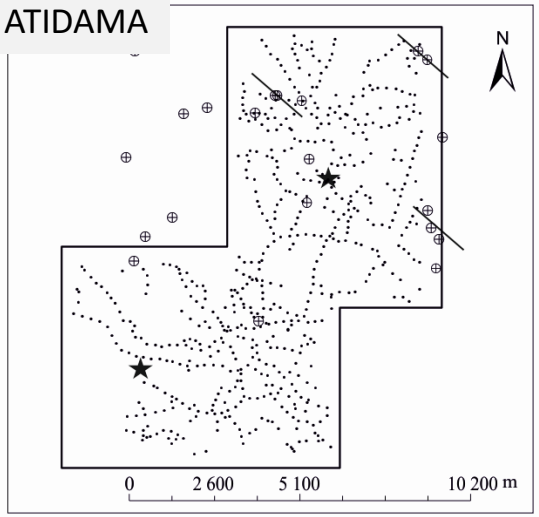
GUAYAFANTA



ABEQUE

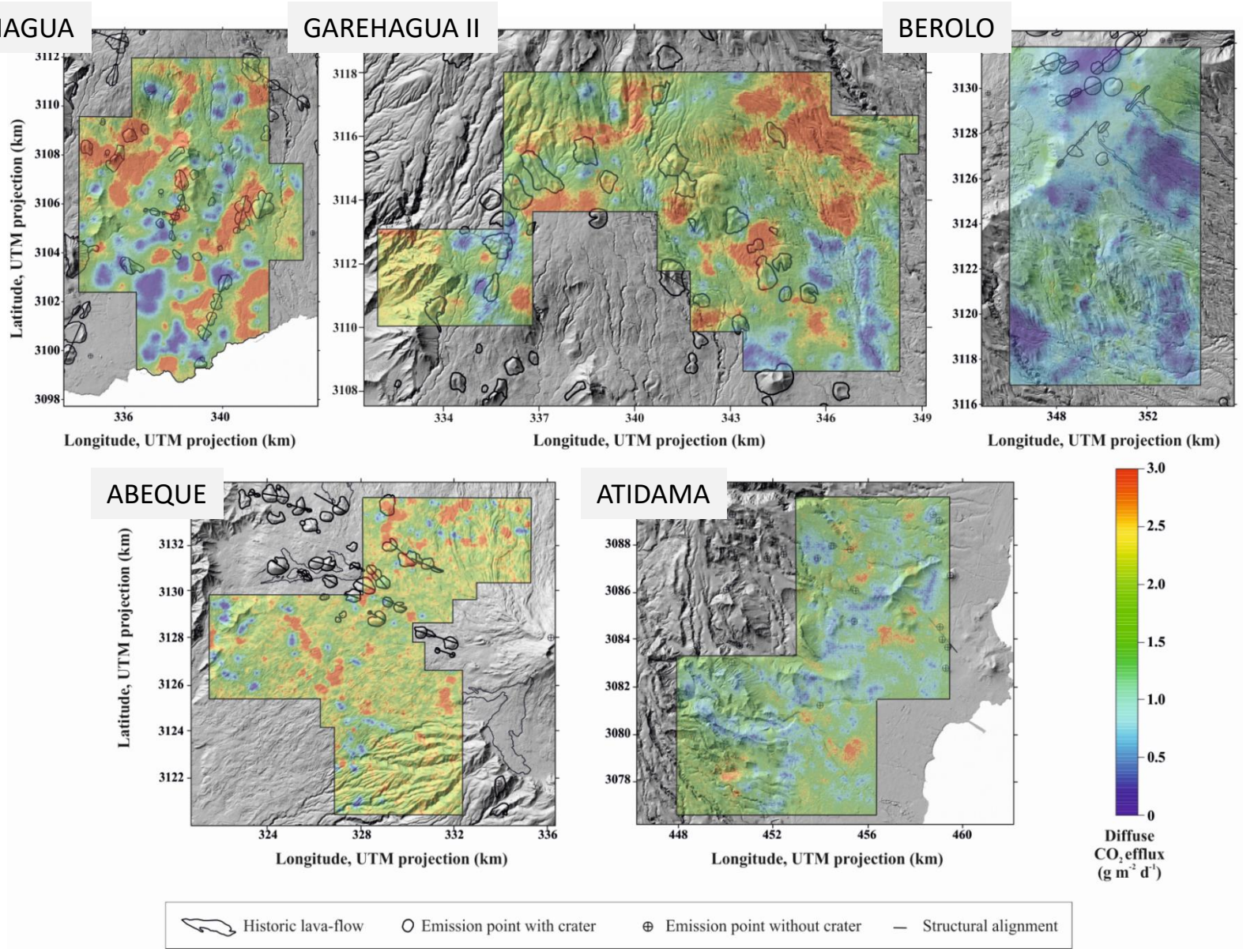


ATIDAMA



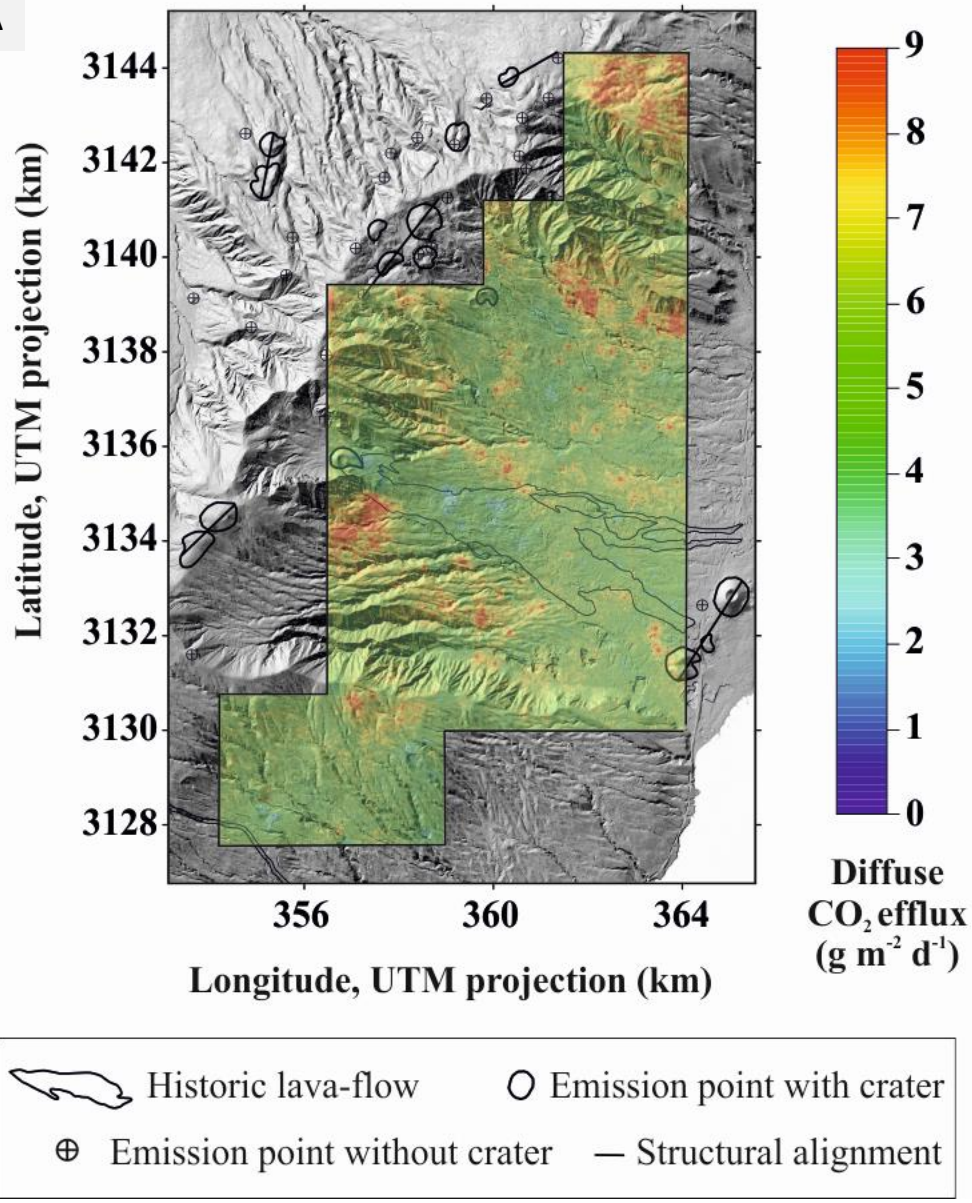
Historic lava flow | Eruption point with crater | Eruption point without crater | Structural alignment | Exploratory drilling | Sample point | Caldera rim

Spatial distribution maps of diffuse CO_2 efflux

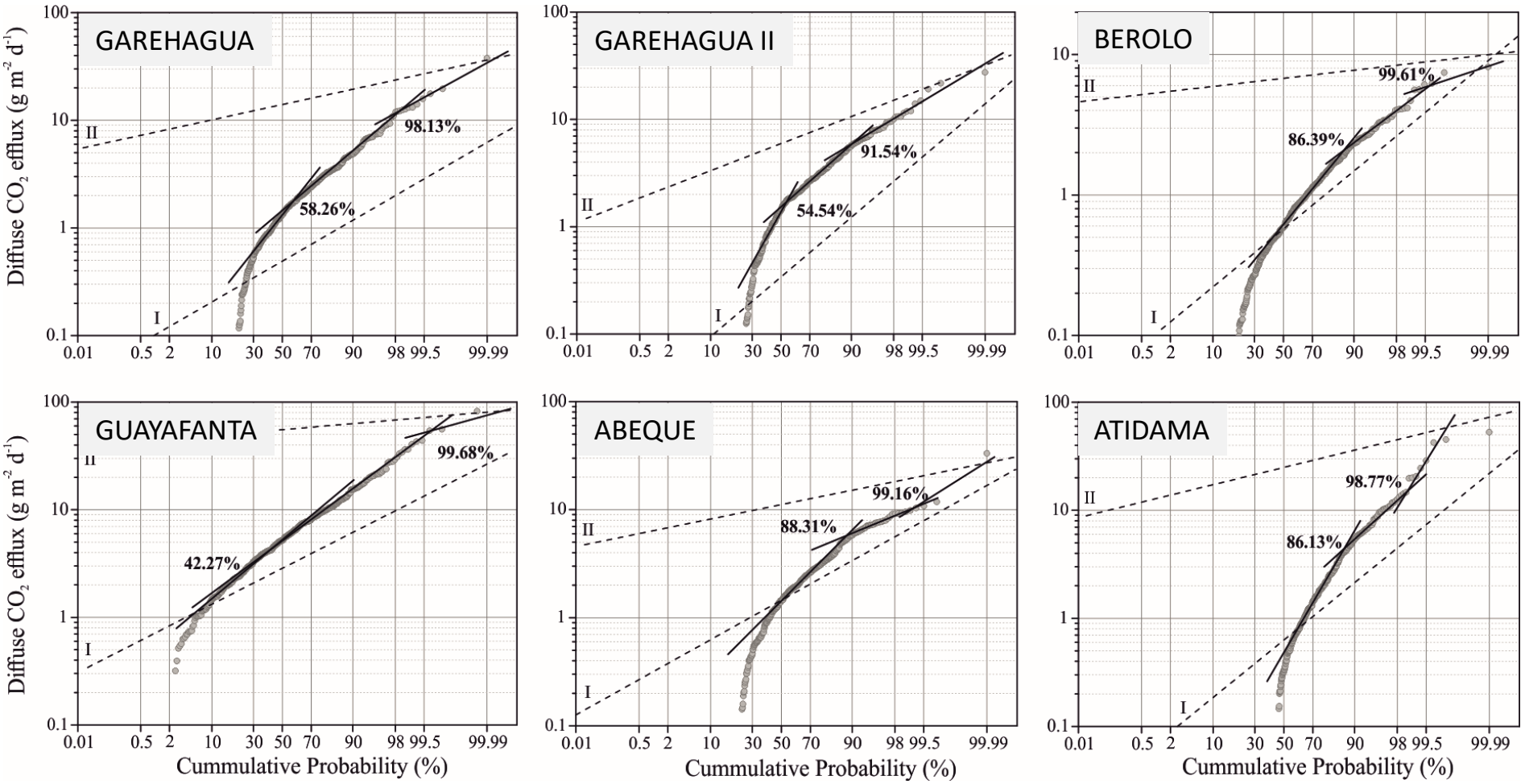


Spatial distribution maps of diffuse CO_2 efflux

GUAYAFANTA

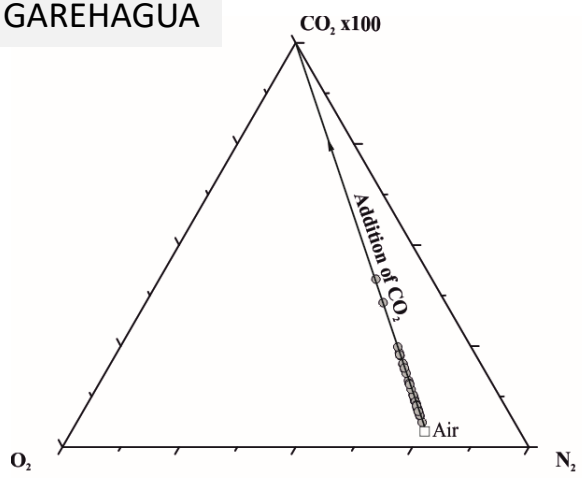


Cumulative probability plots of soil diffuse CO_2 efflux

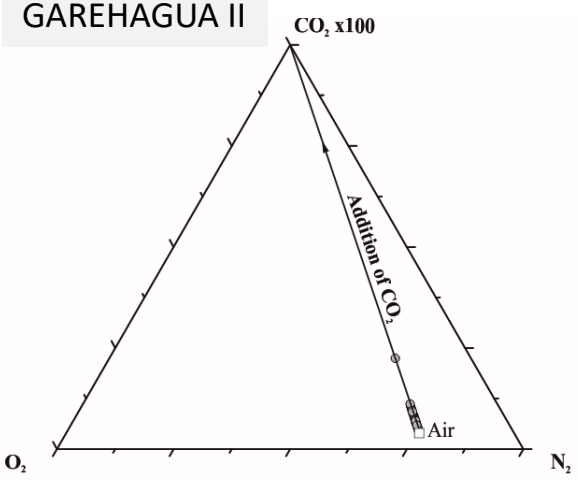


Ternary N_2-CO_2-O_2 diagrams of soil gases

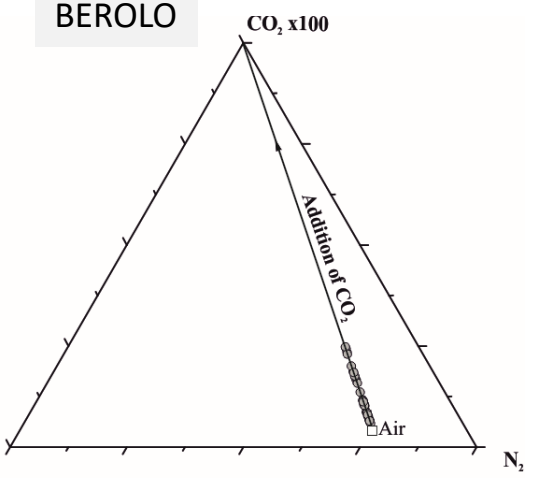
GAREHAGUA



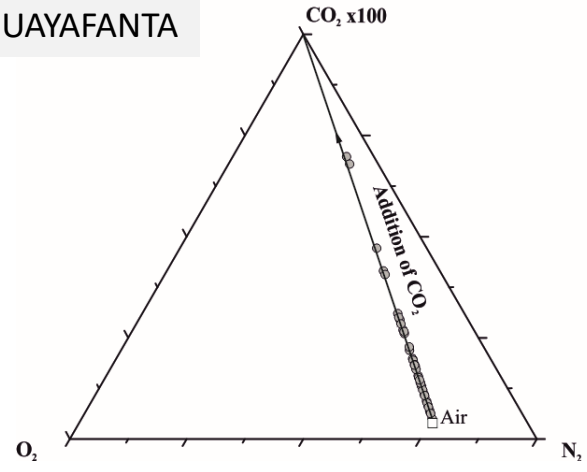
GAREHAGUA II



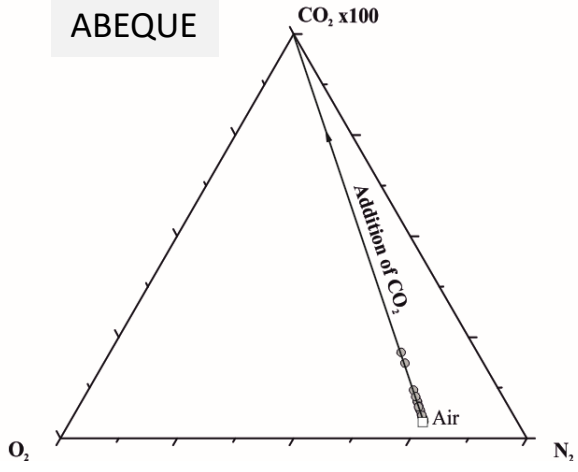
BEROLO



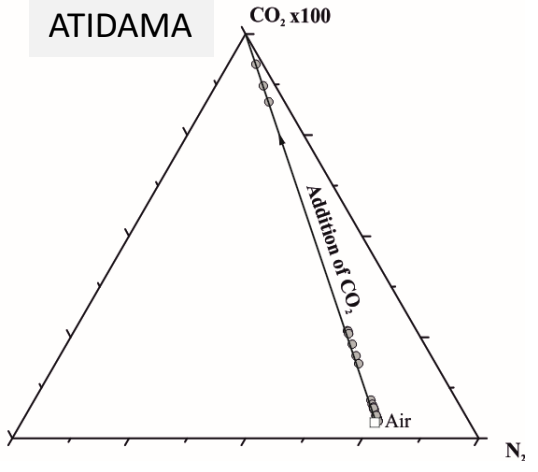
GUAYAFANTA



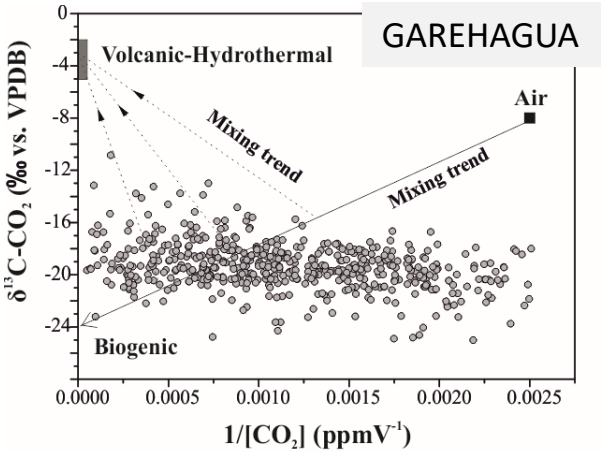
ABEQUE

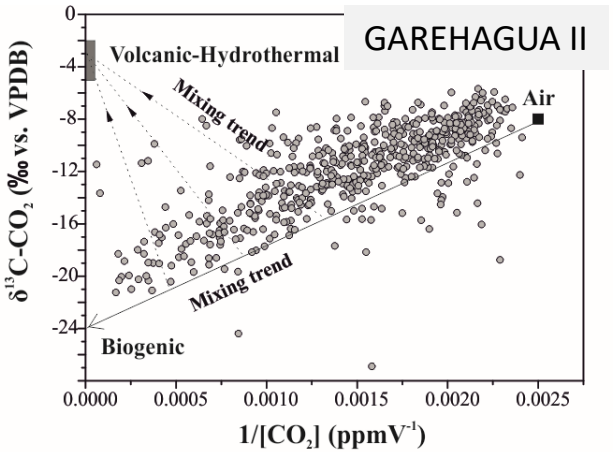


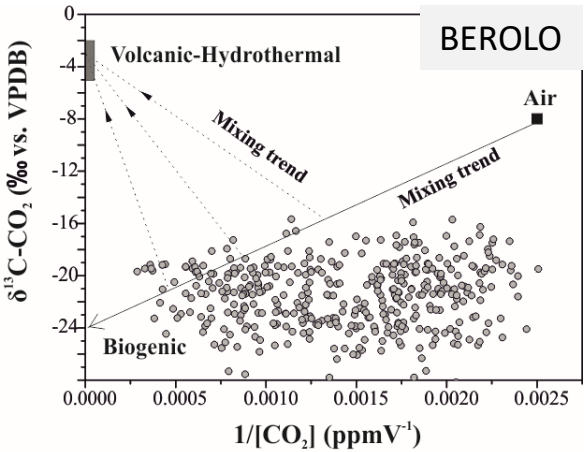
ATIDAMA

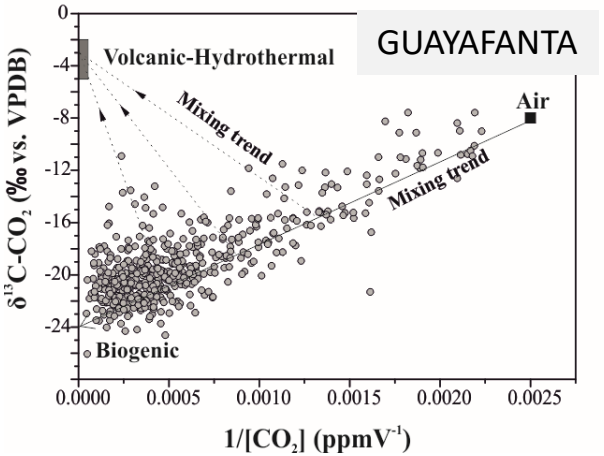


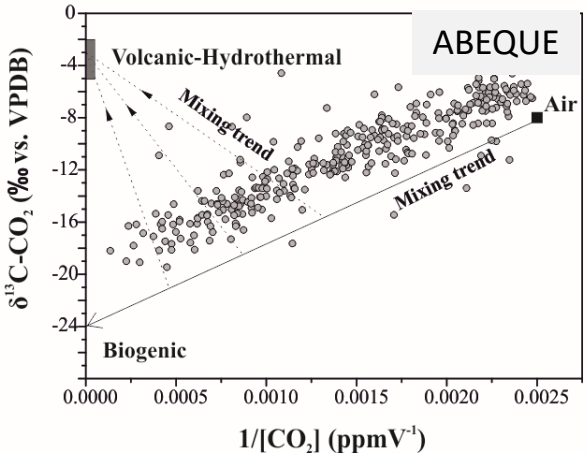
Diagrams of $\delta^{13}C\text{-}CO_2$ against $1/[CO_2]$ ($ppmV^{-1}$)

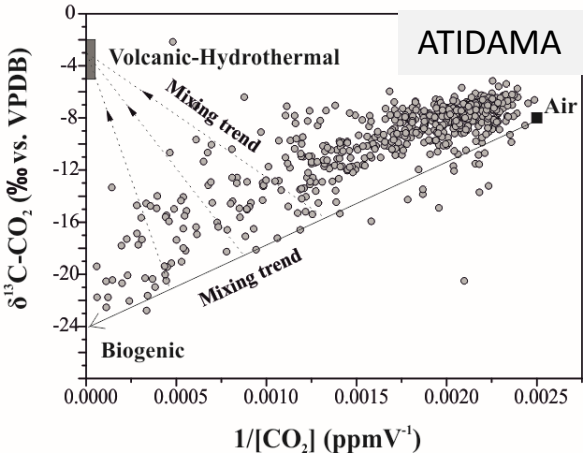












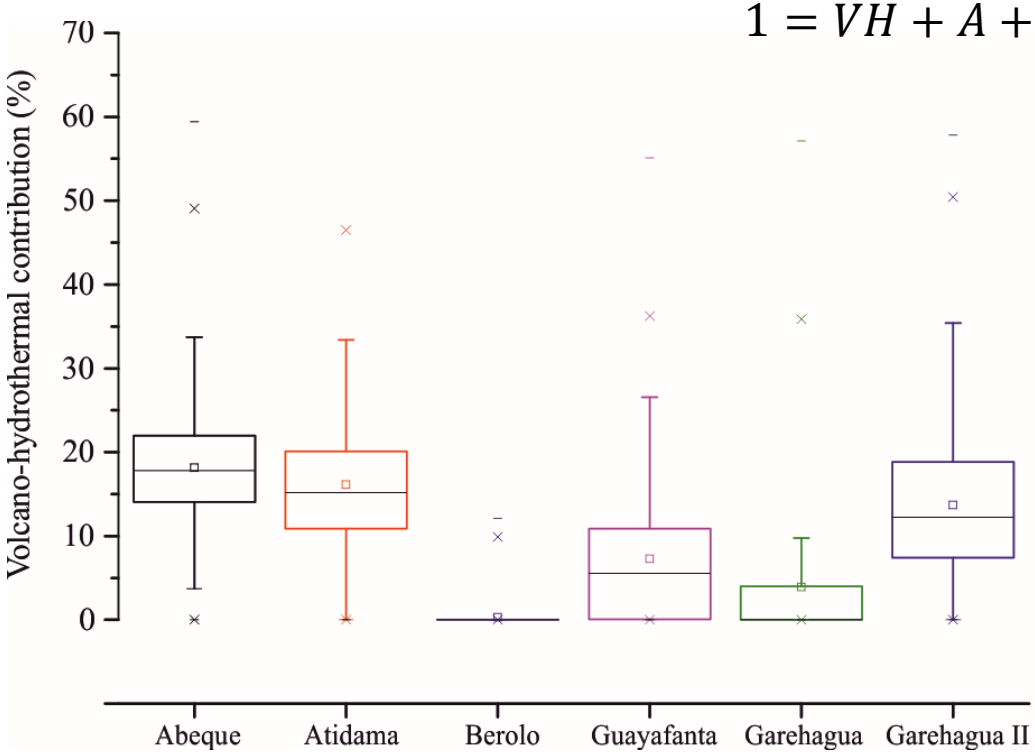
Volcano-hydrothermal contribution

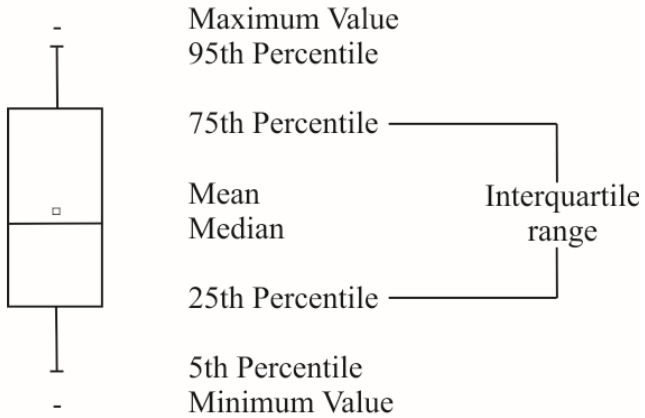
Three different end-members were considered: (1) air (A), (2) volcanic-hydrothermal (VH) and (3) biogenic (B). The relationships of these reservoirs for a gas sample can be defined based on an equation system with three unknowns:

$$\delta^{13}C(s) = VH \cdot \delta^{13}C(VH) + A \cdot \delta^{13}C(A) + B \cdot \delta^{13}C(B)$$

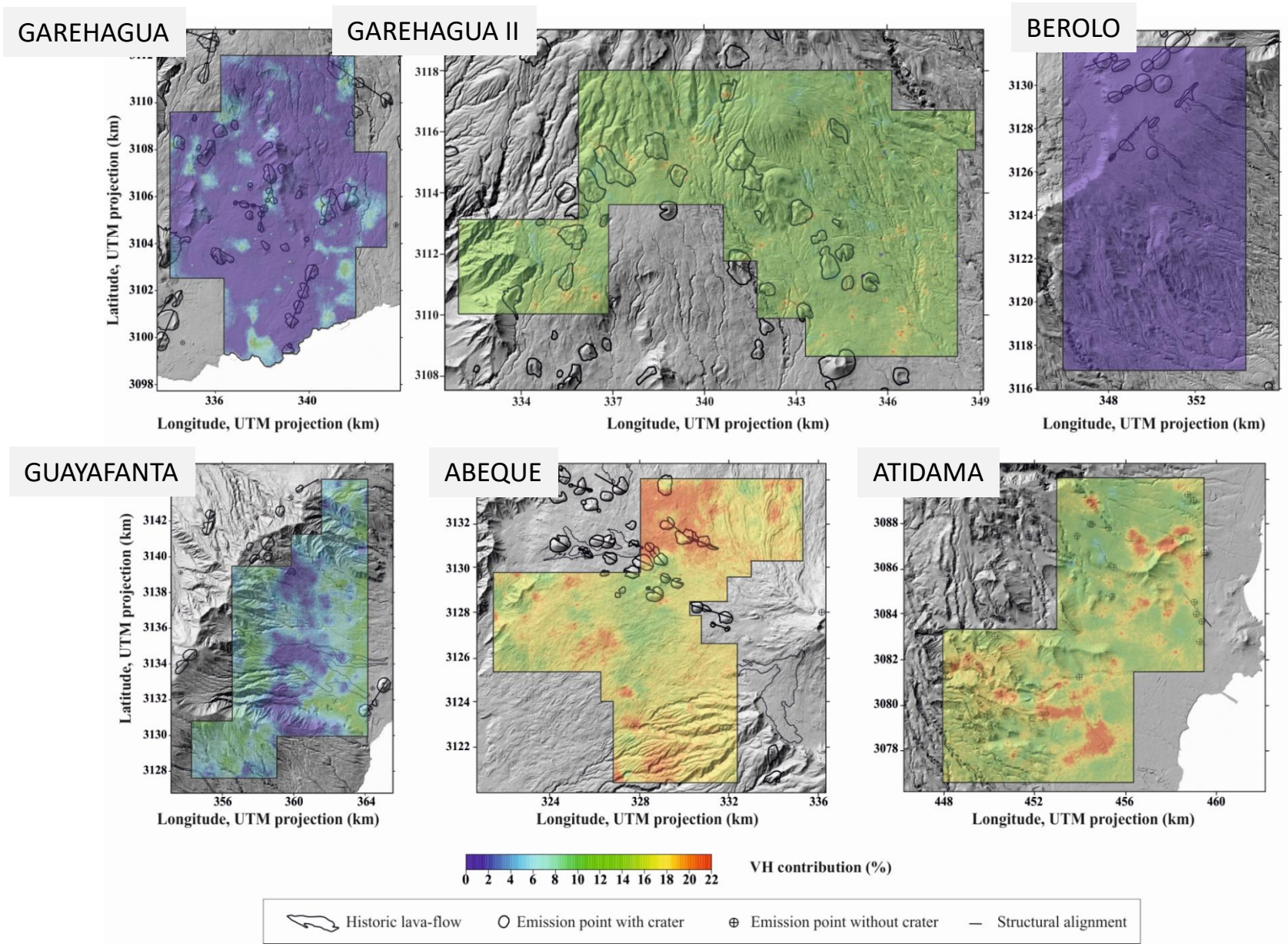
$$\frac{1}{[CO_2]_s} = VH\left(\frac{1}{[CO_2]_{VH}}\right) + A\left(\frac{1}{[CO_2]_A}\right) + B\left(\frac{1}{[CO_2]_B}\right)$$

$$1 = VH + A + B$$





Spatial distribution maps of volcano-hydrothermal contribution (%)



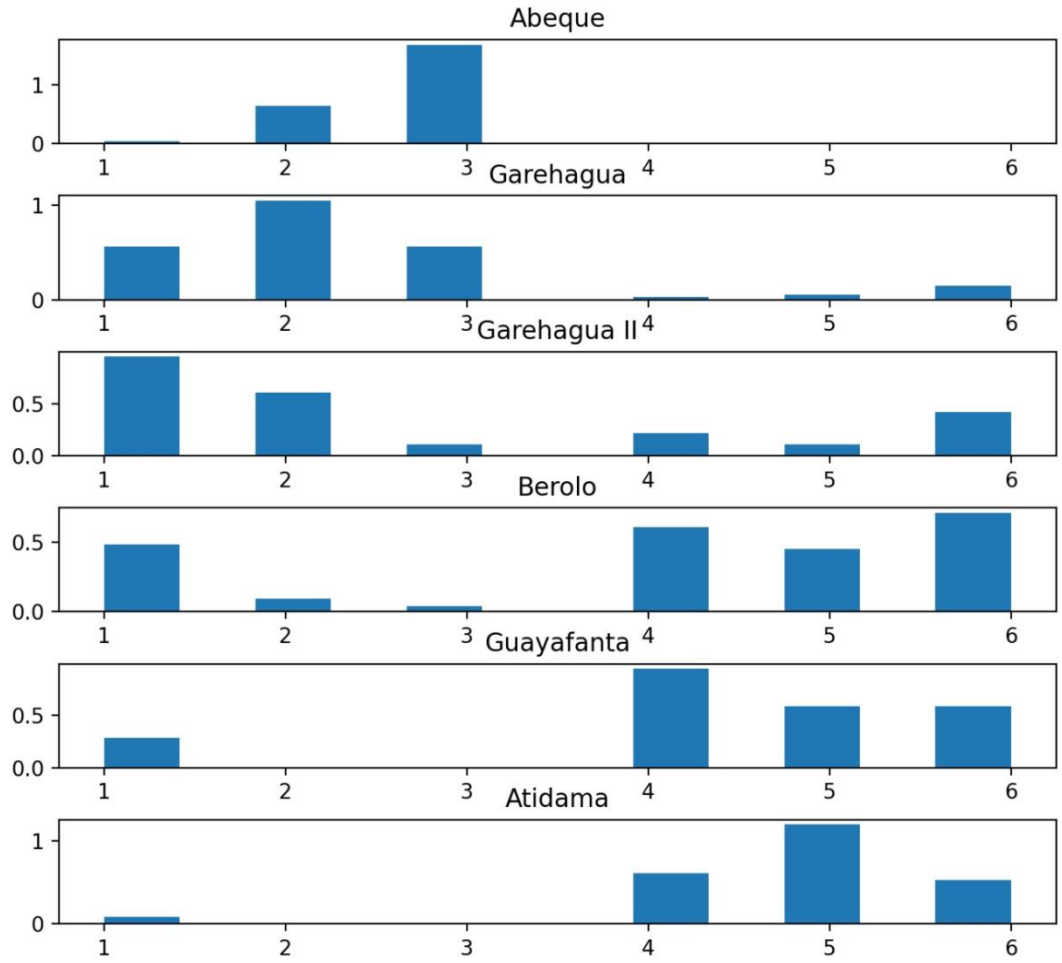
Geochemical and geographical characteristics of the mining licenses

Island	Tenerife					Gran Canaria
Geothermal mining license	**Abeque**	**Garehagua**	**Garehagua II**	**Berolo**	**Guayafanta**	**Atidama**
# Sampling sites	406	557	554	577	541	600
Area (km^2)	102	100	101	130	103	104
Diffuse CO_2 emission (t d^{-1})	217	187	194	109	628	144
Diffuse CO_2 emission rate (t km^{-2} d^{-1})	2.13	1.87	1.92	0.84	6.10	1.38
Peak/Background Pop. ratio of soil CO_2 efflux measurements	7.78	28.36	17.18	12.04	20.10	39.65
Value for Peak/Background ratio[a]	**6**	**2**	**4**	**5**	**3**	**1**
Percentage of the volcano-hydrothermal contribution (%)	18	4	14	0	7	16
Value for percentage of the volcano-hydrothermal contribution[a]	**1**	**5**	**3**	**6**	**4**	**2**
Deep-Seated CO_2 emission (t d^{-1})	40	5.90	28	0.18	43	23
Value for Deep-Seated CO_2 emission (t d^{-1})[a]	**2**	**5**	**3**	**6**	**1**	**4**
CO_2/O_2 ratio - % values > 3 x air ratio	24.93	40.22	17.12	29.51	82.99	14.00
Value for CO_2/O_2[a]	**4**	**2**	**5**	**3**	**1**	**6**
CO_2/Ne ratio - % values > 3 x air ratio	24.15	40.39	17.67	28.47	82.81	13.50
Value for CO_2/Ne[a]	**4**	**2**	**5**	**3**	**1**	**6**
CO_2/Ar ratio - % values > 3 x air ratio	24.93	39.38	17.68	27.01	82.41	13.55
Value for CO_2/Ar[a]	**4**	**2**	**5**	**3**	**1**	**6**
He/CO_2 ratio - % values > 3 x air ratio	0.29	0.00	1.90	0.00	0.00	0.00
Value for He/CO_2[a]	**2**	**6**	**1**	**6**	**6**	**6**
He/Ne ratio - % values > 3 x air ratio	0.80	0.18	4.94	0.00	0.00	0.00
Value for He/Ne[a]	**2**	**3**	**1**	**6**	**6**	**6**
He/Ar ratio - % values > 3 x air ratio	0.57	0.18	5.27	0.00	0.00	0.00
Value for He/Ar[a]	**2**	**3**	**1**	**6**	**6**	**6**
He/CH_4 ratio - % values > 3 x air ratio	0.57	0.18	4.56	0.00	0.00	0.00
Value for He/CH_4[a]	**2**	**3**	**1**	**6**	**6**	**6**
H_2/CO_2 ratio - % values > 3 x air ratio	2.10	4.31	9.11	5.03	0.00	7.83
Value for H_2/CO_2[a]	**5**	**4**	**1**	**3**	**6**	**2**
H_2/Ne ratio - % values > 3 x air ratio	2.89	22.44	41.17	39.76	1.48	42.50
Value for H_2/Ne[a]	**5**	**4**	**2**	**3**	**6**	**1**
H_2/Ar ratio - % values > 3 x air ratio	2.00	19.96	42.21	39.64	1.11	41.97
Value for H_2/Ar[a]	**5**	**4**	**1**	**3**	**6**	**2**
H_2/CH_4 - % values > 3 x air ratio	2.89	22.62	36.98	30.03	1.11	13.50
Value for H_2/CH_4[a]	**5**	**3**	**1**	**2**	**6**	**4**
CH_4/CO_2 - % values > 3 x air ratio	0.00	0.18	0.00	0.00	0.00	0.17
Value for CH_4/CO_2[a]	**6**	**1**	**6**	**6**	**6**	**2**
CH_4/Ne - % values > 3 x air ratio	0.26	0.36	0.18	3.47	0.00	0.17
Value for CH_4/Ne[a]	**3**	**2**	**4**	**1**	**6**	**5**
Total geochemical values	**58**	**51**	**44**	**68**	**71**	**65**

Bootstrapping analysis

- This statistical analysis consists of a random sampling with replacement allowing the assessment of the accuracy of results.

- It was applied to the ranks obtained from the weighting, confirming that the selection of some parameters against others would not influence the final ranking.



CONCLUSIONS

- Combining the overall information shown in this work, based on selected geochemical molar ratios, spatial distribution of CO_2 efflux, statistical-graphical analysis of CO_2 efflux, $\delta^{13}C$-CO_2 isotopic data, the calculated volcano-hydrothermal contribution of CO_2 and the deep-seated CO_2 efflux , it is possible to obtain weighting tools to sort the six different study areas in terms of their relative potential of finding geothermal resources. In this context, **Garehagua II, Garehagua** (both located in the **NS volcanic rift of Tenerife**) and **Abeque** (located in the **NW volcanic rift of Tenerife**) are, in this order, the mining licenses studied that showed the highest potential to contain geothermal resources, based on the geochemical indicators ranking proposed.
- Tenerife Geothermal Power Project is actually in an advanced phase of surface geothermal exploration but additional geochemical and geophysical studies would be necessary to reduce the uncertainty inherent to the selection of the area with the highest success in future exploration/drilling works.

ACKNOWLEDGEMENTS

Project GeoAtlantic (EAPA_527/2016)

Project GEOTHERCAN (IPT-2011-1186-920000)
Project TERMOVOLCAN (RTC-2017-6627-3)

Project TFGeotermia

Project GCGeotermia

Photography: Alba Martín Lorenzo