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CARBON DIOXIDE SOIL EMISSION MONITORING AS A TOOL FOR THE ASSESSMENT OF ENVIRONMENTAL IMPACT OF GEOTHERMAL PLANTS

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ABSTRACT

Volcanic and non-volcanic geothermal areas often exhibit surface emissions of gases and steam, both hot and cold. This study aimed to assess the relative contribution of CO_2 emissions from geothermal power plants compared to natural ground emissions. Diffuse soil emissions were measured using accumulation chambers, while localized emissions were analyzed with volumetric systems and gas composition analysis. In Larderello, a historical reconstruction was used, analyzing emissions from the ancient "lagoni" once exploited for boric acid. Historical production data and gas analyses revealed that natural emissions have nearly vanished due to deep drilling and steam extraction for electricity generation quantifying the depletion of natural emissions. In Monte Amiata, widespread and focused soil emissions were measured, revealing high CO_2 fluxes even in areas without geothermal plants (e.g., Bagni San Filippo). However, total emissions in developed areas were significantly lower than in undisturbed zones. The study quantitatively compared emissions from developed and natural areas, showing that the reduction in natural emissions is of the same order of magnitude as emissions from geothermal plants. This is clearly demonstrated in Larderello, where natural emissions have disappeared. The key finding is that both natural and plant emissions must be measured to accurately assess the total CO_2 balance in geothermal regions. Moreover, CO_2 flux measurements, both diffuse and focused can serve as a practical tool for identifying and evaluating geothermal fields for future development.

INTRODUCTION

The issue of CO_2 emissions from Geothermal Power Plants (GPPs) has gained increasing interest in the context of current climate change discussions. Historically, emissions resulting from geothermal energy utilization were categorized as non-anthropogenic, deriving from natural source fluxes released into the atmosphere via natural surface venting. In a recent report from IPCC[i] Geothermal energy is acknowledged as a renewable and sustainable energy source. With appropriate resource management, the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by injection of the depleted (cooled) fluids. Moreover, hot fluid production can emit varying quantities of GHGs, which are usually small. These originate from naturally sourced CO_2 fluxes that would eventually be released into the atmosphere through natural surface venting. The exploitation of geothermal energy does not ultimately create any additional CO_2

from the subsurface, since there is no combustion process, though the rate of natural emissions can be altered by geothermal production depending on the plant configuration.

Carbon dioxide is naturally released from geothermal fields through various pathways, including soil flux, steam vents, fractures, steam-heated mud-pools, and thermal springs CO_2 transport that occur through groundwater flow, involving the absorption and release of the gas (within the geothermal reservoir) via mineral precipitation or degassing processes[ii]. Although soil emissions of CO_2 manifest in diverse ways, the specific emission rate is strongly dependent on the geological characteristics of the field and, consequently, exhibits significant variability across different sites. The natural emission rate can be substantially altered by fluid extraction conducted through wells for electric power production, district heating, or, as historically observed in the Larderello area, for boric acid production. In Larderello, the progressive disappearance of natural emissions from steam and gas vents coincided with the growth of steam collection via wells[iii]. This observation strongly suggests that the natural soil emission rate is governed by the interplay between the natural mechanism of gas release and the utilization and extraction processes within the geothermal field. A study by Bertani and Thain (2002)[iv] demonstrated that CO_2 emission factors vary across a very wide range, specifically between 4 and 740 gCO_2/kWh with a weighted average reported at 122 gCO_2/kWh. More recent data, such as those reported by Fridriksson (2017)[v] for Turkish geothermal fields, indicate values as high as 1300 gCO_2/kWh. For comparison, emissions from conventional fossil fuels (natural gas, coal, oil) generally range from 350 to 1100 gCO_2/kWh.

It is therefore reasonable to conclude that, although the emissions from geothermal power plants originate from natural sources, the utilization of the geothermal field can significantly impact the emission rate. Current studies indicate that the emission rate from GPPs can be either higher or lower than the pre-existing natural rate, and, moreover, continued utilization can lead to a long-term reduction in the emission factor.

The sources commonly recognized as potential origins of CO_2 in a hydrothermal system include Hydrolysis of carbonate rocks, Crustal magmatism, Subcrustal magmatism following partial melting of mantle rocks, Metamorphic processes[vi] and in general, carbon dioxide emission is a common phenomenon for most geothermal areas. Moreover, the comparison of GPP CO_2 emission with naturally occurring soil emission is a complex task as the soil emission can vary from focused emission areas through vents and faults and to widespread non focused emission through the soil in geothermally developed and non-developed areas.

In this study we report the criterion used to evaluate the total contribution of soil emissions conducted in the Amiata and classical Larderello area using various experimental approaches useful for a more detailed understanding of CO_2 emissions from geothermal areas and propose a general approach to the evaluation of the contribution of geothermal power plants also taking into account the effects that these can induce on natural emissions. The results of this study can be considered valid for a general approach to the evaluation of the relative contribution of emissions from geothermal power plants with respect to the natural emissions of geothermal fields from which these plants draw the endogenous flows containing CO_2 and used in the production of electricity.

TOTAL EMISSION ACCOUNTING BY NATURAL SOURCES AND GPP OF STUDY AREA

Emission factors, conventionally expressed as the CO_2 emission per kWh produced by a geothermal plant, or potentially as a cumulative measure including methane (defined as the Carbon Dioxide Equivalent), only partially represent a power plant's total contribution to atmospheric CO_2 emissions. This limitation exists because the contribution from surrounding soil emissions must be integrated into the total emission balance, while accounting for any depletion observed before and after geothermal development[vii] is necessary. In this sense the

actual geothermal system to consider in the evaluation actual contribution of CO_2 e mission to the atmosphere must be considered rather than focusing on the only contribution of GPP, the whole context of the power plants and their geothermal field on which they lie on and all the possible relation between soil emission evolution after geothermal development. This suggests that in any case, a detailed characterization of soil emission across the field is essential. Even when CO_2 emissions are confirmed to be of natural origin, it is crucial to measure both the natural surface emissions and those emanating directly from the power plant, as the latter is an integral part of the monitored field.
The comparison of natural soil emission in geothermal areas with respect to pre-development soil emission can be an interesting starting point to evaluate eventual depletion effects on soil emission induced by geothermal utilization. On the other hand, most of the geothermally developed areas in operation today have never evaluated the natural soil emission before the initial extraction and utilization of the fluids. In these cases, a pre and post comparison is not possible; however, a correlation between current soil emissions of developed geothermal areas and the emission rates in contiguous areas is achievable.

Soil emission in geothermally developed areas and other volcanic and non-volcanic areas have been studied including Italy: Kerrick (2001)[viii] reports data of discharge from focused emission in Central Italy corresponding to 50 t/h, Sbrana (2020)[ix] reports for the Amiata Area (225 km^2) emission of shallow biogenic + deep origin carbon dioxide of 556.3 t/h, in the same area by a more extended surface (280 km^2) the author[x] reports 747 t/h, Chiodini (2004)[ii] defines the two main emitting areas of central and south Italy, the Tuscan Roman Degassing Structure (TRDS) with an emission of deep CO_2 of 703 t/h and the in Campanian Degassing Structure (CDS) with emission of deep CO2 of 351 t/h (figure 1). For the flux of CO_2 released into the atmosphere in the entire anomalous area of Central Italy Gambardella (2004)[xi] reports values ranging from 1107 to 1940 t/h.

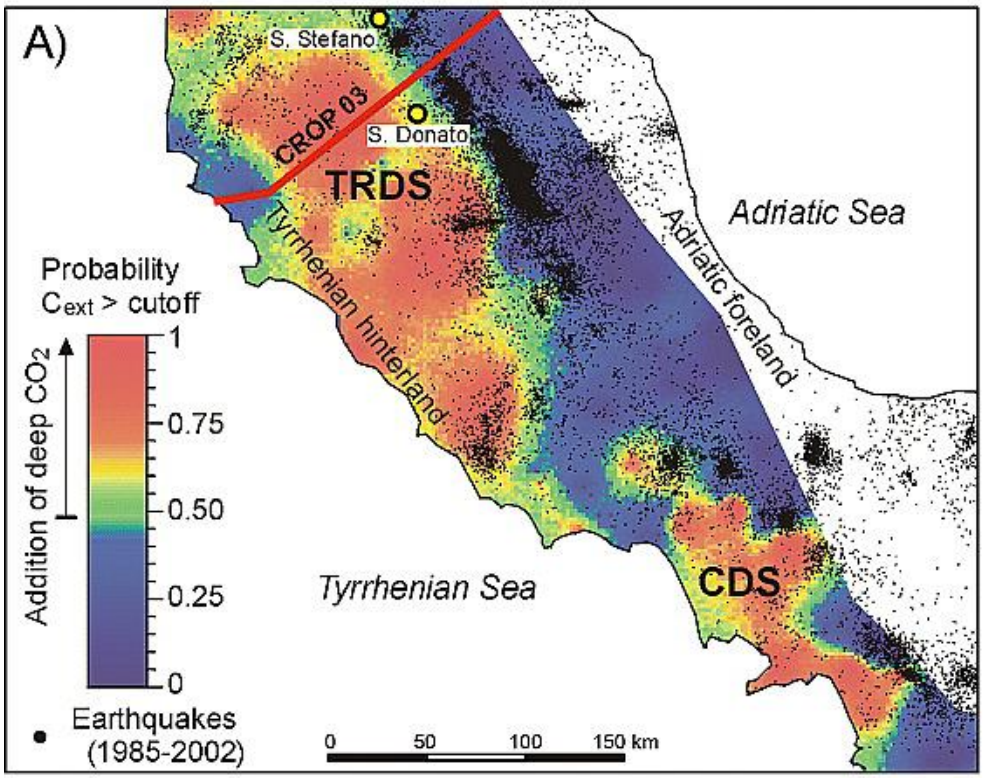


Figure 1: the Tuscan Degassing Structure (TDS) and the Campanian Degassing Structure (CDS) after Chiodini et al. [ii]

GEOTHERMAL POWER PLANTS IN ITALY

Geothermal resources are abundant in Italy, ranging from resources for shallow applications (including heat pump technology), through to medium (> 90 °C) to high (> 150 °C) temperature systems at depths accessible only by wells (usually within 3–4 km). High temperature systems tend to be in tectonically active regions either in volcanic and intrusive or fault-controlled systems. Geothermal resources are today mainly used for generating electricity and air conditioning by means of district heating (DH) and geothermal heat pump systems. The DH systems are mainly located in Tuscany in central Italy, and direct uses are common.

In Italy geothermal power production essentially focused on Tuscany. In the area of Larderello, extending approx. 250 km^2, 200 wells produce superheated steam at a pressure ranging between 2 and 15 bar and temperature ranging from 150°C to 270°C. The non-condensable gas (NCG) content ranges from 1 to 10% by weight. The installed capacity is 594.8 MWe, as of December 2021, with 22 units in operation. In the explored area of Travale-Radicondoli extends for approx. 50 km^2. In this area, 42 wells produce superheated or saturated steam at a pressure ranging from 8 to 20 bars and a temperature of 190-250 °C. The non-condensable gas content is in the range of 5 – 6.5% by weight. The installed capacity is 200 MWe with 8 units in operation. In the Bagnore and Piancastagnaio are present two geothermal fields located in this area. They were discovered between the late 1950s and the early 1960s, with wells producing steam from the shallow carbonate reservoir. In the late 1970s, a deeper exploration program was initiated, with very successful results for both fields, revealing the presence of a fractured Metamorphic Basement, underlying the shallow carbonate reservoir, at depths ranging from 2500 to 4000 m. This deeper reservoir is liquid-dominated, with a pressure of around 200 bars and a temperature of 300-350°C at 3000 m depth (Bertini *et al.*, 1995)[xii]. The produced fluid is a two-phase mixture that is separated at the wellhead at a pressure of 20 bar; the non-condensable gas content in the steam ranges from 5 to 8% by weight. At the end of 2021, the total installed capacity was 121 MWe, with 7 units in operation bringing the installed power of 915.8Mwe. All the 34 power plants in operation (by Enel Green Power) with a net electricity generation of 5675 GWh in 2023 (TERNA, annual report[xiii]). The installed geothermal capacity in the H&C sector in Italy at the end of 2020 corresponds to an installed capacity of 1317 MWth, with a corresponding heat energy use of about 10915 TJ/yr.[xiv]. The installed geothermal power puts Italy between the main 10 producing countries with a total geothermal generation worldwide currently corresponding to 16873MW[xv]. In the Amiata[x] area CO_2 emissions are around 32 t/h and 27 t/h respectively for the Piancastagnaio and Bagnore fields.

MATERIAL AND METHODS

In the evaluation of the CO_2 emission in geothermal fields whether they are green fields or brown fields hence hosting geothermal plants we must consider the complex system formed by soil emission of various nature and the GPP power plant contribution and eventually considering the interplay between field emission and GPP emission. A general approach is to compare the relative amount of GPP emission in respect to the geothermal field and eventually consider the evolution in time of both the GPP and soil emission in an ante-post criterion. A second approach is to evaluate the contribution of the whole system GPP/geo-field and compare it to initial emission state. In any case, field monitoring is necessary and double experimental protocol:

1. Measure of spot and emissive area with proper equipment and protocols
2. Measure wide-spread soil emission on a surface with a sufficient extension to comprehend the geothermal field.

For the first type of focused emission points we have adopted standard methods for measurement with a special care to customize the emission protocol with the use of a system to cover the emission point e measuring the

emitted flow rate by use of a Balometer on a floating capping; Pitot tube without additional tube, Pitot tube with additional tube depending on the extension of the studied area[xvi]. This method has been used to evaluate both gas flow rates and gas composition. Moreover, it has been adopted also as a reference method for odour impact measurements[xvii]. For the second type of emission an accumulation chamber method has been used to the entire Amiata area with a sampling grid of 250 m pass[ix, x].

Finally, in the traditional area of Larderello, a different approach was used by reconstructing the gas and steam emissions associated with the ancient 'lagoni' from which boric acid was extracted since the early 19th century. The analysis of the gas and boric acid content emitted by the endogenous fluids and the historical boric acid production data have allowed to reconstruct the emission of incondensable gases and steam. These emissions have completely disappeared over the years during the deployment of the endogenous steam by deep drilling of wells to produce electricity by geothermal plants. The data obtained estimates the DEPLETION of natural emissions in this area[iii].

RESULTS

The case of the Monte Amiata area where the wide-spread soil emission of gases, and the focused emission of gases have been measured, highlight a complex panorama in which surface emission have high CO_2 rates also in areas without geothermal plants (e.g. Bagni San Filippo). The total soil emission rates, both wide-spread and focused areas, of the areas where geothermal plants are present are significantly smaller compared to the emission rate of the natural undisturbed geothermal areas. In our study the degree of depletion of the emission rate has been calculated quantitatively compared to the gas emission in the developed and undisturbed areas demonstrating that the difference in the emission rates between these two areas are of the same order of magnitude of the emission rates of carbon dioxide emitted by the geothermal plants. This phenomenon has been represented in the Larderello area where natural soil emissions have quantitatively disappeared after geothermal development as shown by historical documentations. The main result of the study is a quantitative estimation of carbon dioxide emission putting in evidence that both the focused and wide-spread soil emission have to be measured together with the emission from the plants in order to estimate the total mass balance of CO_2 emission in geothermal areas and also that the natural emission in the undisturbed area are equivalent to the sum of the soil and plant emission reaching an equivalent substitution in the entire system. To do that it is fundamental to plan an adequate measurement approach that considers the special requirements in terms of method and technology for the investigation of the entire geothermal area to acquire measures that permit to evaluate the relative contribution of geothermal plants respect to the emission of the entire geothermal area. Moreover, the focused and wide-spread emission of carbon dioxide flow rate measurement is potentially an interesting and very easy tool to estimate the presence and extension of geothermal fields for future developments.

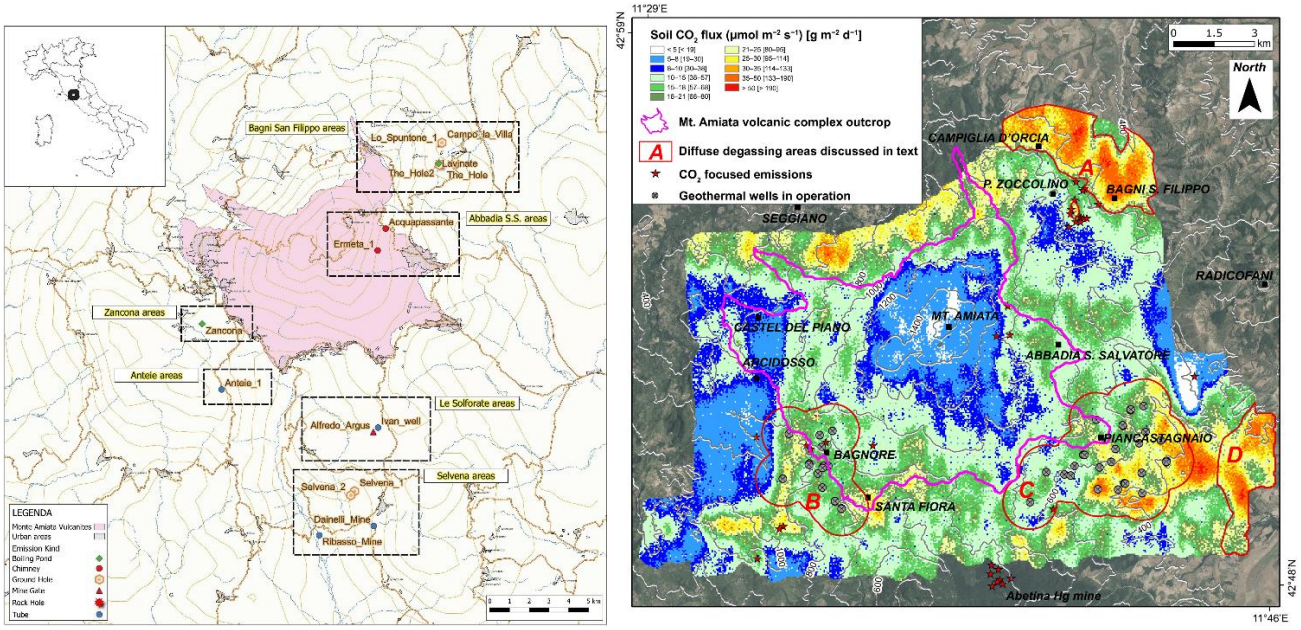


Figure 2: Amiata area, focused emission measurement points (SX) and diffuse emission measurement area (DX)

The area corresponding to each field has been estimated as the effective section of the field calculated as 1 km radius around the barycenter of active wells (Figure2 with indication of focused emission points and the area of diffuse emission). As shown in table 1 according to a 'comparison' criterion the Piancastagnaio GPP account for 39,9% of the Piancastagnaio field emission, the Bagnore GPP for 71,3% of the field emission while total contribution of GPP accounts for a 8.4%. Moreover, the two field and power emission and the green areas of Bagni San Filippo and Paglia river make comparison difficult to be discussed.

Table 1: the Amiata area CO_2 emission framework				
Area	Focused soil emission of CO_2 (t/d) (updated after ref. [xvi])	Wide-spread soil emission of CO_2 (t/d) including biogenetic contribution after [x]	Geothermal Power Plant emission of CO_2 (t/d)	Total emission (t/d)
Amiata area (280 km2)	379	16254		16633
Piancastagnaio field (24.8 km2)	3	1929		1932
Piancastagnaio GPP (PC3, PC4, PC5 plants) – 61 MW[xviii]			770	770
Bagnore field (14.5)	4	905		909
Bagnore GPP (BG3, BG4 #1 and #2)[xviii]			648	648
Bagni San Filippo field (12.3 km2)	39	1415		1454
Paglia valley area (7.13 km2)		732		732

The situation allows a different analysis if we normalize emission data according to their surface, namely the surface of each geothermal field and the entire study area, including the contribution of GPP accordingly normalized for their field extension expressed by the surface of the deep geothermal field, namely the areas where geothermal plants are located.

We can observe that in the geothermal developed area of Bagnore and Piancastagnaio the soil emission per unit of surface is lower than the same emission in non-developed area of Bagni San Filippo and Paglia area. This could be interpreted as a 'Depletion Effect' due to the presence of GPP that are withdrawing carbon dioxide contained in the geothermal fluids from the depth reducing the amount of carbon dioxide reaching the surface. Adding the contribution of Geothermal Power Plant, the total emission becomes comparable to the green field areas. This can be interpreted with a model in which over observing a depletion effect the GPP emission replace nearly totally the missing emission from the soil in what we have named as Substitutive Emission Effect. The total framework is so interpreted as depletion effect that balances the emission of the GPP in coherence with a no-effect of GPP to the total budget of CO_2 emitted to the atmosphere according to 'substitutive emission' criterion.

Table 2: Field and GPP carbon dioxide emission expressed as a flux

Area	Emission by unit surface (t/dkm2)
Piancastagnaio field	77,9
Piancastagnaio GPP	31,0
Piancastagnaio field + GPP	**108,9**
Bagnore field	62,7
Bagnore GPP	44,7
Bagnore field + GPP	**107,4**
Bagni San Filippo field	**118,2**
Paglia river area	**100,3**

In the Larderello area the lack of pre-development soil emission has been faced by calculating Non Condensable Gases (NCG) gas emission extrapolated by boric acid production from natural surface ponds and steam vents that disappeared nearly completely after adoption of deep drilling and extraction of deep geothermal fluids as reported in ref. [iii]. The emerging picture for the Larderello area shows a depletion effect up to 17 t/h of NCG (mainly represented by CO_2 - 97.7% by volume). These emissions from natural 'lagoni' have gradually disappeared and are substituted by power plant emissions. Considering that in the Larderello area, a substantial depletion of gas content has been observed after the systematic application of condensate reinjection practice, by reducing the gas content in steam, in some cases to 2% or less, the same 17 t/h of ancient NCG emission would be equivalent to 850 t/h steam or about 106 to 121 MW power production. Even if the approach is different from the one adopted in the Amiata area, the general criterion of taking account rather than single power plant, the more complex system of the emission from the geothermal field and the hosted power plants, is a valid criterion.

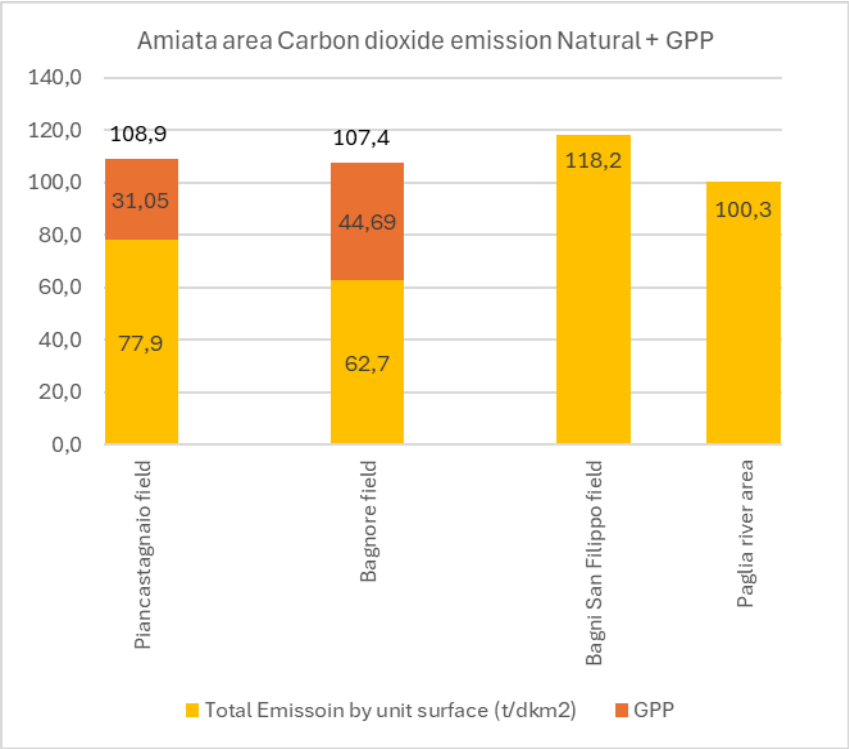


Figure 3: normalized emissions from geothermal field and GPP for the Amiata area as reported in table 2

DISCUSSION

The monitoring of carbon dioxide flux at soil level is an essential investigation in almost all geothermal systems. This measurement requires a detailed analysis of the geothermal field, especially in the presence of geothermal power plants that can alter natural soil emissions.

The emission of CO_2 from the soil can also represent a geochemical indicator of the presence of geothermal resources at depth.

To obtain an accurate assessment, it is imperative to adopt a specific measurement protocol that accounts for the type of gas sources emanating from the soil. Appropriate methods and instrumentation must be selected for the sampling, analysis, and estimation of emission rates, depending on their distribution as Point sources (such as vents) or Areal emission (diffuse areas).

The criteria adopted in the Mount Amiata area can be considered a valid case study for the analysis and quantification of these emissions.

Measuring carbon dioxide soil fluxes is therefore a valid tool for the environmental impact assessment of geothermal plants. The availability of CO_2 soil flux data also allows for the estimation of the actual interplay between geothermal exploitation and the field's response in terms of the evolution of gaseous emissions.

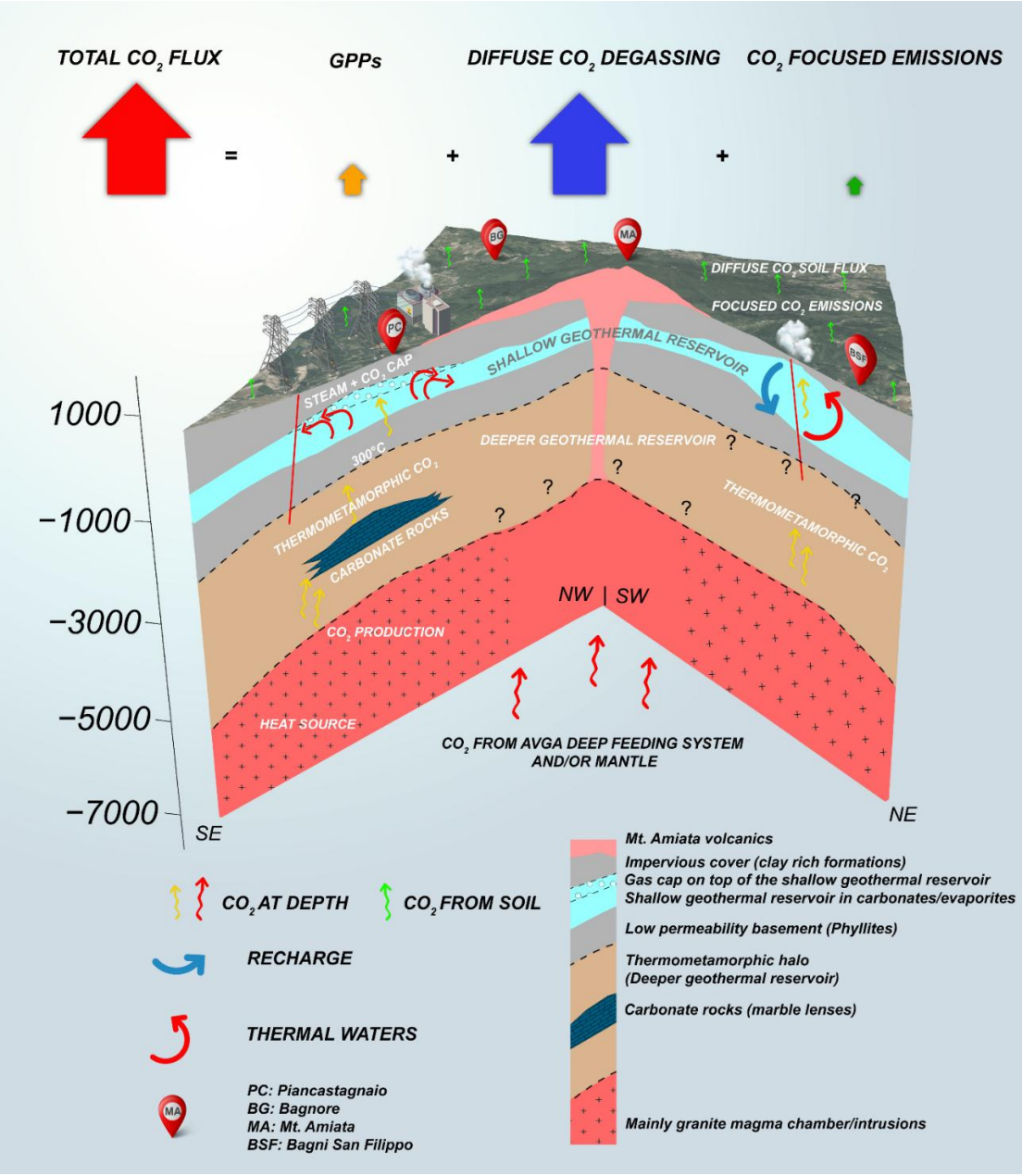


Figure 4: **Conceptual model exemplified in a section crossing the Piancastagnaio geothermal field and the undisturbed Bagni San Filippo area showing focused, diffuse emission and GPP contribution to the emission of carbon dioxide**

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