



What can be learned from natural analogue studies in view of CO₂ leakage issues in Carbon Capture and Storage applications? Geochemical case study of Sainte-Marguerite area (French Massif Central)

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**What can be learned from natural analogues studies in view of CO₂ leakage issues in
Carbon Capture and Storage applications? Geochemical case study of Sainte-
Marguerite area (French Massif Central).**

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Abstract

Natural analogues studies have received much interest over past years through the CO₂ capture and storage applications. In this paper we focus on one natural analogue in leakage situation in order to describe the nature of the gas leakage, its interaction with surrounding rocks and aquifers and its behaviour over time. Soil gas and water monitoring techniques are used to gather point and continuous records. Leakage occurs along discrete sections relying on the nature of surface formations and the permeability of discontinuities. Main gas vents are perennial, relative proportions of different gas phases (CO₂, ²²²Rn and ⁴He) being dependent from the interaction with surface deposits and the distance to main tectonic pathways. Mineral waters were also monitored as they represent integrative bodies that exist above nearly all CCS sites. Constraints on chemical processes occurring at depth are brought by characterisation of the dissolved constituents and by related isotopic systematics. Such determination of mixing processes and their influence is important, as leakage from CCS site may be evidenced through the mixing of the water from the storage complex and overlying aquifers. Longer term monitoring was conducted for physico-chemical parameters highlighting noticeable variations for pH, dissolved oxygen, redox potential and dissolved CO₂.

Keywords

Natural analogue

Carbon Capture and Storage

Soil gas monitoring

Water monitoring

1. Introduction

Natural analogues studies have received much interest over past years through the prism of CO₂ capture and storage (CCS) applications. Several references on this topic may be found in very recent papers such as *e.g.* Schütze *et al.* (2012). Natural analogues can either be in steady state conditions, *i.e.* in a non-leaking state, or at the opposite they can experience more or less developed leakages. In this paper we choose to focus on this second situation in order to evaluate how valuable information may be learnt from natural CO₂ leakages and extrapolated to CCS sites. In this particular case of leaking analogues, features devoted to the study of storage integrity are by definition unrealistic. Nevertheless, such analogues represent a good opportunity to illustrate what must be avoided for CCS sites (Bachu, 2003).

Even if vertical gas flows are often much greater than those expected in case of undesired CO₂ leakage from CCS site, natural analogues provide the opportunity to study the nature of a gas leakage, its interaction with surrounding rocks and aquifers, its behaviour over time or its potential impacts on surface environments (Lewicki *et al.*, 2007). Consequently, natural analogues monitoring is an appropriate way to study natural seepages and is from the authors' point of view complementary with induced leak experiments such as the ZERT (Spangler, 2010) or the CO2FieldLab ones (<http://www.sintef.no/Projectweb/co2fieldlab/>).

The Sainte-Marguerite site allows the study of both CO₂ leakage in shallow aquifers and gas escapes in near surface environments. Apart from pressure and temperature consideration, leakage in aquifers is the most critical parameter to assess for ensuring of CCS sites integrity. One must be confident with near surface monitoring technologies prior to use them in deeper environments. Second, monitoring of CO₂ escapes as a gas phase may consist in the ultimate warner prior to leakage in the atmosphere. Health and risk assessment and public acceptance directly rely on those two aspects.

Another interesting parameter to evaluate is the behaviour of natural analogues over long time periods. CO₂ injection is a very recent process compared to timescale of geological processes. Consequently, apart from failures linked to defective constraint of a CCS site (leakage due to abandoned wells, existence of fractures or leakage through the caprock; Lemieux, 2011), leakage may occur at low rate over years and may not be highlighted by monitoring technologies at depth, especially geochemical ones that rely on discrete measurements. A better understanding of how the gas migrates from depth and how it imprints surface environments is a challenging question that may be addressed by studying naturally leaking sites. Defining the origin of the gas phase is an important issue in case of leakage at a CCS site, helping to decipher whether the gas originates from the reservoir itself or from other sources that do not involve CCS processes (*e.g.* Gilfillan *et al.*, 2011).

The Sainte-Marguerite area belongs to the French Massif Central and more precisely to the southern part of the Limagne d'Allier basin (Figure 1). This tertiary basin is mainly filled by limestones with frequent sandy-clayey intercalations that are contemporary of the Oligocene to Miocene West European rifting. Alluvial and colluvial deposits from the Allier River partly overlie these tertiary strata and from place to place volcanic series crosscut the sedimentary formations. Mineral waters emerging in the Limagne d'Allier basin are strongly influenced by their deep circulation in the crystalline basement and the occurrence of deep CO₂ sources (Fouillac, 1983). The main tectonic structures, inherited from the Hercynian orogeny, are respectively N10-N30 and N110-N130 (Merle and Michon, 2001). The Sainte-Marguerite area is also characterised by the presence of travertine deposits formed from water degassing at springs (Casanova *et al.*, 1999; Fouillac, 1983; Rihs *et al.*, 2000).

While studies on mineral waters – mostly of sodium bicarbonate type with CO₂ present as a gas phase – from the Allier River valley are numerous (*e.g.* Négrel *et al.*, 1997a and

references therein), initial investigations of soil gas composition in the Sainte-Marguerite area were performed during the 90's to locate new boreholes for perpetuating the commercial exploitation of this water (Appora-Gnekindy, 1992; Baubron *et al.*, 1992). Earlier measurements were made in the 70's on the west bank of the Allier River at the Saladis spring (Batard *et al.*, 1978).

The objective of this study is therefore, in light of the work done in the 90's, to compare the similarities and differences of gas emanations separated by 20 years. Point measurements and longer records will be used to examine the relationships existing between the near surface compartment and deeper seated processes.

Figure 1

2. Methods

Two types of investigative methods were used: soil gas characterisation and description of water flows. Soil gas measurements were made using procedures and equipment identical to those described by the authors elsewhere (*e.g.* Battani et al., 2010; Gal and Gadalia, 2011).

The monitoring methodology was based on the following:

- CO₂, O₂ and CH₄ soil gas concentrations were directly quantified in the field using landfill gas analyser (LFG20 gas analyser, ADC Gas Analysis Limited, UK). Gas content was measured at 1 m depth in order to minimize the effect of atmospheric gases. CO₂ and CH₄ contents were determined by non-dispersive infrared absorption and O₂ contents by electrochemistry. No CH₄ was found during the successive surveys indicating concentrations lesser than 0.01% volume in the gas phase. As the CO₂ concentrations ranged from less than 1% up to 100%, precision of the measurements

varied between $\pm 0.5\%$ of the reading for $\text{CO}_2 < 10\%$ to $\pm 5\%$ of the reading for $\text{CO}_2 > 50\%$.

- ^4He and ^{222}Rn concentrations were also systematically determined using samples collected in Tedlar bags for ^4He and vacuumed scintillating flasks for ^{222}Rn , respectively. Concentrations were obtained using mass spectrometry for ^4He (Adixen ASM102S leak detector, France) and scintillation counting for ^{222}Rn (Calen, Algade, France).
- Some additional grab samples were collected for laboratory determination of the $\delta^{13}\text{C}$ of the CO_2 . The isotopic ratio was determined using a Delta S Thermo/Finnigan mass spectrometer and expressed as ‰ VPDB (Vienna Pee Dee Belemnite). A Varian 3400 gas chromatography was used for the determination of N_2 , Ar, O_2 , CO_2 and $\text{C}_n\text{H}_{2n+2}$ ($n = 1$ to 6).
- Continuous data acquisition was also performed on ^{222}Rn content using Barasol probes (absorption spectrometry via a silicon detector; Algade) for long-term acquisitions (from October 2008 to March 2010). Barasol probes were protected by a PVC tube, covered by a Goretex membrane and buried at 1 m depth in the ground.

The joint determination of these gaseous species allow to compare information from tracers that may be enriched through geothermal reservoir processes (^4He), from poorly mobile elements that may help highlight areas with significant gas fluxes (^{222}Rn) and from a widely existing gas (CO_2) that may be tracer of soil/atmosphere exchanges or of deep seated endogenic processes. Weather conditions were also taken into account for the interpretation of the soil gas data and will be discussed together with the data.

Secondly, as the Sainte-Marguerite area is known for its mineral water resources, chemical characterisation of some springs (physico-chemical parameters and dissolved ions content) was also performed as well as the monitoring of the Brissac Geyser during several hours using a multi-parameter Idronaut probe (Idro316*Plus*). Dissolved ion contents were determined at laboratory using ICP-AES (Inductively Coupled Plasma – Atomic Emission Spectroscopy) and chromatographic methods. Isotope ratios were measured by gas phase mass spectrometry ($\delta^{18}\text{O}$ and δD are expressed in ‰ VSMOW – Vienna Standard Mean Oceanic Water). The Idronaut probe was used to monitor the short-time evolution of temperature, pH, specific conductance, dissolved oxygen, redox potential and dissolved CO_2 content of the water.

3. Gas and water measurements

3.1 Soil gas data

A dataset of nearly 1000 data points for each gas specie (CO_2 , ^{222}Rn and ^4He) is available, half of them from the 90's measurements and the rest from more recent measurements (Table 1).

Table 1

CO_2 concentrations range from values close to those of the atmosphere up to 100% vol. The frequency distributions are different between the two measurement periods in relation to the spatial arrangement of the measurements that is dictated by the tectonic and geological structure of the study area. As a consequence, the mean CO_2 concentration is significantly greater for the 2006-2010 dataset than for the 1992 dataset.

Radon-222 (^{222}Rn) concentrations also fall within similar ranges during the two periods, minimum values being close to 150 Bq.m^{-3} and greater ones around $2 \times 10^6 \text{ Bq.m}^{-3}$. The mean

values were again higher for the 2006-2010 period as a consequence of data acquisition mainly focused on the Western part of the area. Nevertheless the variation of mean concentrations is only a factor of two whereas it was a factor of four for CO₂ concentrations. Helium-4 (⁴He) concentrations are on average quite close to the atmospheric content but this value hides important differences. Both in 1992 and 2006-2010 some measurements showed very strong depletions when compared to the atmospheric content while others had strong enrichments (≥ 10 ppm).

Most of the CO₂ measurements made between 2006 and 2010 were also supplemented by measurements of the O₂ concentrations in soils. A very homogeneous inverse behaviour exists between those species (Figure 2). Almost all data exhibit an O₂ decrease that is not proportional with the increase of the CO₂ content on a per mole basis. Depletion of O₂ is much faster with a factor close to 5. This suggests that CO₂ is supplied in abundance by a powerful process probably related to a deep gas source (crustal and/or mantle origin) as will be discussed later.

Figure 2

This strong O₂ depletion is also confirmed by the gas chromatography measurements reported in Figure 3. Correlations with other gas species follow linear regression with r^2 between 0.991 and 0.998, and also suggest a different behaviour between the CO₂ end-member and the N₂-O₂-Ar triptych, with CO₂ becoming predominant as the other three gases diminish and vice-versa. This was particularly true for a 30 m deep borehole where atmospheric constituents were only detected at trace levels (0.13% N₂; 0.023% O₂; 0.002% Ar). Using the relationship presented in Figure 3, it is then possible to recalculate an average composition for the

atmospheric end-member. Ar and N₂ contents were respectively at 0.932% and 79.6%, levels that are very close to those usually reported for the atmosphere (respectively 0.934 and 78.08%; <http://encyclopedia.airliquide.com/>). Unlike O₂, which is subject to a more active kinetic of replacement, N₂ and Ar are diluted in the soil gas by equimolar replacement with CO₂.

Figure 3

Finally, the $\delta^{13}\text{C}$ isotope ratio of the CO₂ gas was also evaluated on these samples and ranged between -3 to -5.1‰ VPDB for CO₂ in the 14 – 100% vol. range.

3.2 Water measurements

The main physico-chemical properties of mineral springs sampled during the study are listed in Table 2. A rain event collected in October 2008 is also reported for comparison. The emergence temperatures range between 16 and 30°C and pH between 6.2 and 7.2, therefore comparable to those reported by Négrel *et al.* (1997b) for the carbogaseous waters known throughout the French Massif Central. Specific conductances vary between 2.5 and 8.4 mS.cm⁻¹, Chapelle springs (used for bottling) having total mineralization approximately half of other sampled waters. The mineralization is dominated by HCO₃ (1.3 to 4 g.L⁻¹), Na (0.3 to 1.5 g.L⁻¹) and Cl (0.2 to 1.5 g.L⁻¹). If this Na-Cl-HCO₃ facies predominates, the Ca and Mg amounts, less variable (respectively 120 to 310 mg.L⁻¹ and 100 to 140 mg.L⁻¹), allow the Chapelle springs – due to their lower dissolved elements concentrations – to be linked with the Ca-Mg pole, suggesting a secondary enrichment associated with the chemical hardness of bicarbonate-rich waters (Michard *et al.*, 1981). Similarly, the Chapelle springs have an

oxidizing character contrary to Tennis and Geyser Brissac waters that are characterized by a marked reducing character. Characteristics of isotope ratios reported in Table 2 will be discussed in section 5.

Table 2

4. Interpretation of soil gas data

4.1 Point data

One of the first steps to considered for highlighting a potential leakage at a CCS site is to characterise the CO₂ phase. Concentration measurements are of great interest but they may not be sufficient *e.g.* in case of small leakage rate. Additional information may be gathered using isotope systematics, mobile systems nowadays allowing on-site measurements (*e.g.* Picarro or Aerodyne lasers). $\delta^{13}\text{C}$ isotope ratio measurements will not give direct indication of the process that may be involved in the production of the CO₂ phase but will allow 1) to discriminate between several origins and 2) to discard some unrealistic origins.

In the case of Sainte-Marguerite, CO₂ concentrations in soils are supposed to evolve primarily under the influence of deep seated processes rather than surface processes. Indeed, the range of $\delta^{13}\text{C}_{\text{CO}_2}$ isotope ratios in soil gas (-3 to -5.1‰) is related to deep crustal and/or mantle degassing (-4 to -8‰; Gerlach and Taylor, 1990). Similarly, $\delta^{13}\text{C}_{\text{CO}_2}$ are close to ratios measured on the gaseous phase of low helium concentrated, CO₂-rich waters from the Massif Central (-6.4‰; Dégranges *et al.*, 1978). The more depleted ratio (-5.1‰) was measured in the 30 m borehole, where the gas phase was 100% CO₂ with no ⁴He (< 0.05 ppm), whereas soil gas measurements (1 m depth) were slightly enriched in carbon-13 (*i.e.* greater than -4.8‰). This slight isotopic enrichment of upper soil horizons may be the result of two

complementary phenomena, first the percolation of CO₂ through surface aquifers ($\delta^{13}\text{C}$ of dissolved carbon from local springs close to 10.2‰; Mercier, 1987) and second the interaction with travertine deposits ($\delta^{13}\text{C}$ between 5.4 and 7.7‰; Casanova *et al.*, 1999).

In the case of leakage originated from a CCS site, such characterisation using the only $\delta^{13}\text{C}$ isotope ratio will be much more difficult as overlaps between several gas origins and frequent re-equilibration will certainly occur. A way to better constrain gas emanation is to measure other gas species with different chemical properties.

In the present study we mainly refer to ^{222}Rn and ^4He . As ^{222}Rn and ^4He are only present as trace levels in the free atmosphere (respectively around 50 Bq.m⁻³ or less and 5.24 ppm), an enrichment would favour the existence of phenomena occurring either in the soil or in the upper regolith (^{222}Rn) or deeper in the ground (^4He ; Battani *et al.*, 2010; Gilfillan *et al.*, 2011). Relationships between CO₂, ^{222}Rn and ^4He are presented in Figure 4.

Figure 4

For $^{222}\text{Rn}/\text{CO}_2$ and $^4\text{He}/\text{CO}_2$ couples, graphical relationships (Figure 4A) confirm the different origin of these two gases and highlight that the genesis of ^4He from radioactive decay of uranium in the near surface has little influence on the ^4He concentrations. This should also result in an increase of the ^4He concentration when ^{222}Rn activities are high. This is not the case, since there is rather a gradual depletion when the ^{222}Rn activities exceed 10⁶ Bq.m⁻³ (Figure 4A). Moreover, these high ^{222}Rn concentrations are measured at precise locations which correspond to surface discharges of springs (old factory and Tennis; Figure 1) that form tens of centimetres to several meters thick travertine beds. These very high ^{222}Rn activities are presumably related to these travertines, consequently richer in uranium than the alluvial

formations and the local waters (Casanova *et al.*, 1999). In this particular case, the CO₂ source is not strong enough to dilute the ²²²Rn as may occur farther from travertine deposits. As a consequence, perennial ²²²Rn high concentrations exist locally.

The behaviour of ²²²Rn and CO₂ is also complex for ²²²Rn concentrations lesser than 300,000 Bq.m⁻³ (Figure 4B). Two distinct trends seem to exist, one with fast ²²²Rn enrichment with low CO₂ concentrations (red squares), and the other with weaker ²²²Rn enrichment when CO₂ concentrations rise (blue lozenges). These two behaviours correspond to various spatial locations (Figure 5). Most of the “high ²²²Rn – low CO₂” samples plot on the eastern part of the site on sedimentary deposits (mean altitude 350 to 365 m), whereas the majority of the “low ²²²Rn – high CO₂” group is restricted to a lower terrace of the Allier river (westward from longitude 669,100 in Figure 5 – mean altitude 335 to 345 m; see also Battani *et al.*, 2010 for geological cross-section). Near the Allier River, the thickness of geological formations overlying permeable paths is lesser than eastward. The CO₂ gas interacts to a lesser extent with surface formations, leading to moderate ²²²Rn enrichment. On the contrary, on the eastern part of the site, CO₂ has to go through thicker formations (alluvial and Oligocene formations), leading to smaller CO₂ amounts and also to ²²²Rn enrichment due to the percolation of the CO₂ into these formations. An intermediate behaviour occurs above travertines deposits (Figures 4 and 5) where the ²²²Rn content is also dependent from the uranium content of these formations. An additional process can also act in a complementary fashion. Deep CO₂ may be less diluted on the western part of the site than on the eastern part, indicating a more pronounced upward flow that allows the dilution of radon signal (Baubron, 1992; Gal *et al.*, 2011).

No relationship can be highlighted for the ⁴He/CO₂ couple except from a very weak tendency of having slightly lower ⁴He concentrations when CO₂ concentration is greater than 50% (Figure 4A). If considering the 30 m depth borehole as the most representative of the deep

end-member, then uprising gas flow is ^4He depleted. A strong CO_2 flux can act as a flushing agent on ^4He . For lesser CO_2 amounts, flushing effect may be less important and ^4He concentrations are higher or even enriched depending on the amounts of ^4He upward migrating.

Figure 5

The great variability of soil gas concentrations on a small area is not only dependent from deep processes but also from the heterogeneity of surface formations and pathways. Such a problematic is critical for CCS sites especially in areas where potential leakage pathways are not well characterised. This will raise the question on how detect surface leakage if *e.g.* a leakage occurred in deep groundwaters. Nevertheless, a positive point is the persistence of leakage structures over years.

As a result, the Sainte-Marguerite area presents a patchy repartition of anomalies at surface, as evidenced by the equal concentration lines reported on Figure 6. Data are interpolated using natural neighbour algorithm. This interpolation method is more rugged than *e.g.* kriging, but it has the advantage in not extrapolating the contours beyond the convex hull of the dataset. The whole dataset is presented top of Figure 6. Separate contributions from the data acquired during the 90's and during the 2000's are respectively presented middle and bottom parts of Figure 6. A good match is highlighted between these 15-year interval datasets especially on the Western part of the study site where strong CO_2 enrichments remain perennial. The match cannot be achieved for the Southern part as a new bottling facility has been built in between time therefore no measurement is yet possible. The North-South to N10 anomalous zone is well in agreement with structural directions reported in the Limagne d'Allier basin (Merle and Michon, 2001). This direction is also suggested by variogram

computations (data not shown) which suggest, under a spherical model, a significant nugget effect (40% of the variability) and a reduced leg (20 m). Consequently, there seems to be at site scale a structure directly related the Hercynian tectonic and at a smaller scale a less obvious structure that is difficult to model even with a large amount of data. For CCS site management, this suggests that once fed by seepage or microseepage, a leakage pathway will remain active over a long time period. Its characterisation will then be possible but remediation actions will be very difficult to undertake.

Figure 6

The complex CO₂ distribution in soils is not restricted to this gas phase. A well characterised time coherence for ²²²Rn concentrations (90's and 2000's datasets) also exists and reveals an anomalous area close to the flow axis of the Allier river (Figures 2 and 6). A N170 direction is suggested by variogram calculations, with a leg identical to that defined for CO₂ but with increased nugget effect (50% of the variability). This may be linked to the location of the area of maximum ²²²Rn concentrations, close to the high CO₂ area but with no coinciding peaks, and due to the difference of origin for these two gases, radon being preferentially produced in shallower environments than CO₂ in the present case.

The evolution of ⁴He concentrations in the area where ²²²Rn and CO₂ anomalies are located is very interesting to detail (Figure 6). This area is characterized by a complex intricacy of positive and negative anomalies in helium *i.e.* tracing enrichment or depletion with respect to the atmospheric content. This complexity in ⁴He emanations is remarkably stable over time. Low ⁴He concentrations are preferentially measured along a N10 axis, locally reinforced by a

complementary N160 direction. The adjustment on a spherical model of the variogram suggests a maximum correlation distance of 40 m between two points without a nugget effect.

In order to better assess the behaviour of CO₂, ²²²Rn and ⁴He, a linearization of the data was made using the scheme proposed by Michel – Le Pierrès *et al.* (2010). The resulting interpolation map is presented in Figure 7. By assumption, CO₂ and ⁴He are considered as deep end-members and ²²²Rn as a near surface produced gas. This is consistent with gas origins suggested by Jeandel *et al.* (2010) that found a nearly half/half mantle/crust origin for helium and a predominant crustal origin for CO₂. This strengthens previous results indicating that CO₂ and ⁴He amounts are not directly proportionally linked. The linearization process is then intended to lower the influence of ²²²Rn and to over-estimate the one of ⁴He by assigning a value between 0 and 1 to each of the gas specie. The 0.05 to 100% CO₂ range is restricted in the 0 – 1 interval and so on for ²²²Rn (140 to 248,000 Bq.m⁻³) and ⁴He (0.05 to 9.83 ppm). Using this procedure, ⁴He concentrations account for *c.a.* 75% of the total variability, CO₂ for 22% and ²²²Rn for the rest (*c.a.* 3%). Despite this bias introduced in the dataset (Figure 7), the surface geometry of the anomalies is still primarily guided by the distribution of CO₂ concentrations, the influence of ⁴He been of second order. Consequently, it is the deep CO₂ source that governs the spatial distribution of anomalies in soil gas through the N10-N30 and N110-N130 structures (Merle and Michon, 2001). Other gaseous species evolve either through the heterogeneous composition of the regolith or through the existence of complex phenomena including convective transport, stripping or mixing. This strong imprint of geological structures on the occurrence of anomalies also appears in the comparison of data acquired 15 years apart, since changes between these two periods remain small. This statement is strengthened by comparison with CO₂ flux data available in the area (Battani *et al.*, 2010). The most anomalous CO₂ areas correspond to those marked by fluxes reaching or

exceeding $500 \text{ cm}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$, while the radon anomalies are superimposed on areas where the fluxes are smaller (lesser than $100 \text{ cm}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$).

Figure 7

4.2 Time evolution of soil gas concentrations

Evaluation of short-term variability of soil gas concentrations was evaluated using point measurements (CO_2 , ^{222}Rn and ^4He) and continuous measurements (on the CO_2 phase using Fourier Transform Infrared gas spectrometry). Repeated point measurements over 3 days (points 1 to 4 in Figure 1) indicated that the points located northward of the site experienced low variability of their gas concentrations ($\pm 60\%$ for CO_2). At the opposite points located in the southern part of the site had much greater variations rising up to a factor of 80 for CO_2 and 200 for ^{222}Rn (point 4). Continuous measurements in upper soil horizons in the vicinity of the Brissac Geyser had an intermediate variation factor of 8 over few hours, with periodicity influenced by the geyser own kinetic (mean period of 21 minutes).

Assessing the variability of gas emanations at short time scale is important for the comprehension of phenomena occurring at a natural analogue, but such a time scale is not fully matching requirements of CCS site monitoring. Longer chronicles shall be available in order to highlight any deviation from environmental background noise. The Sainte-Marguerite site has then been instrumented for longer-term measurements. They were performed only on the ^{222}Rn phase for practical reasons. Even if deviations that may be recorded will not be linked to deviations from an environmental background noise in the present case, one must be confident in the capacity of monitoring devices to properly register unexpected events.

Points 2 and 4 (Figure 1) were instrumented with Barasol probes from October 2008 to January 2009 for hourly monitoring and afterwards only the point 4 remained. Soil temperature and barometric pressure were simultaneously recorded at 1 m depth in the soil. Meteorological data were got from an airport weather station located 14 km NNW from Sainte-Marguerite, at similar altitude. Two distinct time responses exist (Figure 8):

- Pressures measured at 1 m depth in soils perfectly replicate the variations of atmospheric pressure and provide accurate description of local evolutions (Figure 8a);
- Temperatures measured in the soil are different from those measured in the atmosphere (Figure 8b). Soil temperatures exhibit a smoother daily variability and are higher than atmospheric temperatures. There is a time-lag between the maxima of temperature in the atmosphere and in the soil, the former occurring 5 to 6 hours before the later.

In December 2008 and January 2009, there is however a difference between temperatures measured by the two probes (Figure 8b). The probe located in the southern part of the study area (point 4 in Figure 1) recorded higher temperatures (from 5 to 10°C) than those measured a few hundred meters northward (point 2 in Figure 1). Point 4 being located in a depression close to mineral springs (25 to 29°C at the orifice), this warming may be related to their influence into higher groundwater level during winter times.

Figure 8

Radon activities measured by the 2 probes during the October 2008 - January 2009 period showed trends with site-specific evolution but the variability of the measurement remained in a similar range (Figure 8c). There is a good agreement between average ^{222}Rn concentrations computed from Barasol records (Table 3) and that from point measurements performed at site

scale (Table 1). Marked activity peaks nevertheless occurred. At the end of January 2009 (Figure 8c), phenomenal concentrations were reached (up to 80×10^6 Bq.m⁻³). Such concentrations remain under saturation threshold of the probe (10^9 Bq.m⁻³) but are far greater than maximum values found during spot sampling (2.5×10^6 Bq.m⁻³). During this January 2009 event, a perfect synchronism was found between the 2 probes with a very quick increase followed by very small ²²²Rn amounts few hours later. This event is therefore not related to malfunctioning of the equipment. The measurements suggest a gas burst sweeping the area of Sainte-Marguerite, leading to a huge increase in ²²²Rn and a subsequent strong depletion. Concentrations remained low until radioactive decay produced again a sufficient amount of ²²²Rn. Another peak of activity was also detected in September 2009 (Figure 8c). However, as only one sensor was deployed and as it experienced some operational problems, we prefer not trying to interpret this latter signal.

Table 3

Apart from these specific periods, the ²²²Rn concentrations change cyclically (Figure 8). Cycle analysis returned variable results depending on the analysed time period and even on the location of the probe (Table 3). There was no clear influence of external forcing such as daily or diurnal variations over long time periods or the existence of pulsation of longer duration. It is therefore not possible to highlight regular gas emanations as may be possible regionally such as in the vicinity of Lake Pavin (Gal and Gadalia, 2011).

Nevertheless, during periods characterised by less noisy ²²²Rn signals (March 2009; Figure 9a, b and c), a daily cyclicity (24 hours period) clearly appeared even if trends of greater wavelength may also contribute to the shape of the recorded signal (Figure 9d). Principal Component Analysis were calculated by combining the factors accounting for maximum

variability (Figures 9e and f). The only apparent trend was an inverse correlation between ^{222}Rn concentration and soil temperature. Given the interdependence between soil and atmospheric temperature, this trend can be extended to this second parameter. Thermal forcing seemed to be more efficient than pressure gradients to influence the short-term temporal evolution of ^{222}Rn concentrations, apart from sudden phenomena such as “gas bursts”.

Figure 9

As previously described, the occurrence of large ^{222}Rn concentration peaks was very intriguing. The origin of such short pulses may typically be attributed to external causes such as earthquakes. Radon is frequently used as an indicator of crustal movement (precursor), although each earthquake does not raise an ^{222}Rn anomaly and each anomaly is not necessarily followed by an earthquake (*e.g.* Al-Hilal *et al.*, 1998). According to dislocation model (Fleischer, 1981; Fleischer and Mogro-Campero, 1985), variations of ^{222}Rn concentrations issued from stress changes can be detected even at great distances from epicentres, involving a wide set of mechanisms (Kharatian *et al.*, 2002). Continuous measurements of ^{222}Rn in soil gas sometimes allow the identification of spike-like anomalies just before the earthquake, the post-seismic stage being characterised by a rapid return to natural background values (Chyi *et al.*, 2002). Although highly variable, increases in ^{222}Rn concentrations at 1 m depth in soils (Wattananikorn *et al.*, 1998) often occur between 4 and 15 days before earthquakes of magnitude 2 to 6 with distances from the epicentre to the measuring station comprised between 15 to 250 km (Das *et al.*, 2006; Ghosh *et al.*, 2007; Ramola *et al.*, 2008).

Referring to these constraints, we searched the available databases (<http://www-dase.cea.fr/>) for events reported in an area covering 4 degrees in longitude and 3 degrees in latitude, centered on Sainte-Marguerite. Twelve earthquakes were recorded between January 28 (12 hours after the ^{222}Rn peak) and February 13 (17 days after the ^{222}Rn peak) within this area, at distances between 40 and 70 km from Sainte-Marguerite. All were characterised by very low magnitudes less than 2.5. Although some of the cited literature reports a sensitivity of ^{222}Rn measurements for low seismic magnitudes, no clear relationship exists in the present case between ^{222}Rn peaks and tectonic activity.

Such excursions of ^{222}Rn signal were earlier reported on the Weyburn site, which is not known to be tectonically active (Riding and Rochelle, 2009). Phenomena observed at Weyburn were short (3 hours) and activities varied by factors of 7 to 15. At Sainte-Marguerite variations were consequently higher (100 to 1000 times) and the sensitivity of ^{222}Rn concentrations to pressure changes was less obvious than stated at Weyburn. This renders improbable an origin related to transient phenomena affecting the pressure.

Even if not really successful during the monitoring period, long-term measurements of soil gas emanations are of strong interest in view of CCS applications. Data main not only be gathered on the ^{222}Rn phase but mostly on CO_2 and/or O_2 phases. This is crucial for assessing if variations are linked to natural processes, either originated from surface processes or deeper ones, or caused by CCS operations. Continuous monitoring is not designed to cover great areas, one limiting factor being costs, but is complementary with point techniques and may be deployed in most prominent locations highlighted by point monitoring.

5. Chemistry of mineral waters

The Sainte-Marguerite site offers the opportunity to monitor gas escapes into more or less mineralised water bodies. We will first describe water chemical compositions and then discuss what is important in view of long term water monitoring.

5.1 Point sampling

Mineralisation of these waters form two groups, one rich in dissolved constituents and belonging to the Na-Cl-HCO₃ end-member, the other (Chapelle springs) more influenced by the Ca and Mg species. This distinction remains when referring to $\delta^{18}\text{O}$ and δD isotope ratios (Table 2). Chapelle springs are always under the local meteoric water line (Fouillac *et al.*, 1991), *i.e.* enriched in heavy isotopes contrary to other springs which fall on this meteoric water line. This may be related to evaporation (Négrel *et al.*, 1997b and references therein), to mixing in various proportions between deep and surface end-members (*e.g.* Michard *et al.*, 1981) or to mixing between different deep end-members (Négrel *et al.*, 1997b; Rihs *et al.*, 2000). These differences in isotope ratios denote spatial disparities within walking distance but do not imply the existence of compartmented geological structures. Theoretical calculations of the ^{13}C isotope signature of gas in equilibrium with the waters provide ratios between -2.8 and -5.1‰ (Table 2) that exactly match the range measured in soil gas. Water mixing must then occur under open system conditions allowing different end-members to interact one with each other, *pro parte* explaining temporal variations reported in the area (Négrel *et al.*, 1997b).

Strontium isotope ratio of water ($^{87}\text{Sr}/^{86}\text{Sr}$) is known to derive from that of minerals with which the water interacts and to be lower than that of the whole rock, in response to different dissolution rates between the mineral species (*e.g.* Michard *et al.*, 1978). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 2) suggest that Tennis and Geyser Brissac waters fall in the range of ratios known across the Limagne d'Allier (0.71338; Stettler, 1977) and therefore reflect the signature of a

deep end-member. Lower ratios of Chapelle springs suggest either an interaction with lithologies different from those present in the supply circuit of Tennis and Geyser Brissac springs (*e.g.* plagioclase from the Coudes granite at 0.71028; Rihs *et al.*, 2000) or a mixing with near surface groundwaters (ratio close to 0.71102; Négrel *et al.*, 1997b). In the first case (mixture of 2 groundwaters, one coming from plagioclase weathering), a contribution of the deep end-member (represented by Geyser Brissac or Tennis springs) close to 32% can be calculated using a binary mixing law, whereas in the second case (dilution by surface water), the proportion of the deep end-member may be close to 57%.

Using this deep end-member – or at least the end-member less affected by mixtures – equilibrium temperatures with basement rocks may be evaluated referring to cationic geothermometers. As geothermometers induce the existence of equilibrium between waters and rocks, we neither refer to Ca and Mg geothermometers, strongly affected by mixing processes (Michard *et al.*, 1981), nor to silica -rich species, oversaturated with water at the spring orifice. Na/K (Michard, 1979, 1990, Truesdell, 1975) and Na/Li (Fouillac and Michard, 1981; Michard, 1990) geothermometers are preferred as saturation indices of mineral species containing Na indicate under saturation with water. Deep reservoir temperature is estimated between 180 and 210°C (Na/K) and 195 and 205°C (Na/Li). This estimate is in agreement with that of Fouillac and Michard (1981) and Fouillac (1983).

Isotope characterisation of waters is often restricted to the monitoring of ^{18}O , ^2H or ^{13}C species in view of CCS problematic. Such characterisation is important but water monitoring of deep aquifers, such as the storage complex itself of overlying aquifers, may include other species. O, H, C species may suffer from several processes such as water/rock interaction of mixing between different water bodies. Monitoring other isotopes, such as Sr, Nd, B, Li, Ca

or U may also allow getting information on deep seated processes, better define water/rock interaction or describe redox processes. A better comprehension of deep phenomena may allow improved constraint on CO₂ migration in deep horizons if leakage from the storage reservoir may occur.

5.2 Continuous monitoring of Geyser Brissac

Here we describe short-term evolution of some key physico-chemical parameters of the Geyser Brissac mineral water. Requirements of CCS monitoring will obviously not imply high frequency measurements but one must be confident on the short time scale before assessing variations of longer period.

Results of this monitoring are presented in Figure 10 and Table 4. Two days were characterised by sunny conditions whereas rainfall events of variable magnitude occurred during day 4 and especially day 3. The evolution of dissolved CO₂ is reported on Figure 10 even if quantification is not accurate using pH-based sensors (Gal *et al.*, 2011), in order to bring qualitative information.

Figure 10

Table 4

A cyclical pattern is clearly apparent for all the parameters, directly related to Geyser Brissac dynamics (Figure 10). Two parameters mainly influence the water temperature: 1) intrinsic processes, the eruption of the geyser progressively warming the water and 2) atmospheric forcing, higher water temperatures being recorded around 16:00 in the evening. This is due to the location of the Geyser Brissac, emplaced in a 1 m deep, 5 m diameter bowl filled with mineral water. Measurements were performed at the bottom of this bowl, closest to the drain

where the geyser overflows. The presence of non-flowing waters induced the occurrence of thermal forcing on this water mass: time is needed for the water directly flowing from the geyser when it erupts to warm up the bowl. Similarly, amplitude of the temperature peaks becomes smaller through the day and the water mass becomes hotter as solar heats the water mass. Dilution effects due to rainfall may happen and significantly affect the water temperature and the specific conductance (day 3, Table 4).

Apart from external causes, time evolution of the records is dependent from the geyser activity. Temperature peaks, which correspond to the maximum of the activity of the geyser, lasted 4 to 5 minutes. They are synchronous to increase of the dissolved CO₂, slight decrease of the pH value (-0.05 pH unit) and decreases of the dissolved O₂ concentration and of the redox potential. Such evolutions are self-consistent and reflect the progressive replacement of O₂ by CO₂ in the bowl as the eruption takes place. Specific conductance is also affected, CO₂ inflows leading to harmonic variations of the record. Nevertheless, diurnal heating affects the dissolved CO₂ measurements, one of the drawbacks of this sensor elsewhere reported (Gal *et al.*, 2011).

Spectral density analysis is best constrained using dissolved O₂, pH and redox potential redox. Main period is around 22±1 minutes in good agreement with infrared measurements performed in soils (see section 4.2). As measurements were not conducted over several days, it is not possible to identify periodicity of greater wavelength such as that determined from Barasol probe acquisitions.

Long-term monitoring of water bodies is one of the key procedures in order to ensure of the safety of CO₂ storage. Monitoring performed at Sainte-Marguerite natural analogue shows that this method is sensitive to strong CO₂ leakage well over thresholds expected in deeper environments. Nevertheless devices have the capacity to record variations of lower

magnitude. The main issue nowadays existing relies on the stability of the sensors over time. Long-term deployment at depth generally involves CTD probes, *i.e.* probes that measure only temperature, specific conductance and depth. This only involves solid state sensors. Idronaut probe has chemical sensors for all other parameters and such sensors are subject to drift. Dissolved oxygen may be better constrained using optical sensors. Until now, no long-term pH or redox monitoring has been reported without frequent recalibration of the devices. This question is of crucial importance, as pH is one of the most sensitive parameter to monitor changes linked to CO₂ dissolution.

6. Concluding remarks

This case study of Sainte-Marguerite natural analogue allows investigating both soil gas and water compartments.

Point soil gas measurements have suggested the presence of perennial pathways that favour gas escape from depth to the surface by comparing data acquired 15 years apart. Leakage does not occur along all the fault length as may be derived from geological maps but rather along discrete sections. At Sainte-Marguerite there is no visual impact on the vegetation as could exist in other similar environments (Krüger *et al.*, 2011; Schütze *et al.*, 2012). Permeability of faults does not exist as a whole mechanism but rather as narrow structures separated by less permeable sections filled by secondary mineralization. In terms of CCS monitoring strategy, this suggests that potential pathways that may be deduced from geological or geophysical works may not be the most prone to become pathways. It would be better to search for structures that are still open to fluid draining *i.e.* secondary fractures that are more likely to have intrinsic permeability than main discontinuities.

The CO₂ gas was found to be the main carrier gas leading to the existence of gas anomalies in near surface environments. Carbon isotope ratios are mainly imprinted from deep seated

processes with little interaction in near surface environments either resulting from percolation into surface waters or into travertines horizons. Helium concentrations measured in CO₂-rich areas also highlighted this strong imprint of crustal contribution (Jeandel *et al.*, 2010). The interaction of fluids with travertine deposits also influenced the ²²²Rn concentrations of the gas phase. Consequently, gas emanations were found to be mainly oriented along known regional directions of the tectonics with some complications induced by local surface geology. When alluvial deposits were the less developed the gas emanations were stronger. Thicker alluvial deposits were found to be less representative of the deep end-member due to more pronounced interaction with these formations. Gas migration from depth is a highly complex phenomenon that must be better constrained in order to build confidence in safety rules and remediation strategies of CCS projects. Even at the upper level, near surface features have a strong influence on degassing pattern as pointed out by coupled geochemical/geophysical investigations (Schütze *et al.*, 2012).

Soil gas surveys performed under “point acquisition” schematic are relevant for the thorough description of surface leakage over a restricted spatial array. They are not fully appropriate for the monitoring of large areas and may be time consuming for repeated data acquisitions. They do not allow to take into account for the variability linked to external causes such as climatic variability and its imprint on surface environments. They are nonetheless crucial to best settle monitoring equipment for long-term surveillance. Investigation done at Sainte-Marguerite was mostly oriented on the ²²²Rn specie. It allowed highlighting excursion from background noise under “gas burst” event. Such events were characterised by influence radius of at least 200 m. Scaling effects in case of leakage from CCS storage may not allow to get such amounts of gases percolating up to the surface.

Therefore, there is also a need to monitor integrative bodies such as aquifers. In nearly all cases, CCS sites are more or less deep and overlying aquifers exist. Monitoring aquifers in the

case of natural leaking analogues is from one side little frustrating as the initial composition of the waters is not known – water properties prior leakage from a CCS site are known a priori – but on the other hand these waters represent an opportunity to study deep degassing through the interaction with water and rocks – that will be the case for CCS sites. The harmonic pulsation of Geyser Brissac is an extreme case relying on the accumulation of gas until the degassing due to overpressure.

Point monitoring of waters is by definition subject to heterogeneity of spatial coverage, ways to collect samples being restricted to available outlets or wells. Constraints on chemical processes occurring at depth may be brought by specific characterisation of the dissolved constituents and by related isotopic systematics. Particularly, the determination of mixing processes and their influence is important, as leakage from CCS site may be evidenced through the mixing of the water from the storage complex and overlying aquifers. Such methodology is not restricted to dissolved constituents and can also be extended to associate gases such as ^4He (Gilfillan *et al.*, 2011).

As for soil gases, monitoring at regular frequency of water bodies is complementary with point methods. Time scale of recording depends on the kinetic of the processes. At Sainte-Marguerite such monitoring was performed at high frequency in order to take into account variations over short time scales, cyclicity of the geyser being around 22 minutes. Most prominent variations were stated for pH, dissolved oxygen, redox potential and dissolved CO_2 content. From soil gas measurements it was also stated that geyser “breathing” influences the soil gas evolution over short periods at a radius close to 20-30 m.

Several conclusions arise when moving from analogue scale to industrial scale. Basically studies devoted to CCS projects separate into baseline data acquisitions, then monitoring actions during the injection and final monitoring operations after well closure and

abandonment. Baseline studies are essential as they represent the only data that will allow definition of anomalies during injection and post-injection. Establishing baseline values is a site-specific procedure but often their definition is based on a restricted dataset of measurement over limited time in order to match scientific issues on one side and industrial approach on the other side.

Natural analogue monitoring suggests that data acquisition should not be restricted in narrow perimeters above the storage complex itself but should encompass all the areas that may potentially be affected by leakage. One of the main concerns is the capability of the monitoring system to detect potential leaks. Anomalies are often restricted on narrow areas at surface and deploying monitoring devices on such small grids (20 to 200 m of array) is absolutely unrealistic if only considering costs. At surface, apart from such a net, it is therefore hypothetical to ensure a safely monitoring over great distances simply using punctual and point methods. Installation of equipment just above a potential leaking pathway that may not have been recognized by geological studies would be too lucky to be reproduced regularly over several deep CO₂ storages. Surveying methodologies are nowadays adapted to integrate gas emanations characteristics from hectometer to kilometer scales. Methods such as eddy covariance, open path laser, airborne hyper-spectral monitoring etc... are promising ones but until now they are not as robust as required for storages monitoring as they are often dependent from modeling of the atmosphere compartment that is strongly turbulent over short time periods and may therefore induce undesirable effects and false warnings (*e.g.* Klusman, 2011).

Ways to overcome this limitation may be of several types. Monitoring at depth through boreholes, using geochemical and/or geophysical methods, appears to be the best way to get early detection and warning of unexpected events by focusing on the water phase and on dissolved gas contents. Monitoring should be performed under continuously deployed devices

or at least consisting in repeated measurements. Nevertheless, from a geochemical point of view, lot of the available monitoring equipment that may be deployed at depth has nowadays not reached the desirable level of reliability over long time periods.

Many efforts have been done in recent years to adapt technologies to CCS monitoring and to gain confidence in results, but long-term recording of parameters remains a challenging question.

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Figure captions:

Figure 1: location of the study area: dots locate points where soil gas data are available: black dots refer to 2006-2010 data acquisitions, red contoured dots are from the 90's dataset. Red dots represent the main mineral waters that are labelled in the inset. Yellow dots (labelled 1 to 4) represent points where continuous monitoring was performed. Grey lines represent main roads.

Figure 2: O₂ – CO₂ relationship for the 2006-2010 soil gas measurements; the equimolar replacement line (1 mole CO₂ ⇌ 1 mole O₂) is represented. Model line corresponds to the regression line between the 2 species; the 95% confidence interval of the regression is also indicated.

Figure 3: relationships between Ar, N₂, O₂ and CO₂ concentrations (% vol.) on samples analysed using laboratory gas chromatography (samples from year 2007).

Figure 4: A: Relationships between CO₂, ²²²Rn and ⁴He in soil gas (2006-2010 dataset); B: detail of the CO₂ - ²²²Rn relationship for low ²²²Rn concentrations (lesser than 300,000 Bq.m⁻³).

Figure 5: Relationships between CO₂, ²²²Rn and ⁴He in soil gas.

Figure 6: spatial distribution of soil gas species (from left to right: CO₂, ²²²Rn and ⁴He) along with time (from top to bottom). Interpolation is done using natural neighbour contouring.

Figure 7: CO₂, ²²²Rn and ⁴He concentrations (2006 to 2010 measurements) recalculated in the 0 – 1 interval to lower the influence of ²²²Rn and strengthen the one of ⁴He (arbitrary units). See text for explanation.

Figure 8: a: temporal evolution of pressure for Barasol probes (labelled as F10X) for points 2 and 4 (Figure 1) and comparison with atmospheric data (Clermont-Ferrand Aulnat airport; <http://french.wunderground.com/>); b: evolution of soil temperatures and atmospheric temperature (same chart as for 8a); c: ²²²Rn concentrations over time; blanked areas (F109 probe) correspond to power supply deficiency or to electronical malfunctioning of the ²²²Rn detector.

Figure 9: F109 Barasol probe (point 4 in Figure 1); period from the 26 February 2009 to the 07 April 2009; a: temporal evolution of soil temperature and ²²²Rn concentrations; b: temporal evolution of atmospheric pressure and ²²²Rn concentrations; c: temporal evolution of atmospheric temperature and ²²²Rn concentrations; d: spectral densities of ²²²Rn concentrations; e and f: Principal Component Analysis using these 4 parameters.

Figure 10: a: temporal evolution of water temperature of Geyser Brissac during deployment; b: temporal evolution of temperature (°C), pH, specific conductance at 25°C (mS.cm⁻¹), dissolved oxygen content (mg.L⁻¹), redox potential (Eh, mV) and dissolved CO₂ (expressed as a mV value) during the second day of deployment.

List of tables:

Table 1: statistical parameters for the CO₂, ²²²Rn and ⁴He concentrations during the 90's and 2000's surveys (Sainte-Marguerite area; see Figure 1 for location).

Table 2: physico-chemical parameters of mineral waters from the Sainte-Marguerite area (see location in Figure 1). Major ion contents are reported; blanks indicate a non-detection of the specie or a non-measurement (isotope ratios). $\delta^{18}\text{O}$ and δD isotope ratios are reported as well as the δD difference to the local meteoric water line ($\delta\text{D} = 8 \delta^{18}\text{O} + 13.1$; Fouillac *et al.*, 1991). Equilibrium partial CO₂ pressure is computed using Diagrammes software (<http://www.lha.univ-avignon.fr/>).

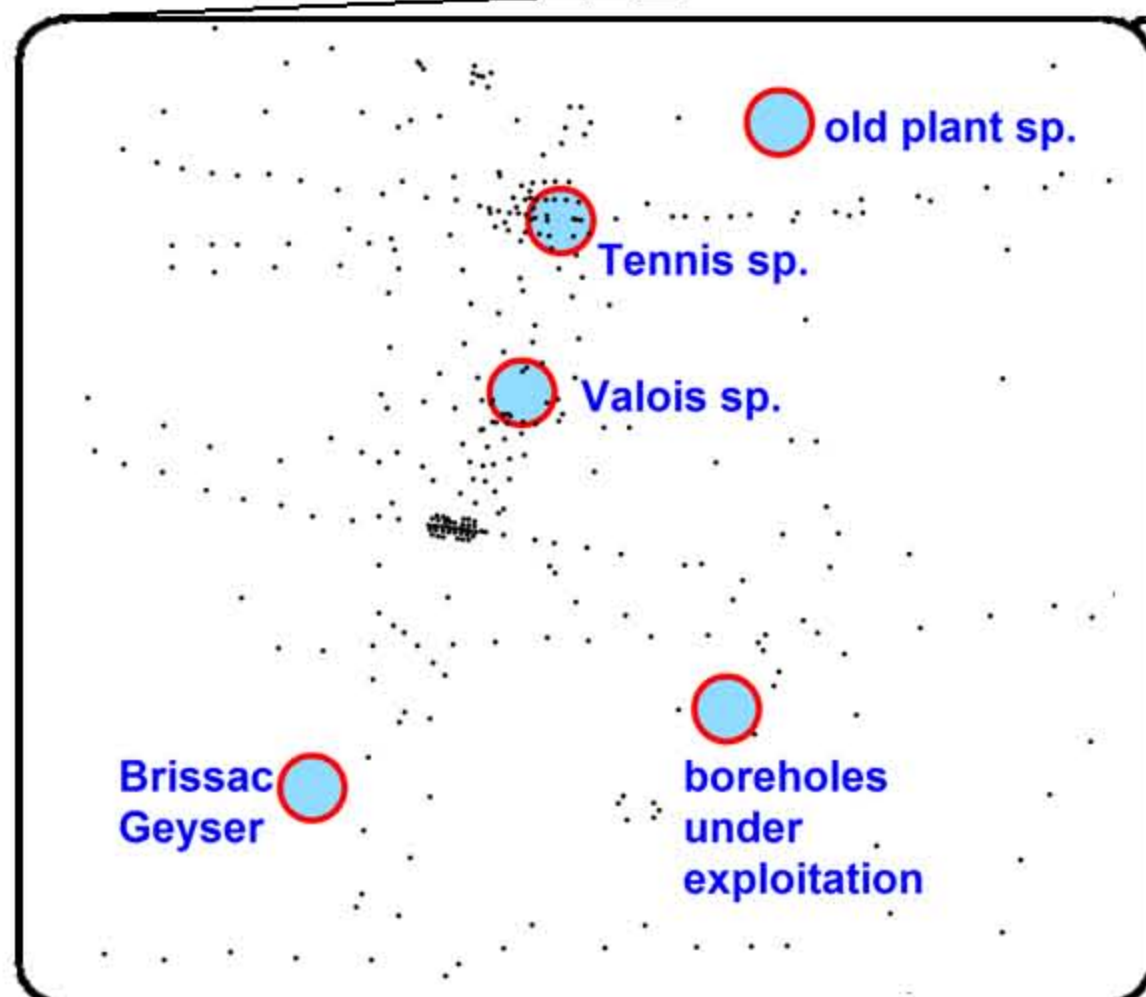
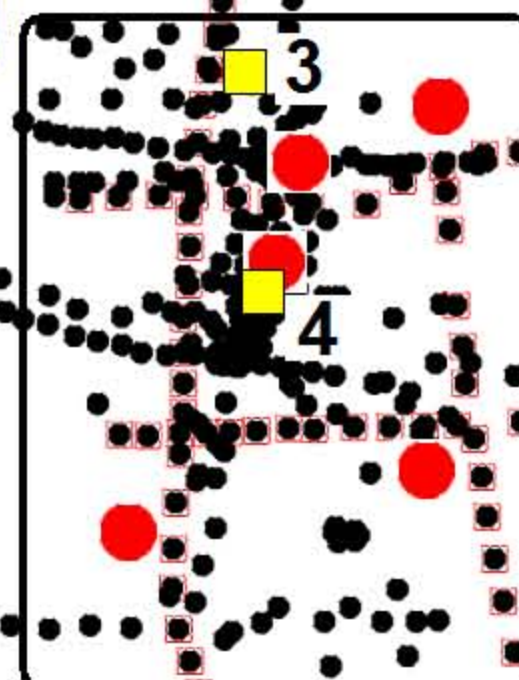
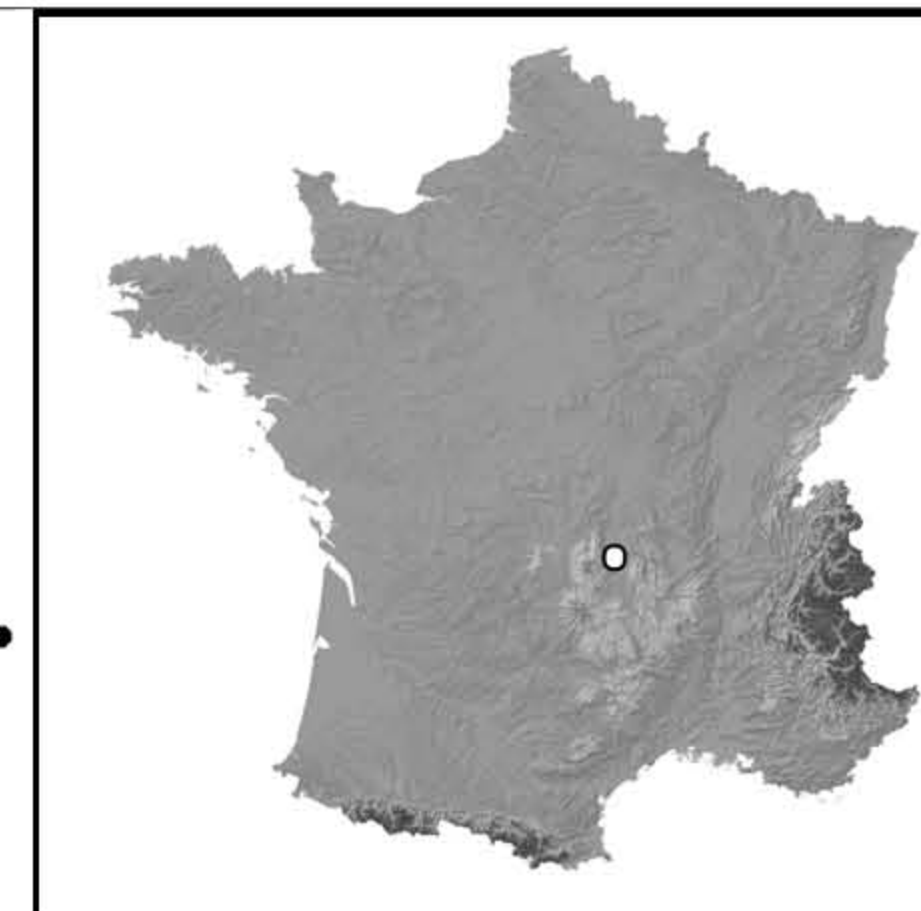
Table 3: descriptive statistics for ²²²Rn concentrations acquired using Barasol probes.

Table 4: top: evolution of temperature (°C), pH, specific conductance at 25°C (EC, mS.cm⁻¹), dissolved oxygen content (mg.L⁻¹), redox potential (Eh, mV) and dissolved CO₂ (expressed as a mV value) along the 4 days of monitoring of the Geyser Brissac (monitoring duration indicated into brackets); bottom: correlation matrix for each daily dataset. Geyser Brissac was sampled on day 3 (Table 2).



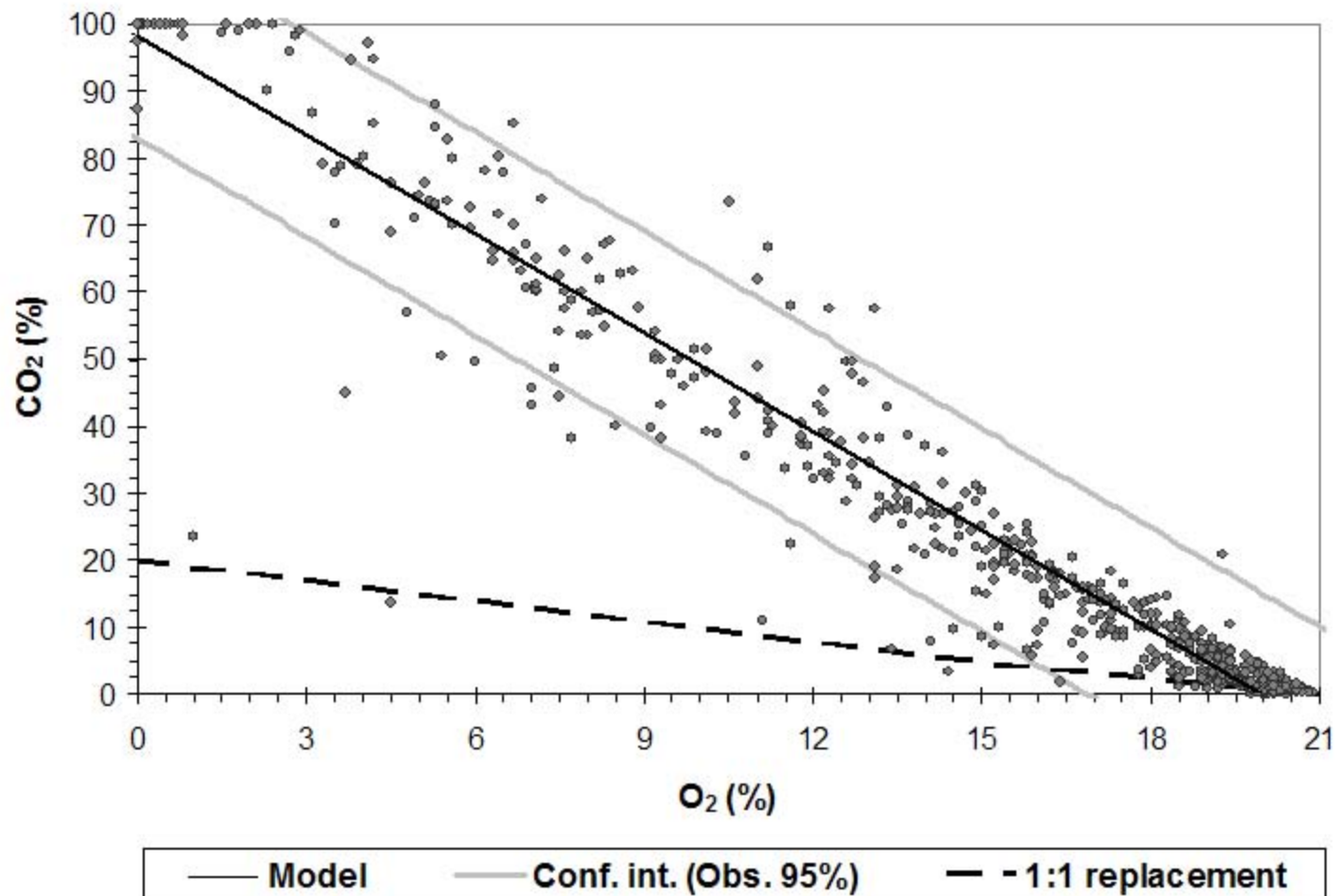
Saladis
springs

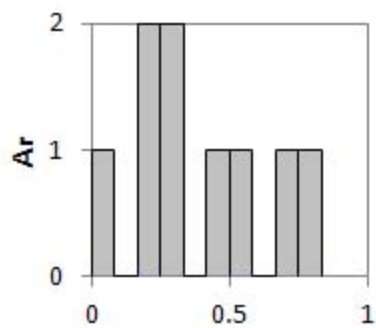
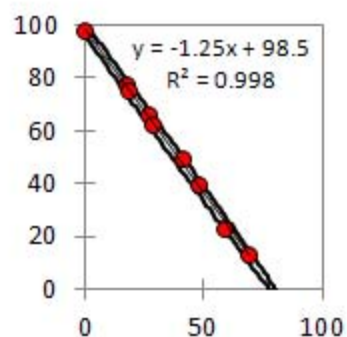
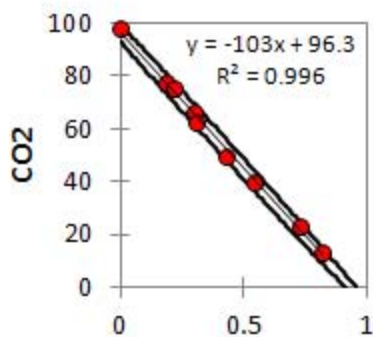
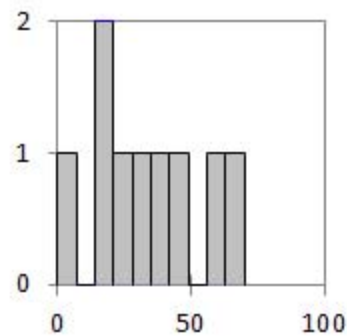
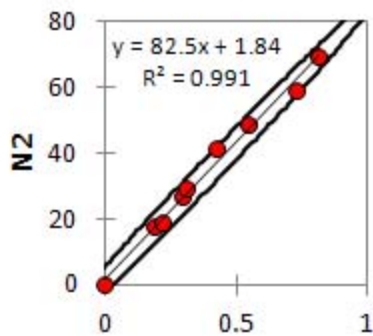
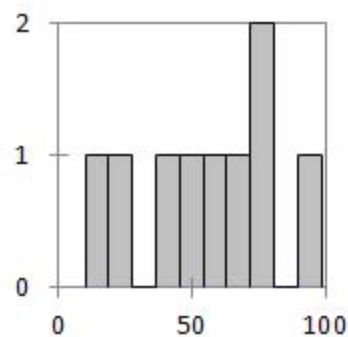
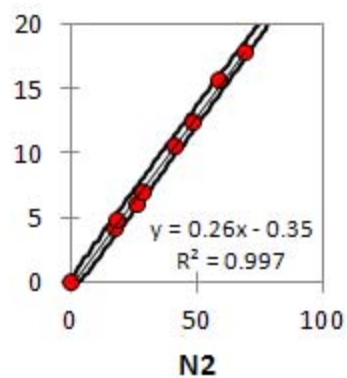
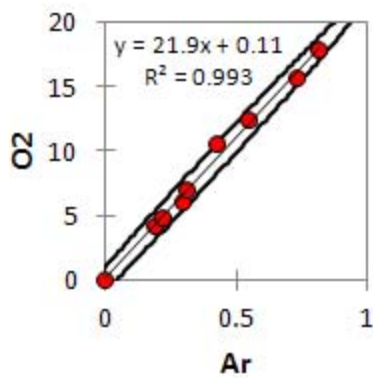
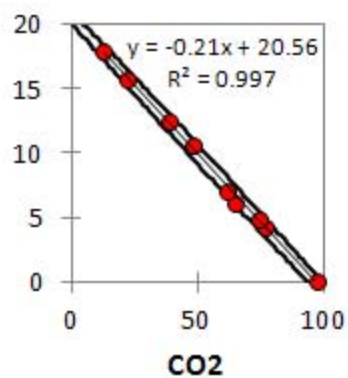
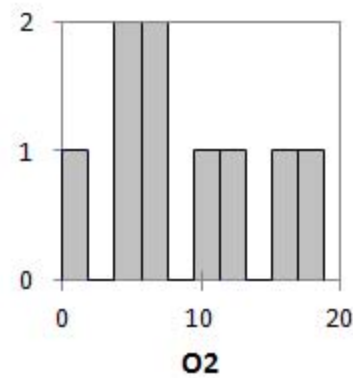
Allier River



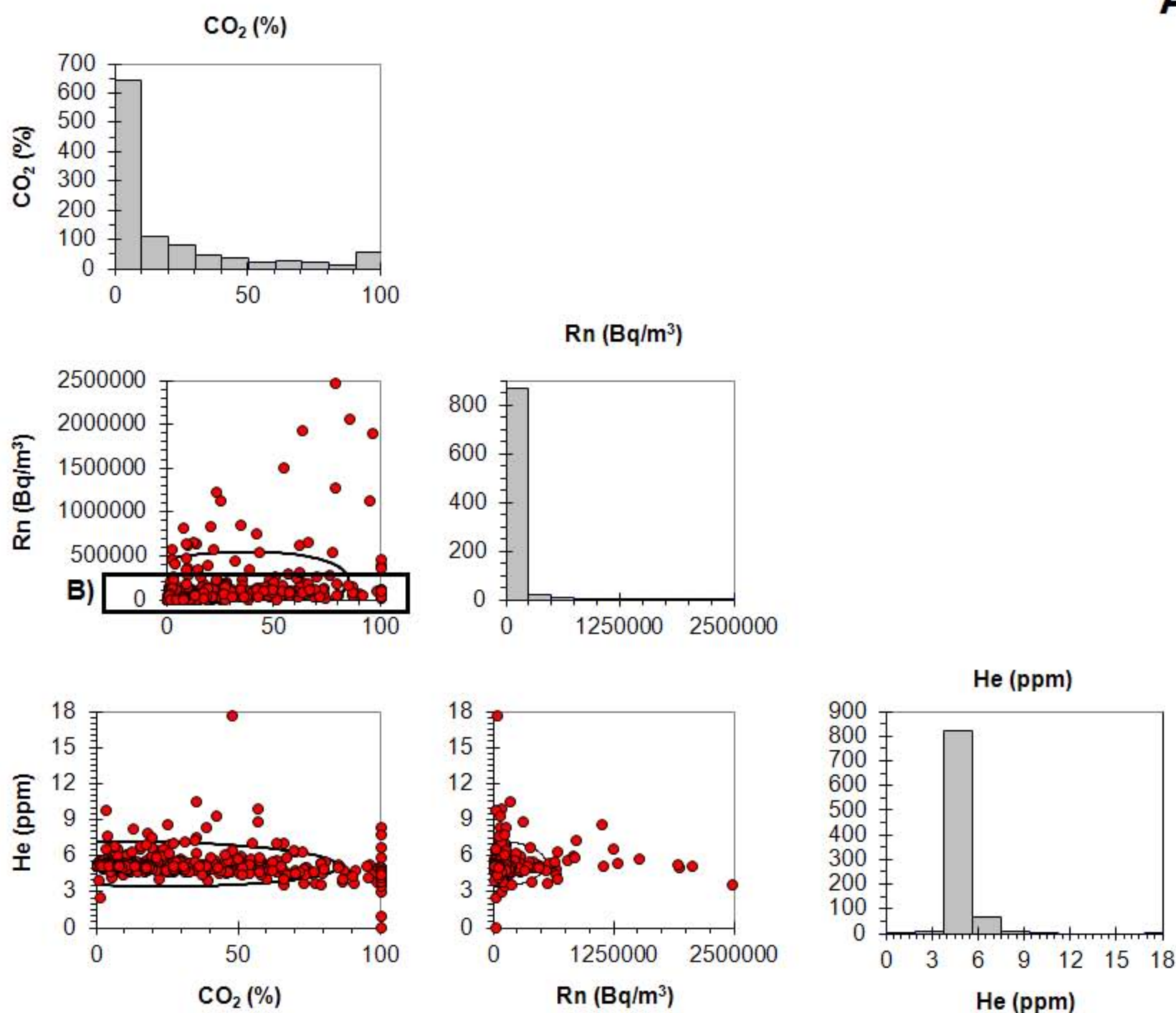
0 50 100
Metres

$$\text{CO}_2 (\%) = 98.2 - 4.92 \times \text{O}_2 (\%) \quad (R^2=0.943; n = 566)$$

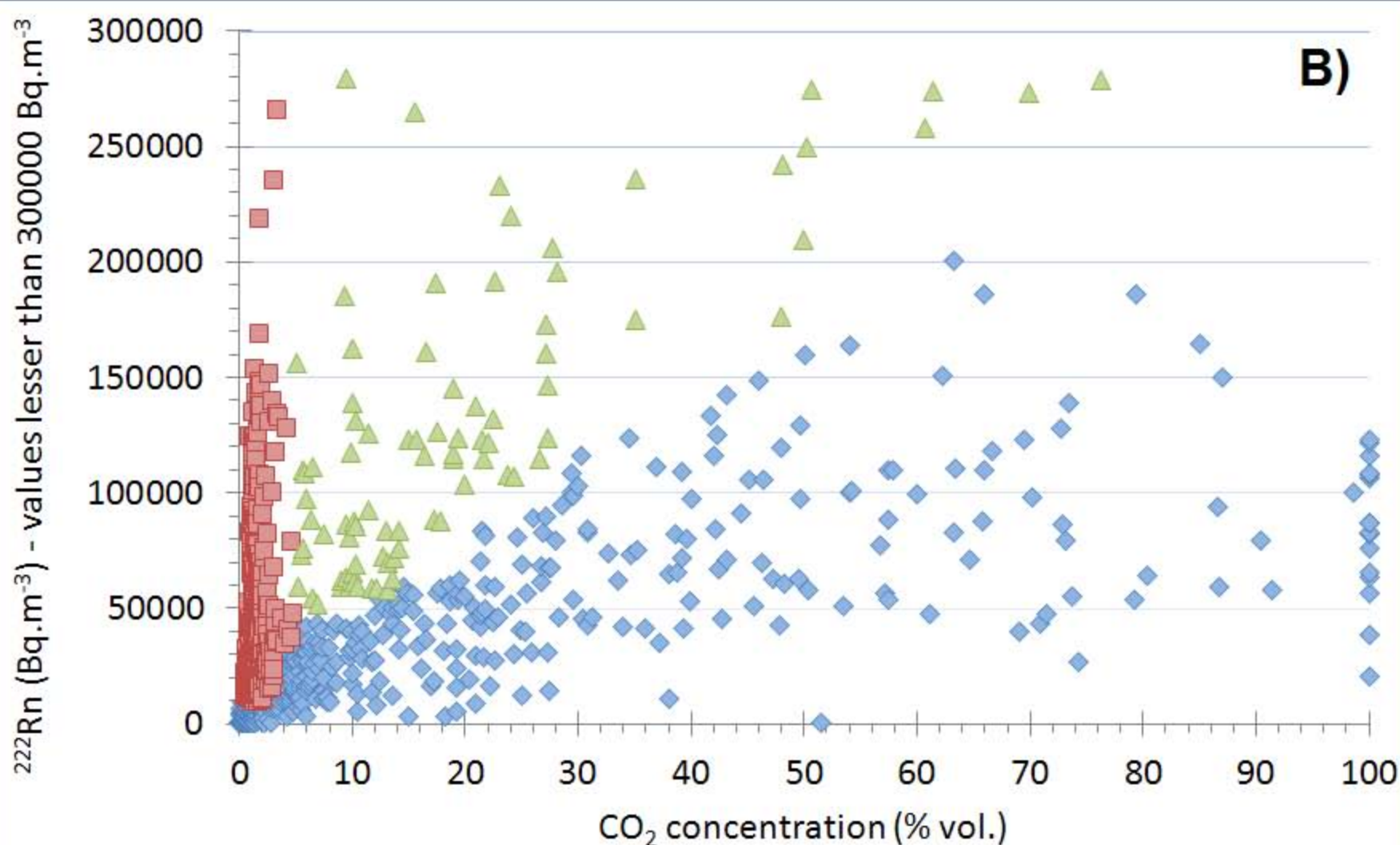


Ar**N2****CO2****O2****CO2****O2**

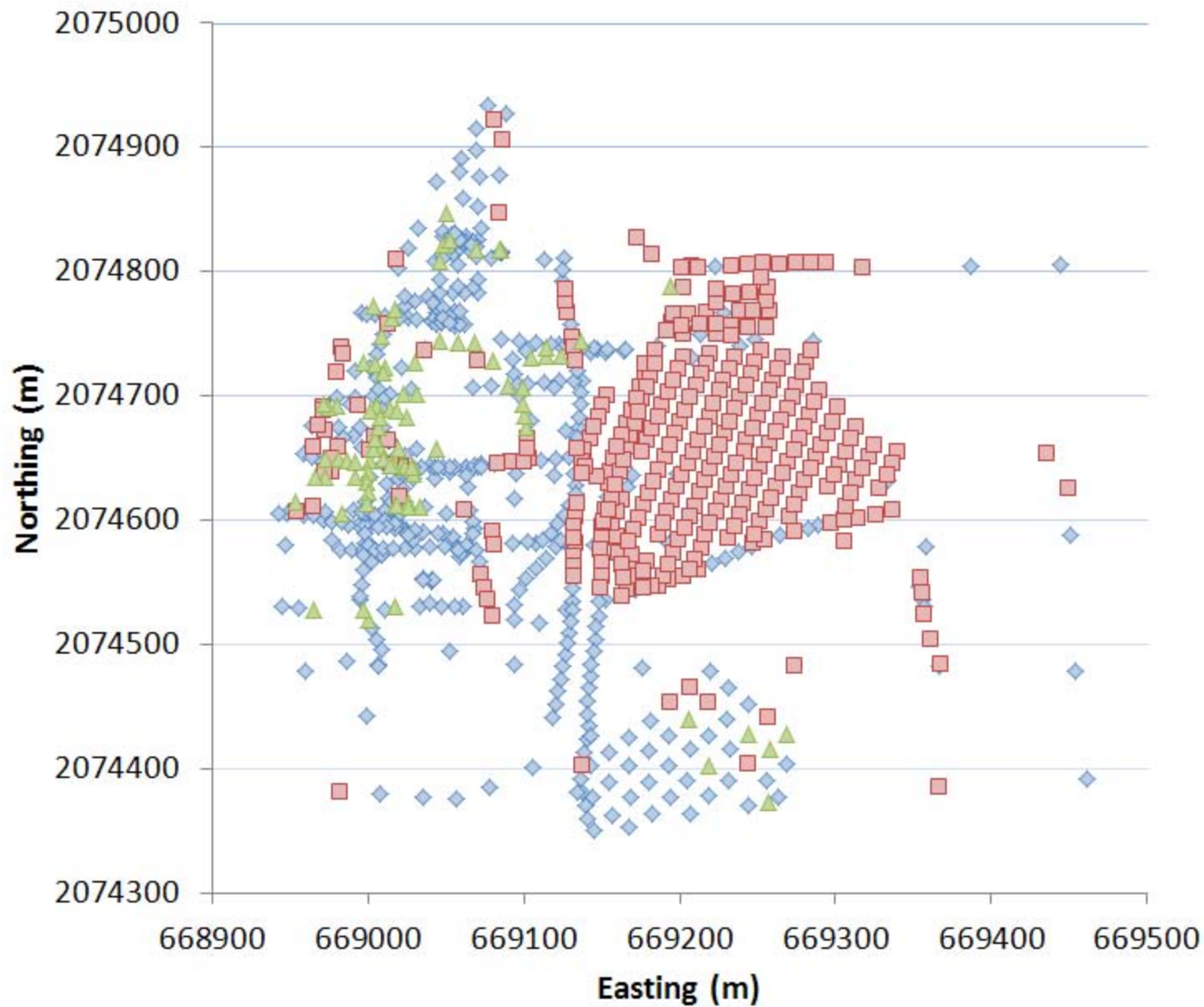
A)

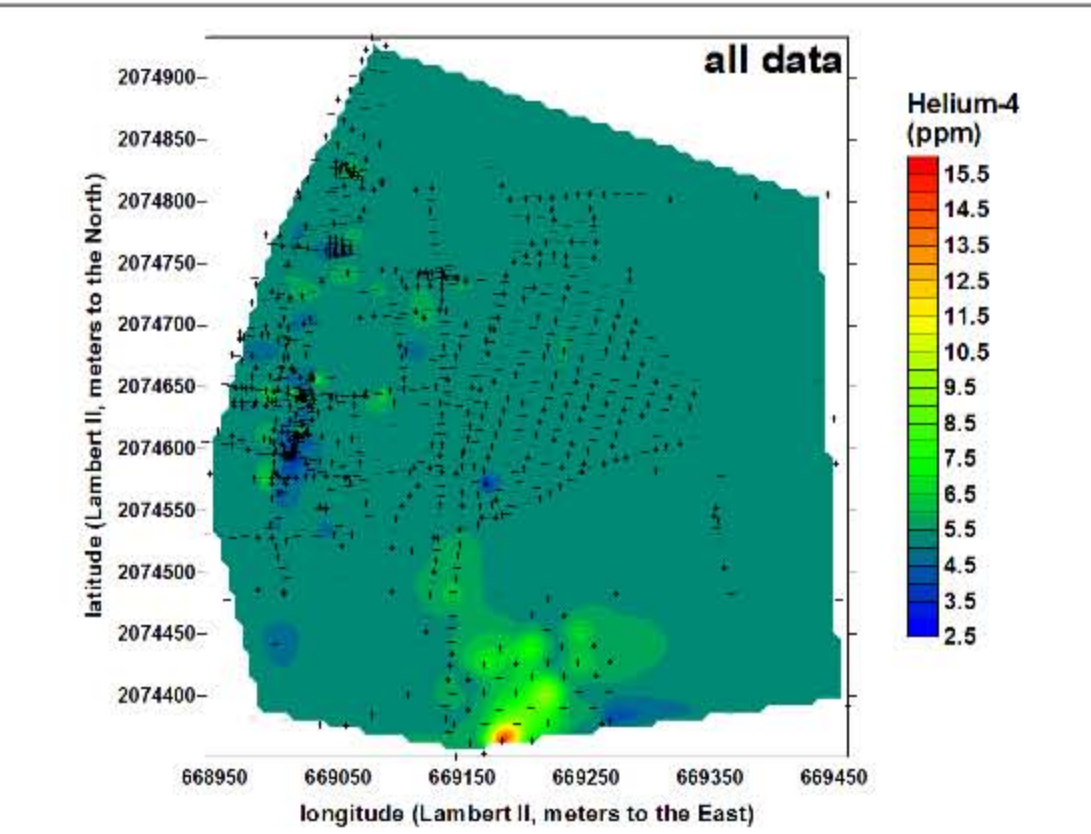
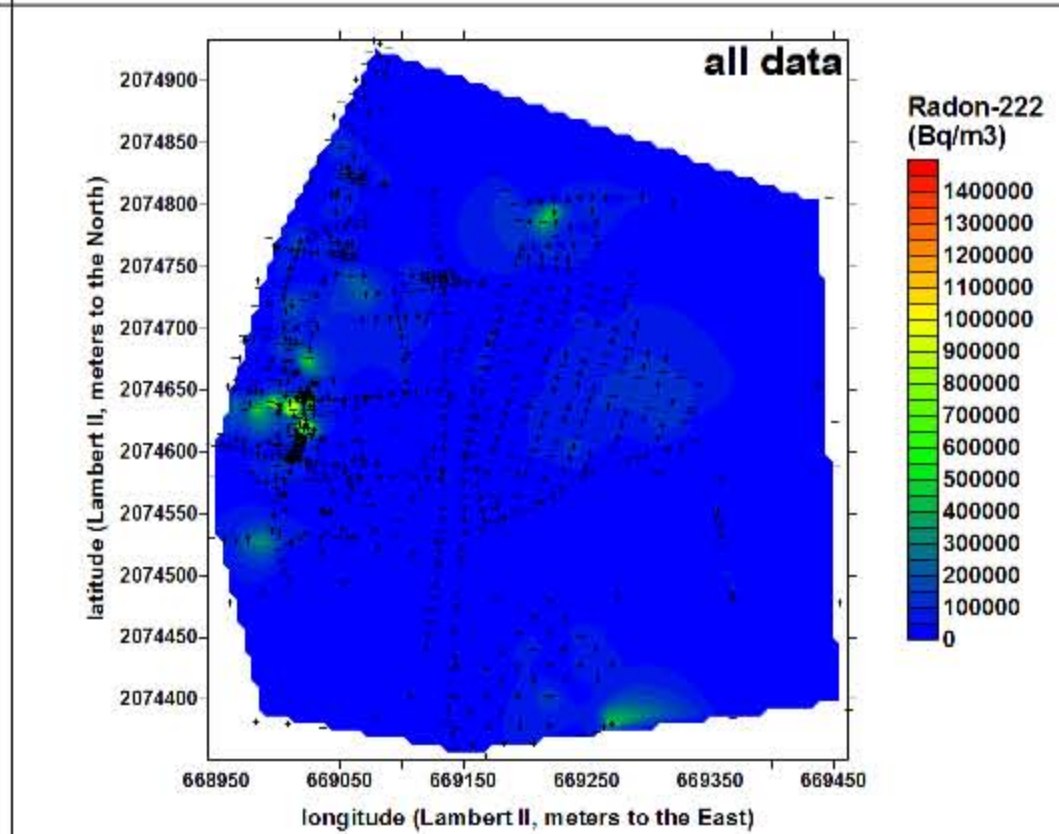
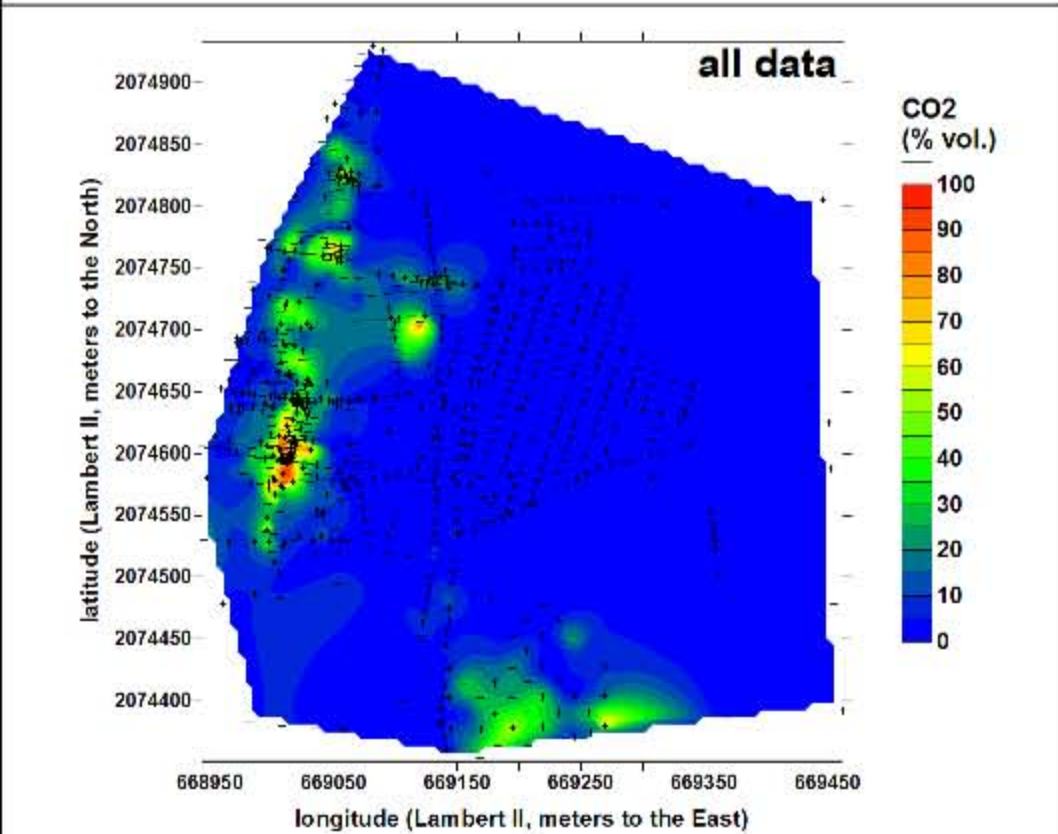
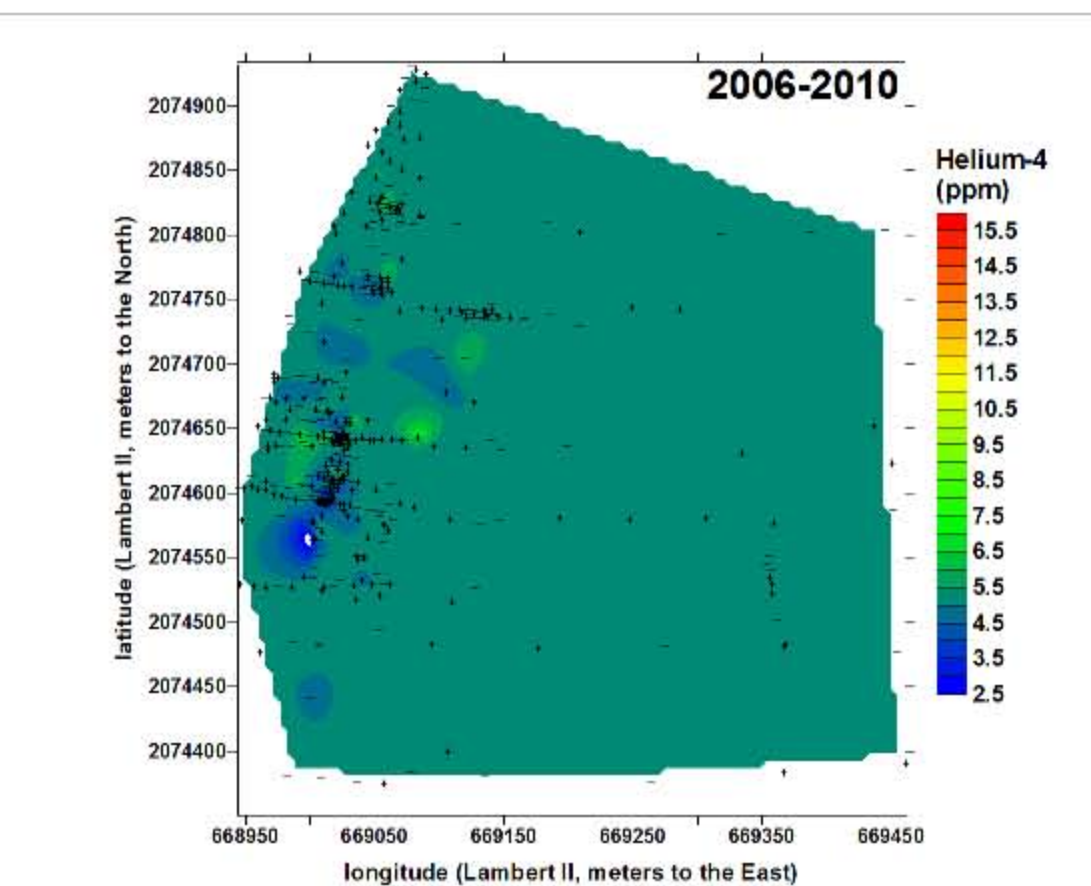
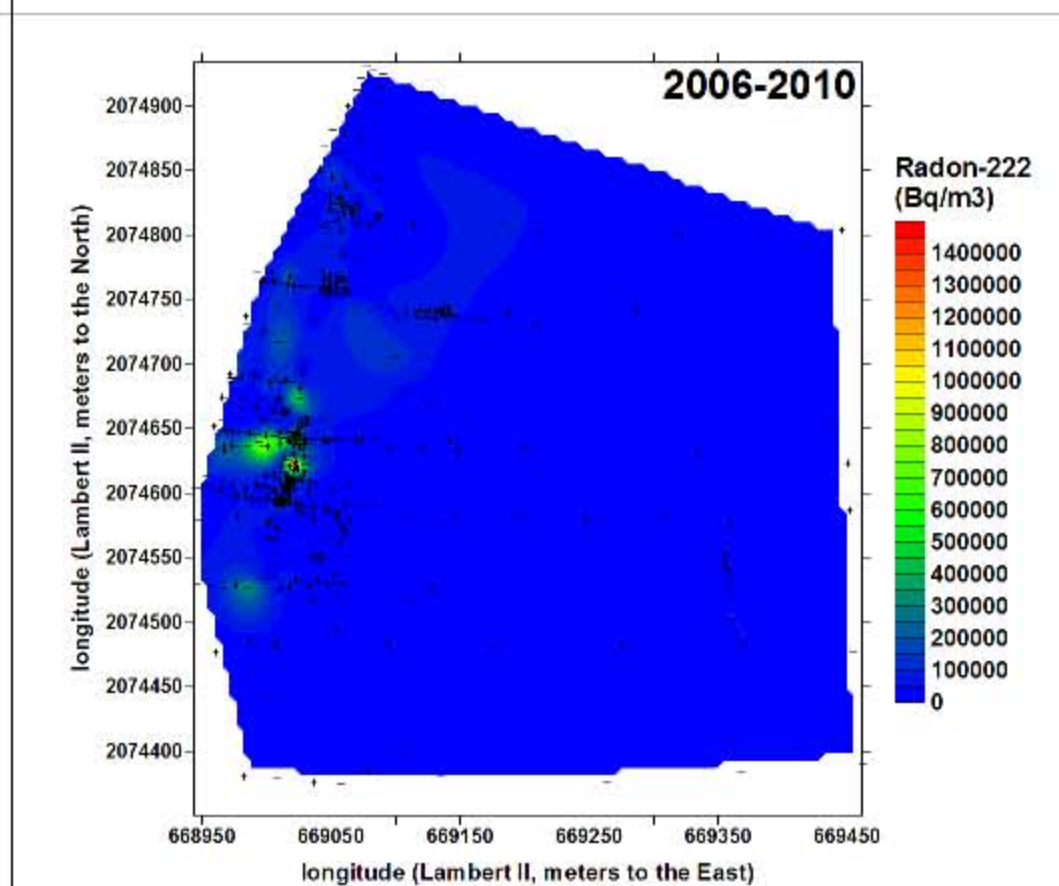
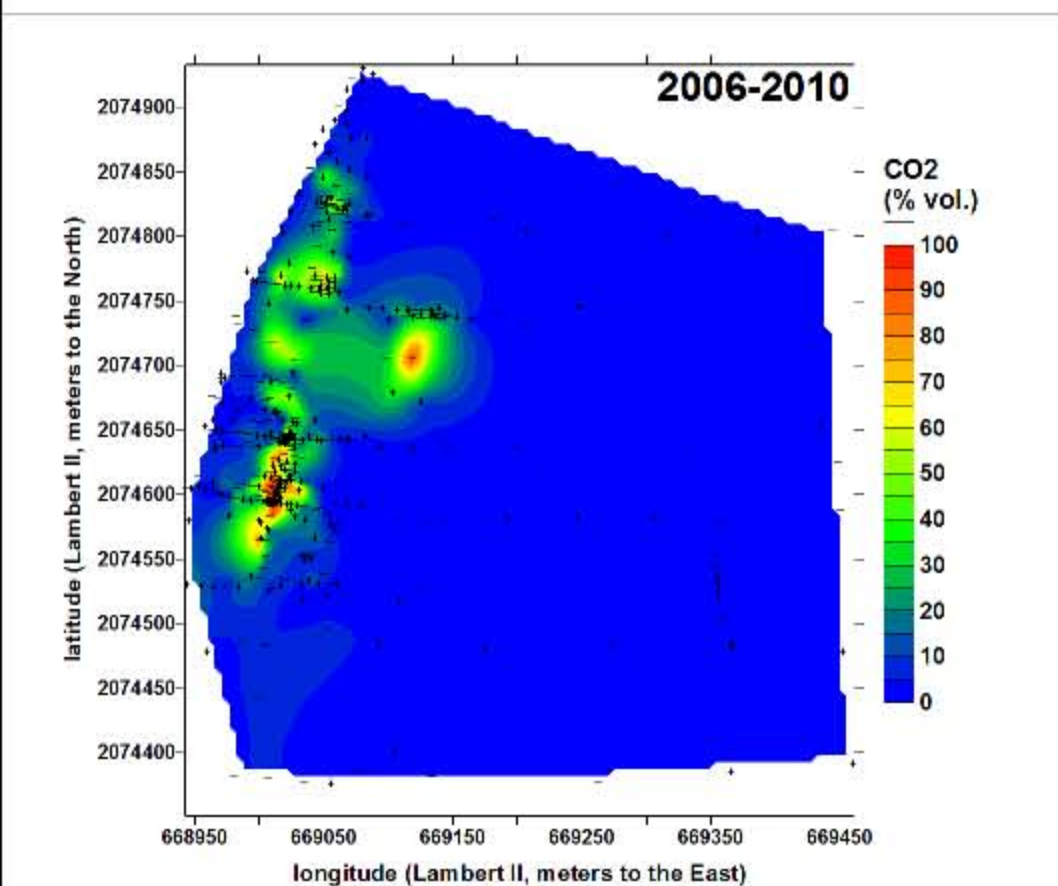
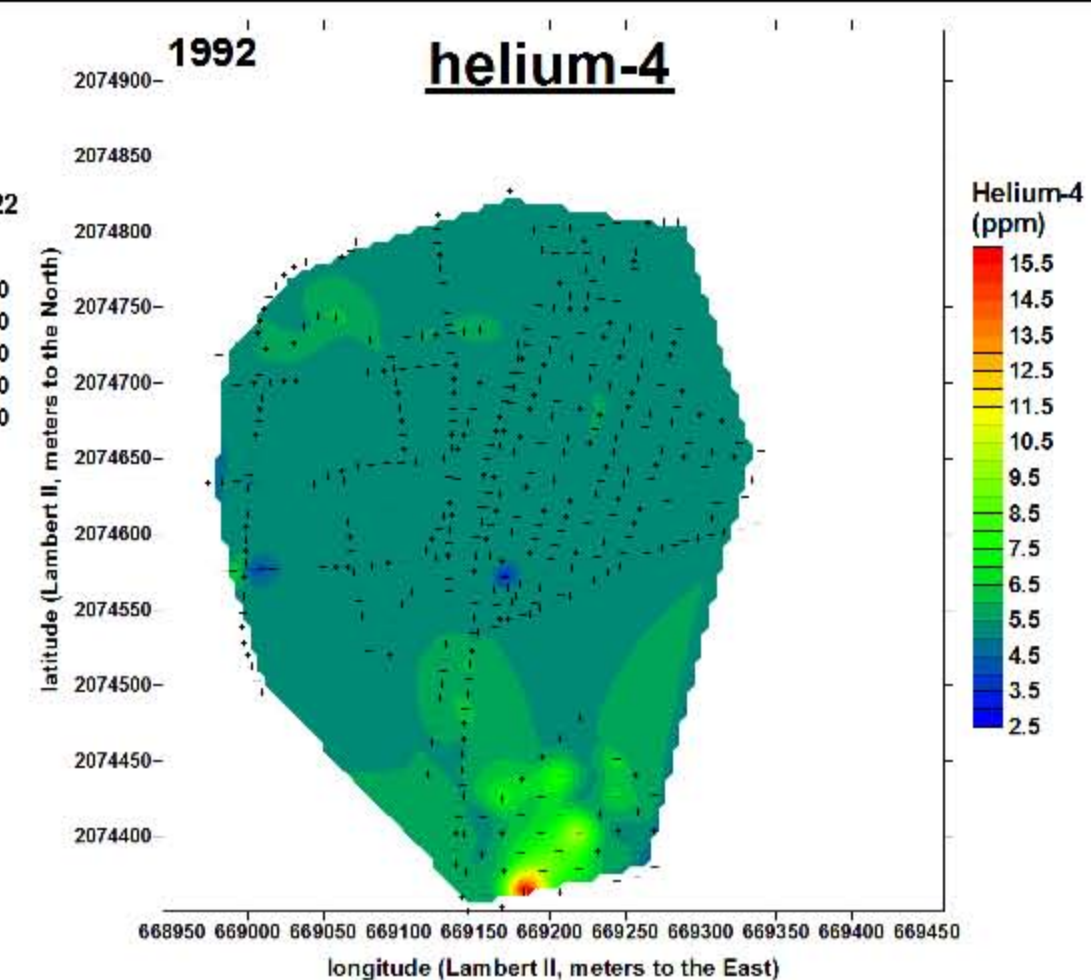
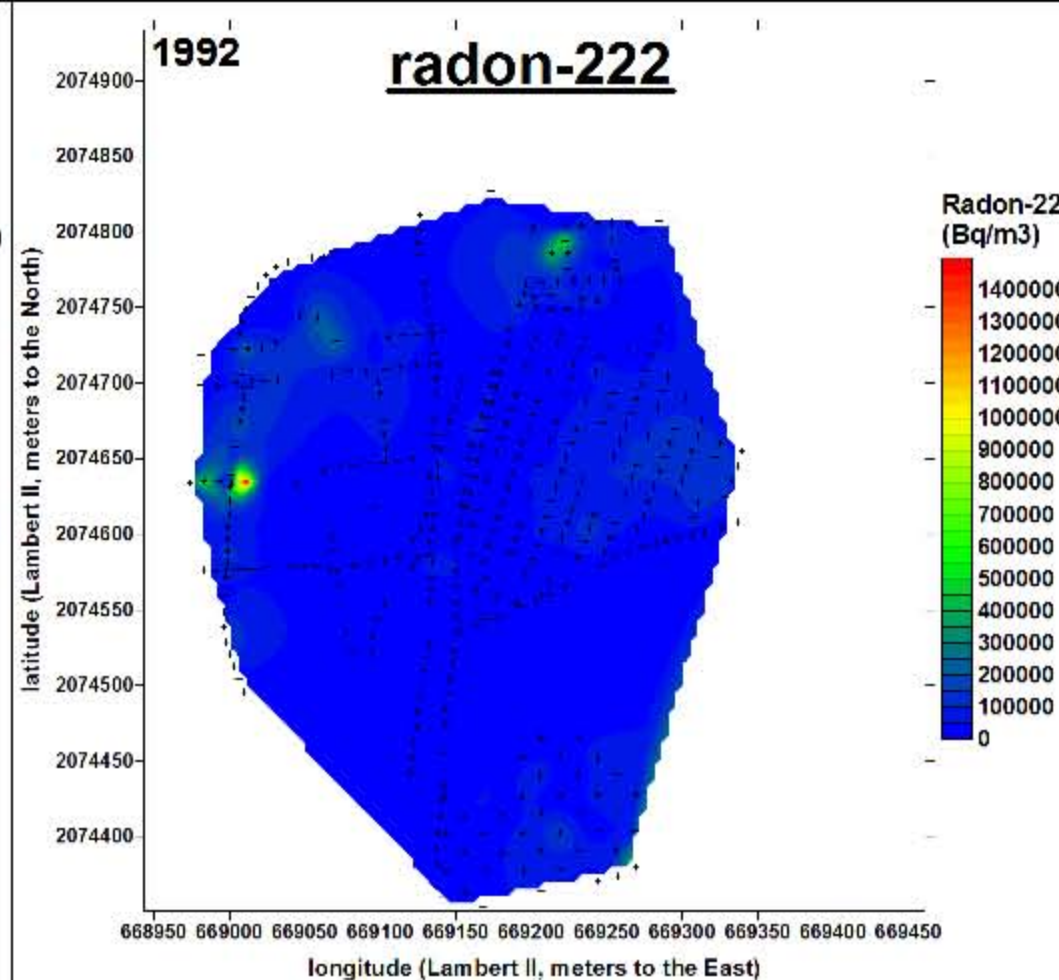
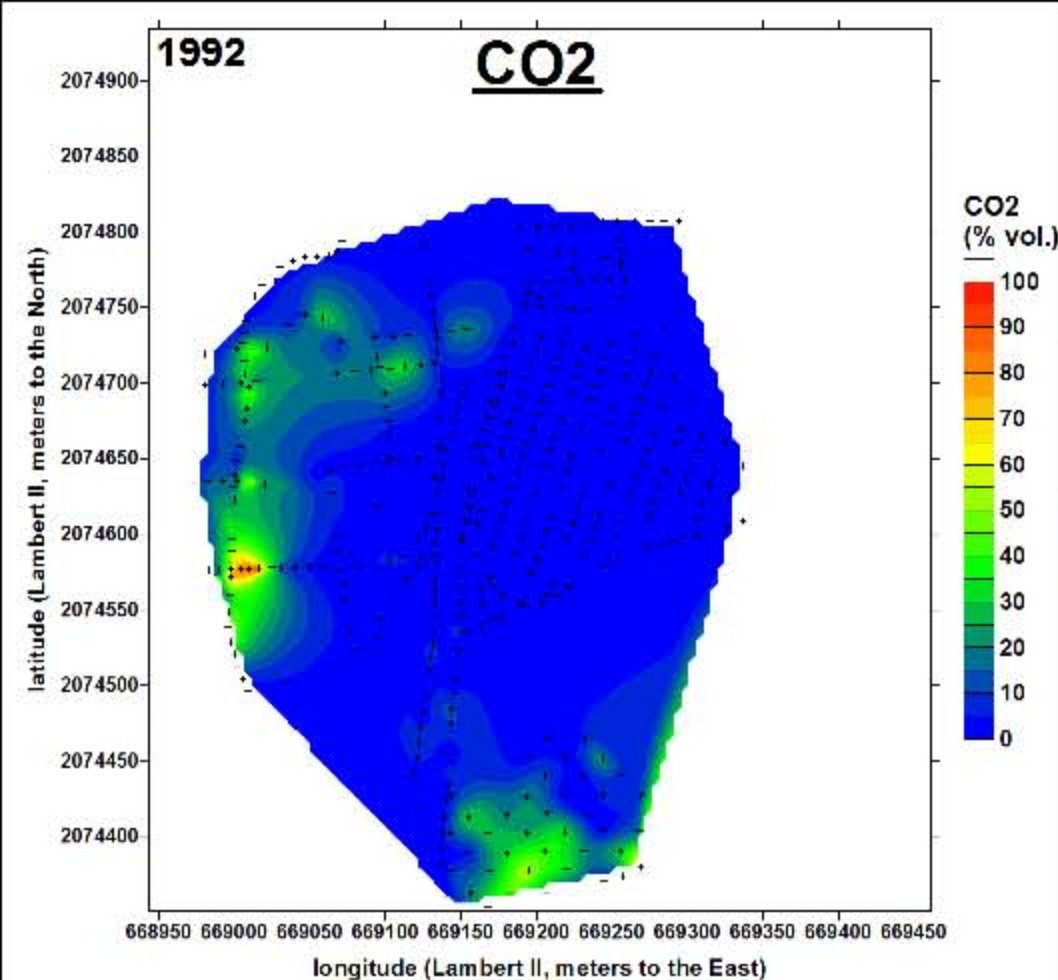


B)

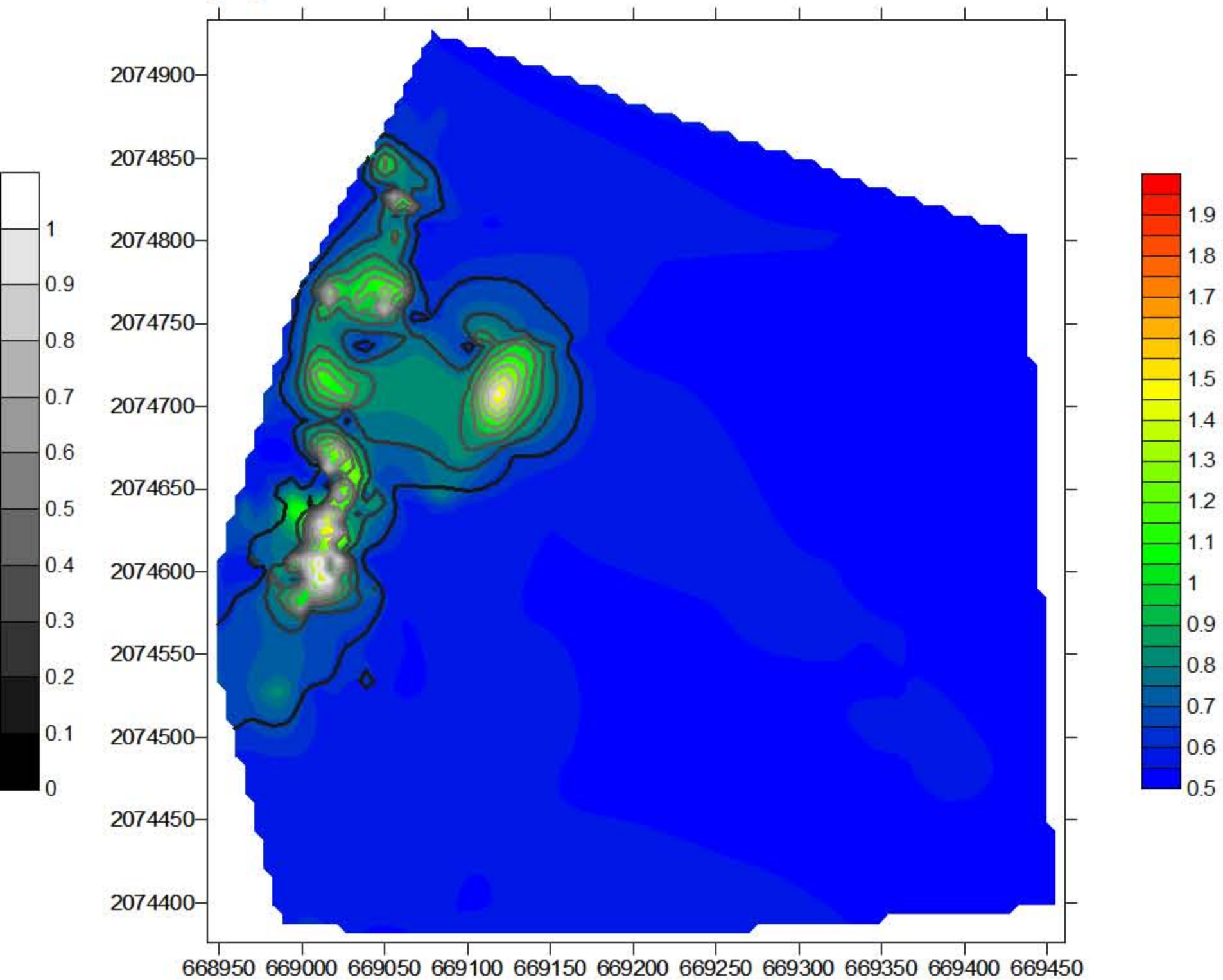
◆ slow ^{222}Rn enrichment vs. CO_2 enrichment■ fast ^{222}Rn enrichment vs. CO_2 enrichment

▲ intermediate tendency

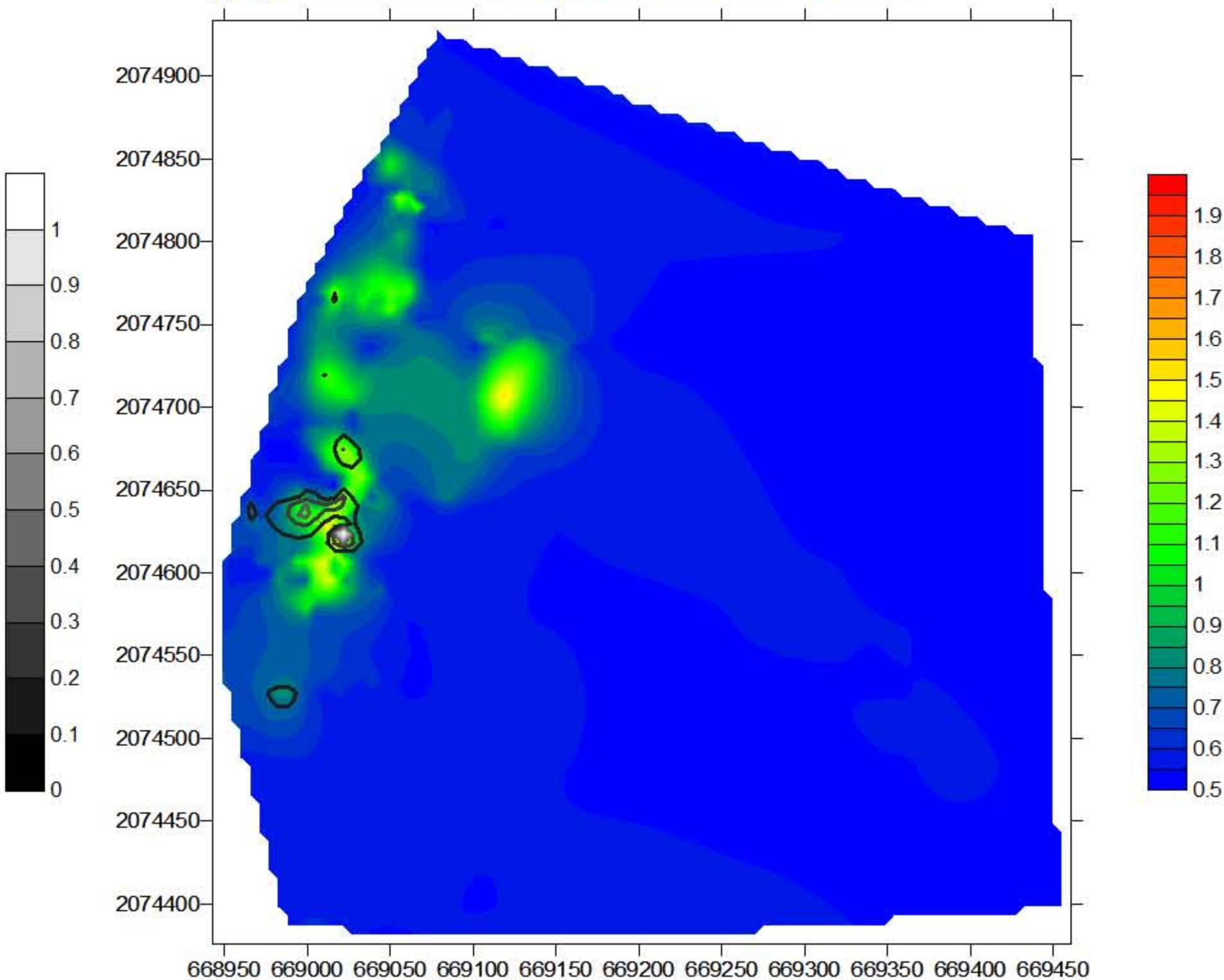




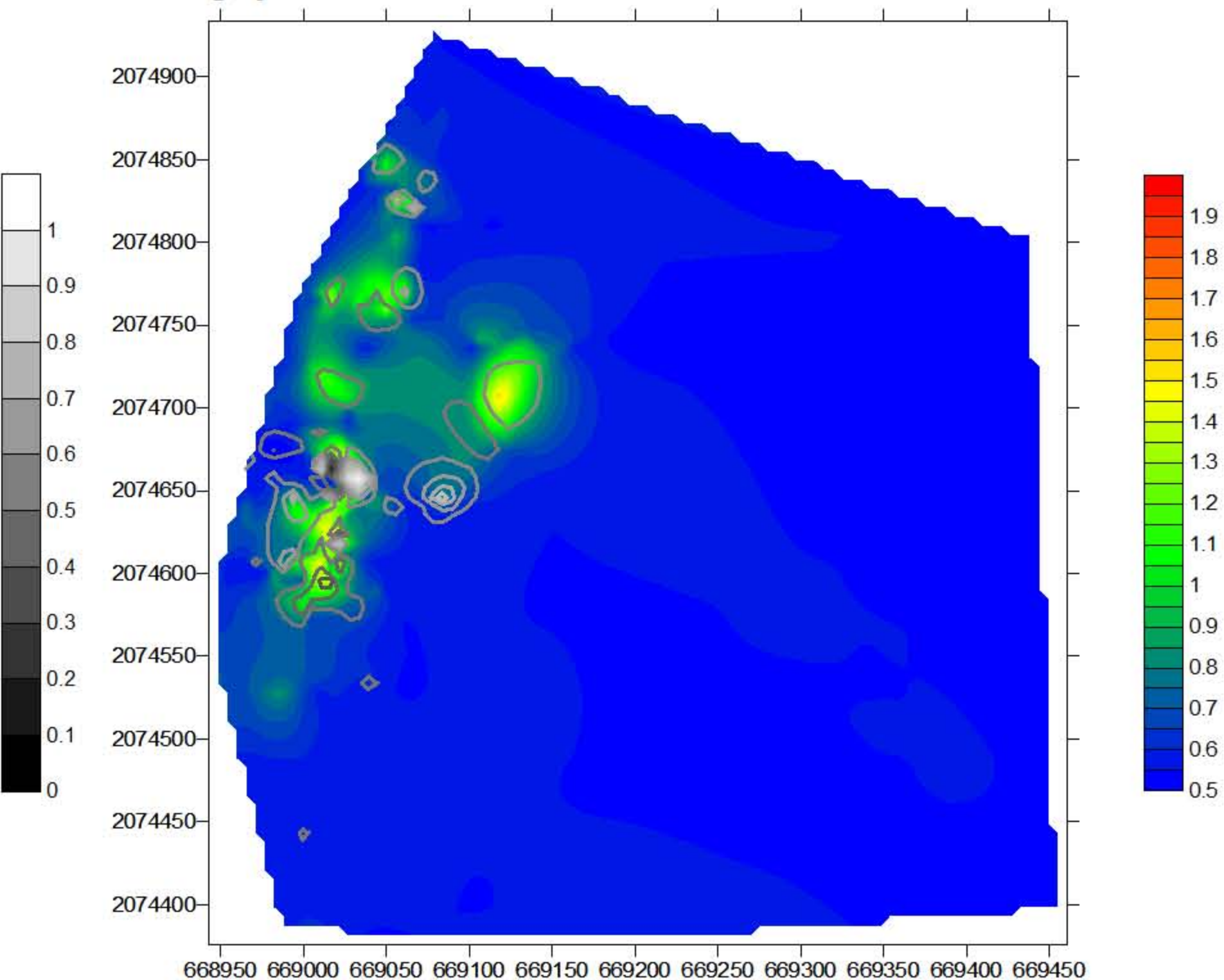
colorscale: sum of CO2 + radon + helium fitted in the 0 - 1 interval
greyscale: CO2 distribution in the same interval

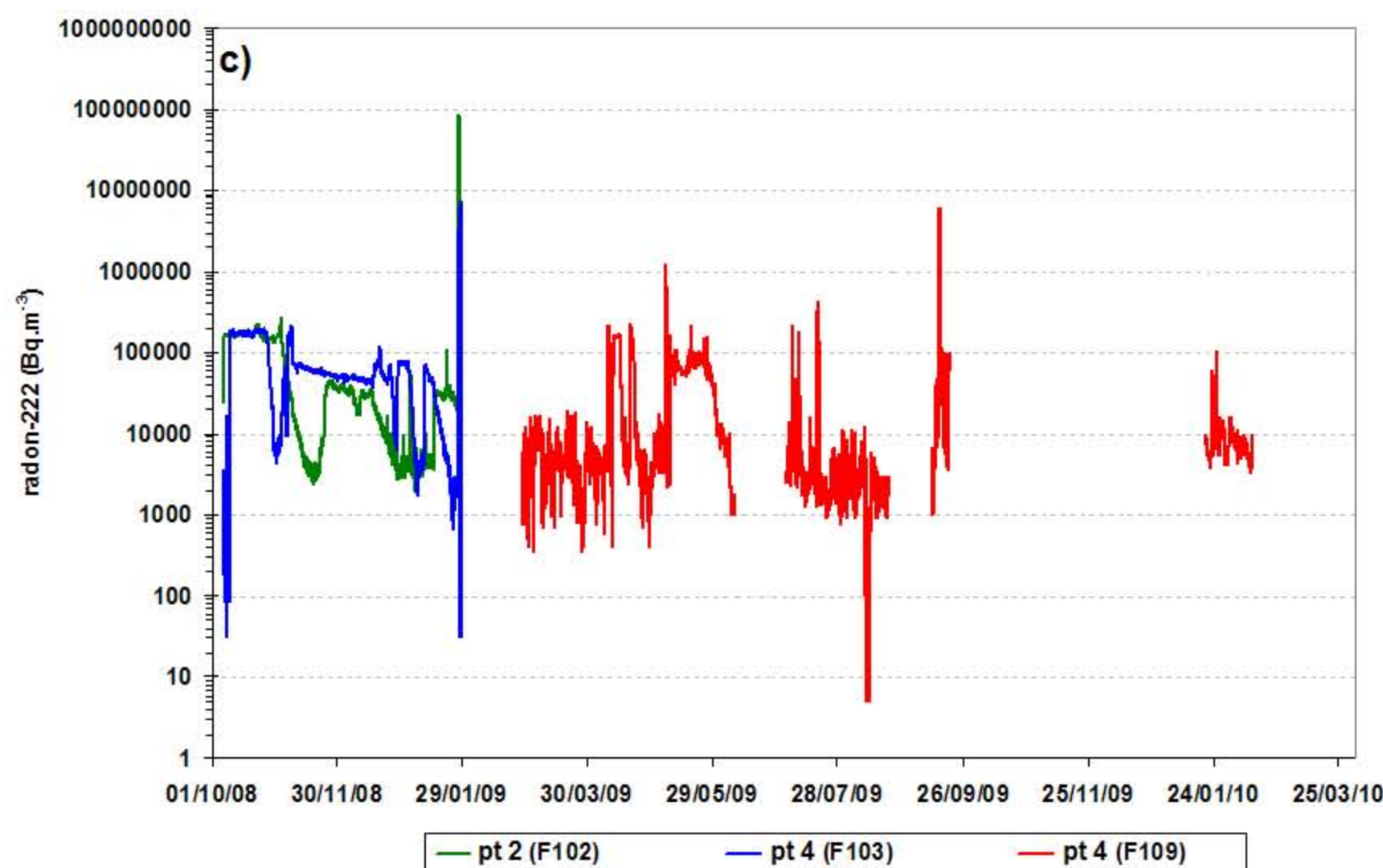
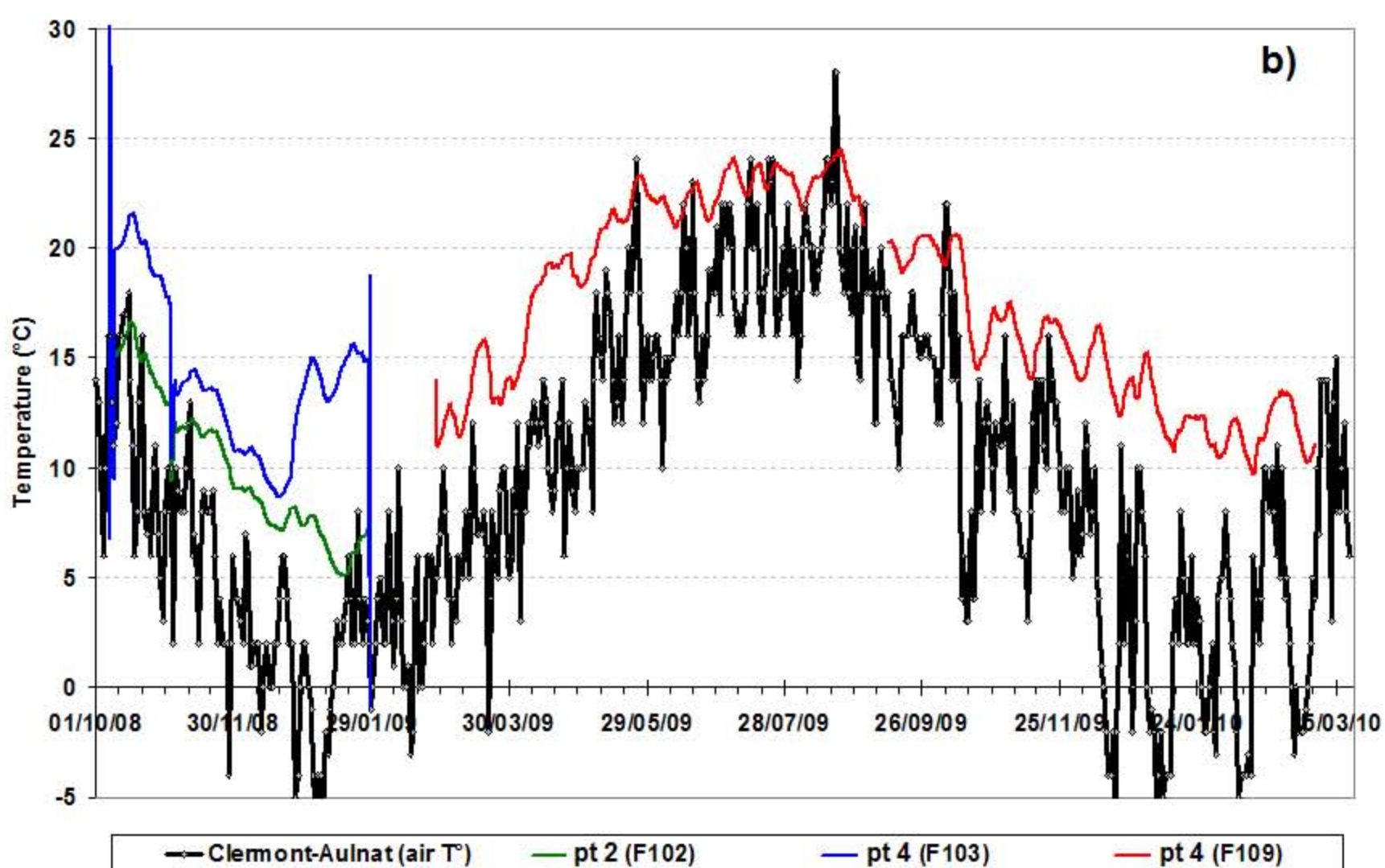
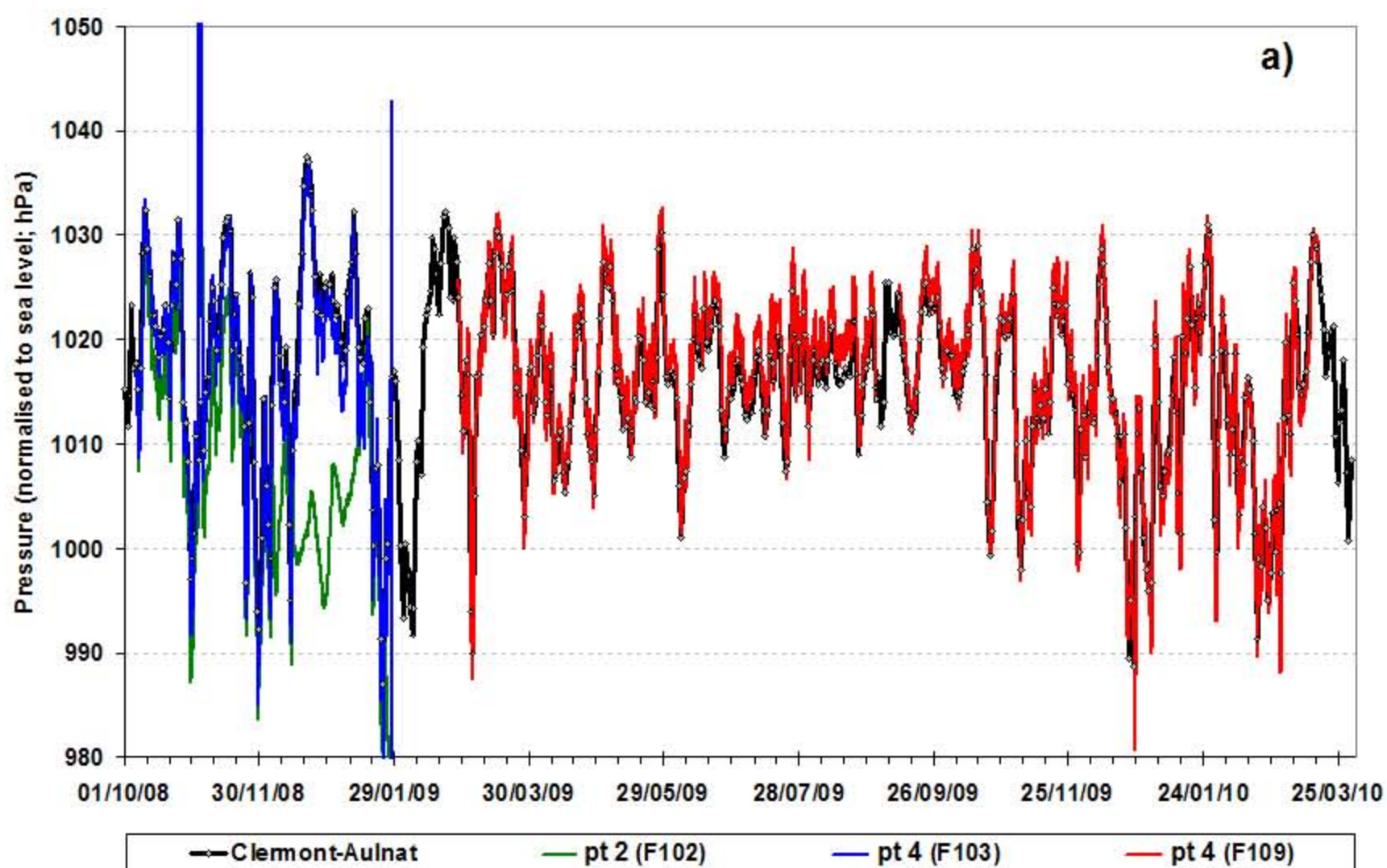


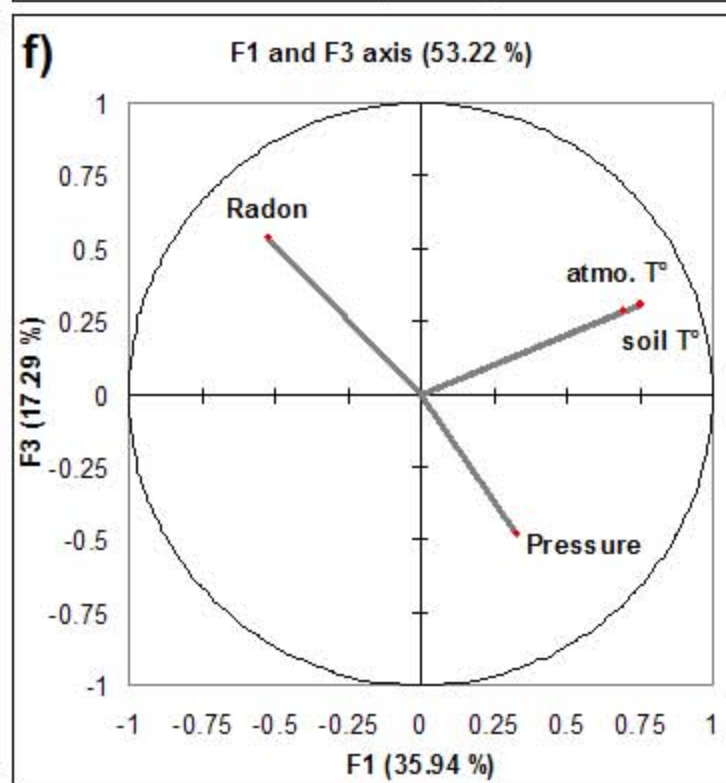
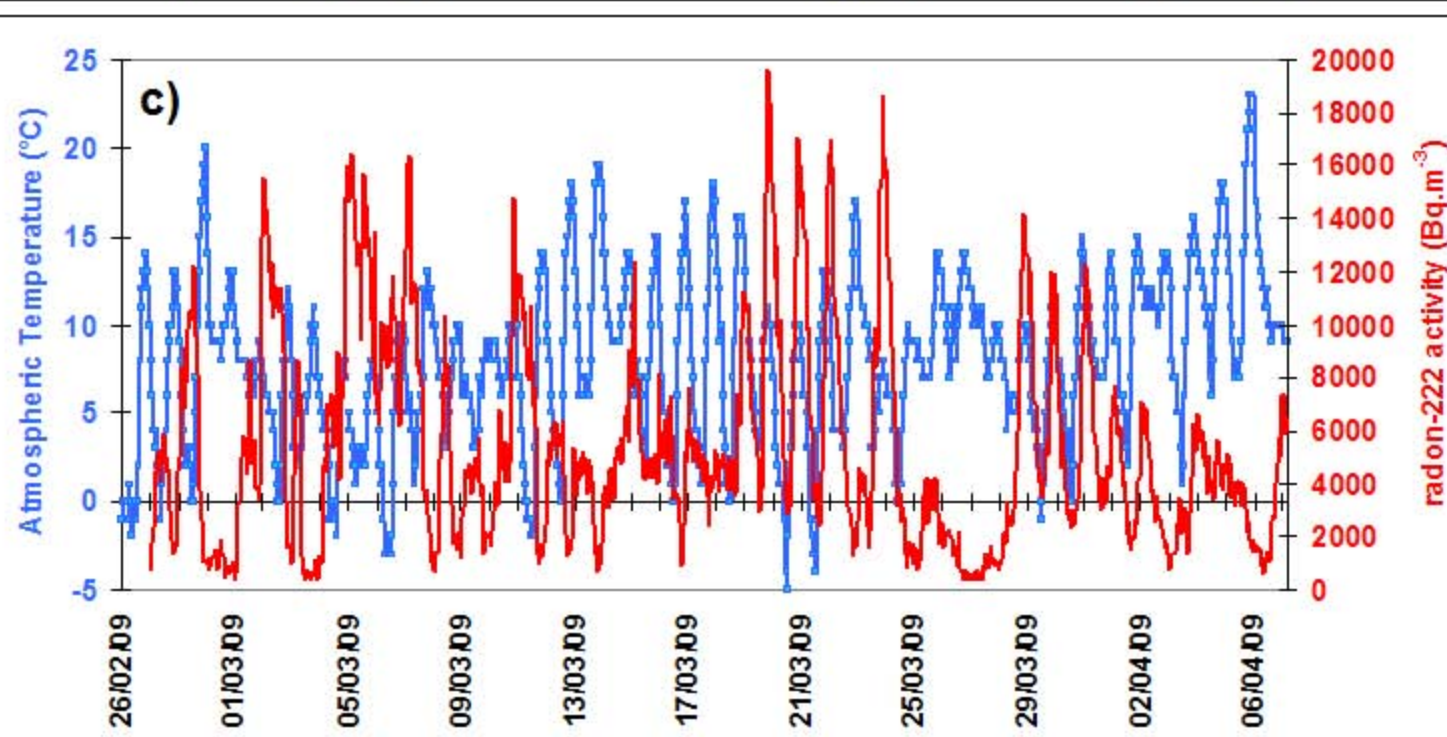
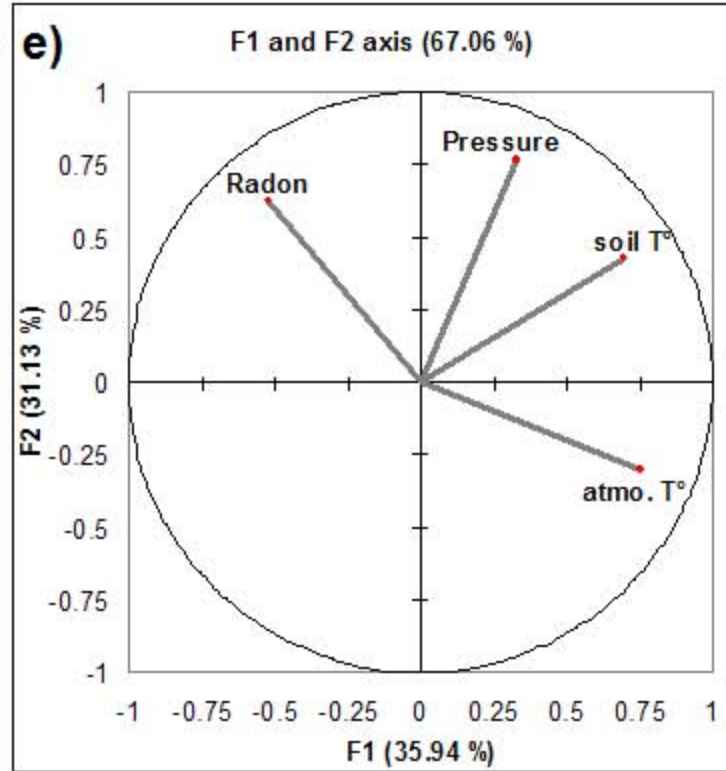
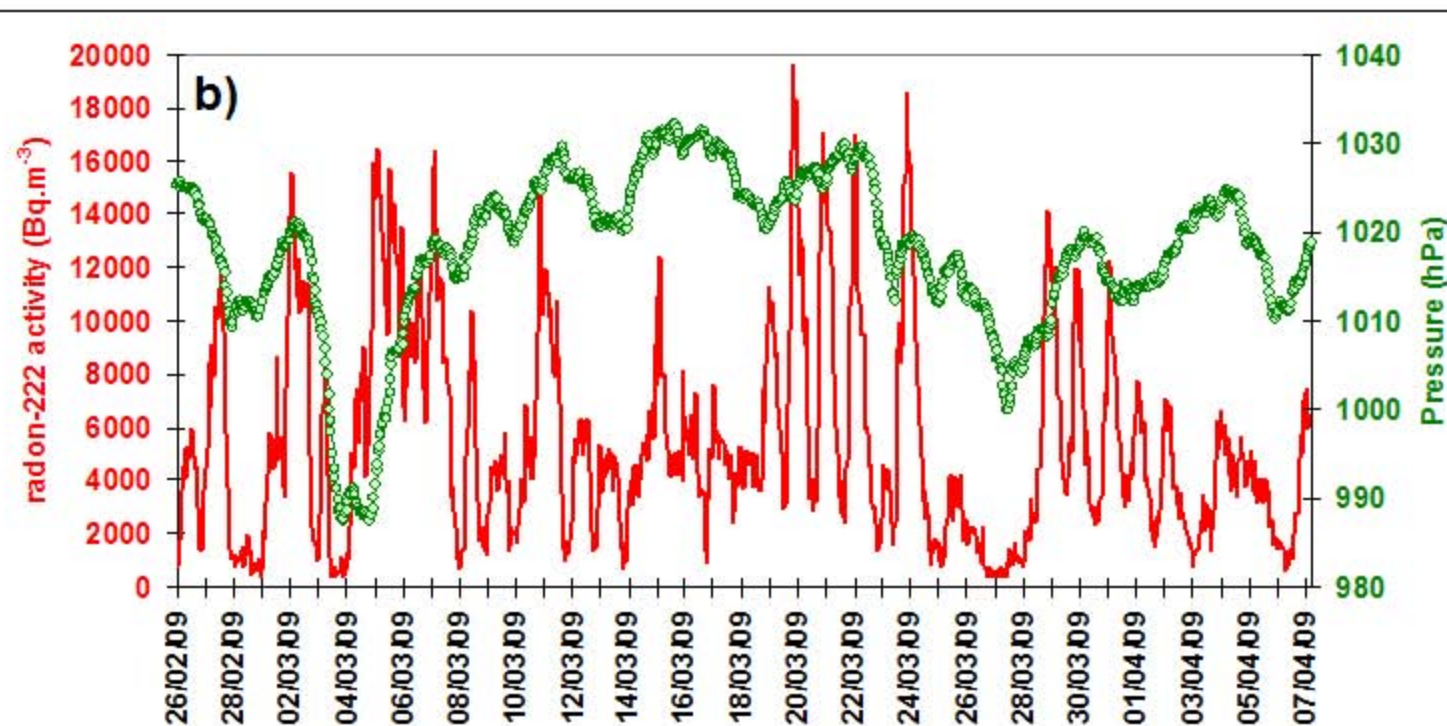
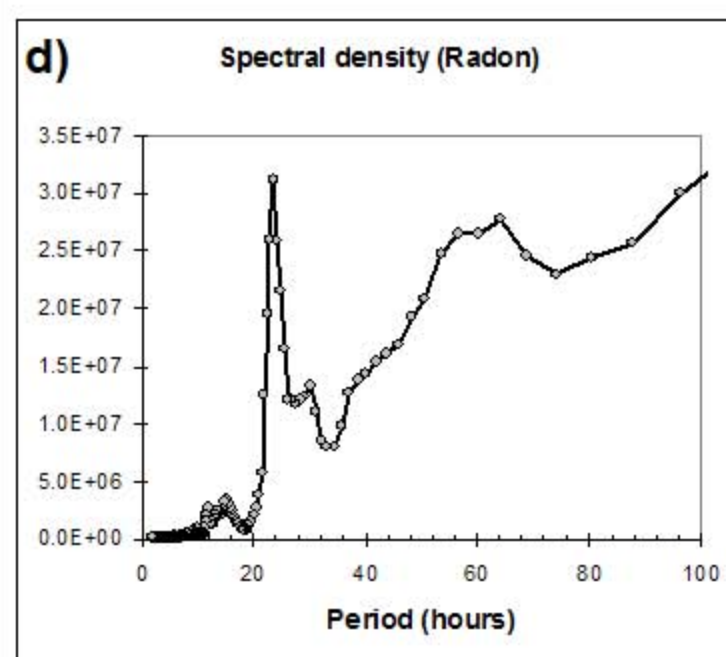
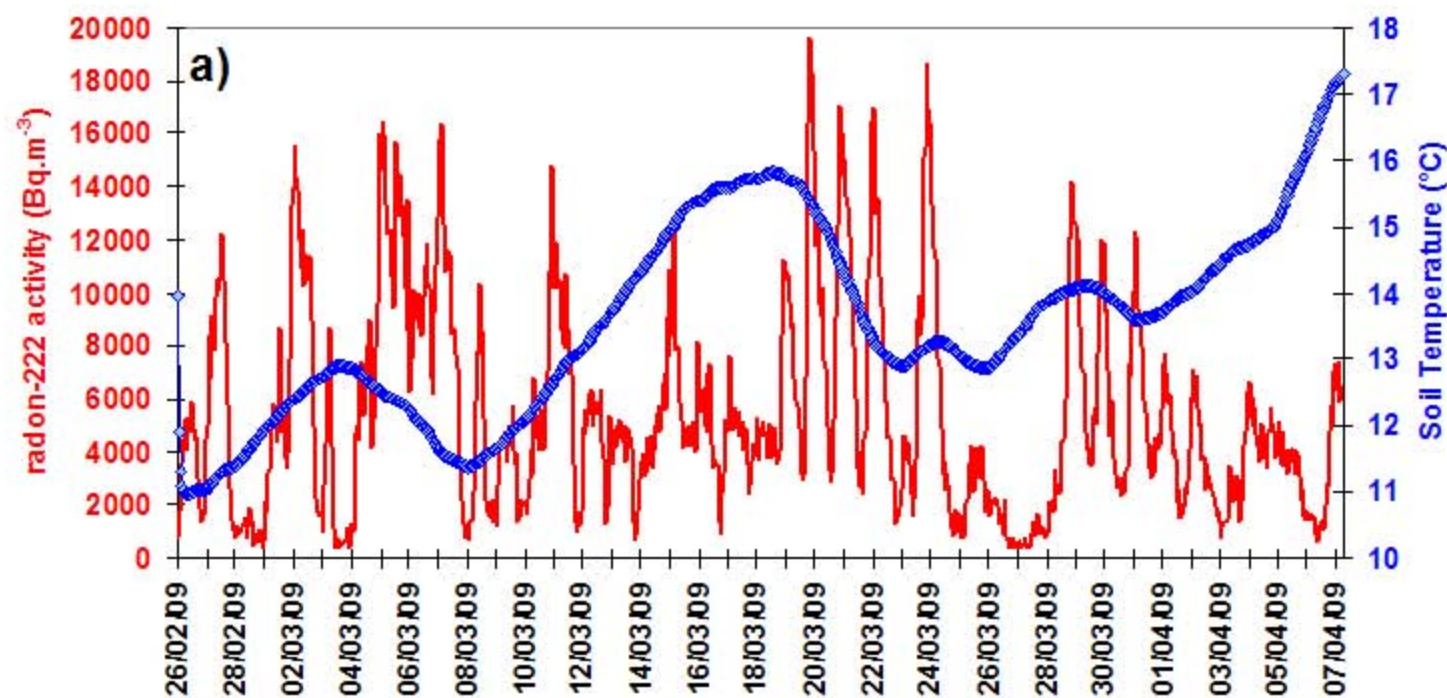
colorscale: sum of CO2 + radon + helium fitted in the 0 - 1 interval
greyscale: radon distribution in the same interval



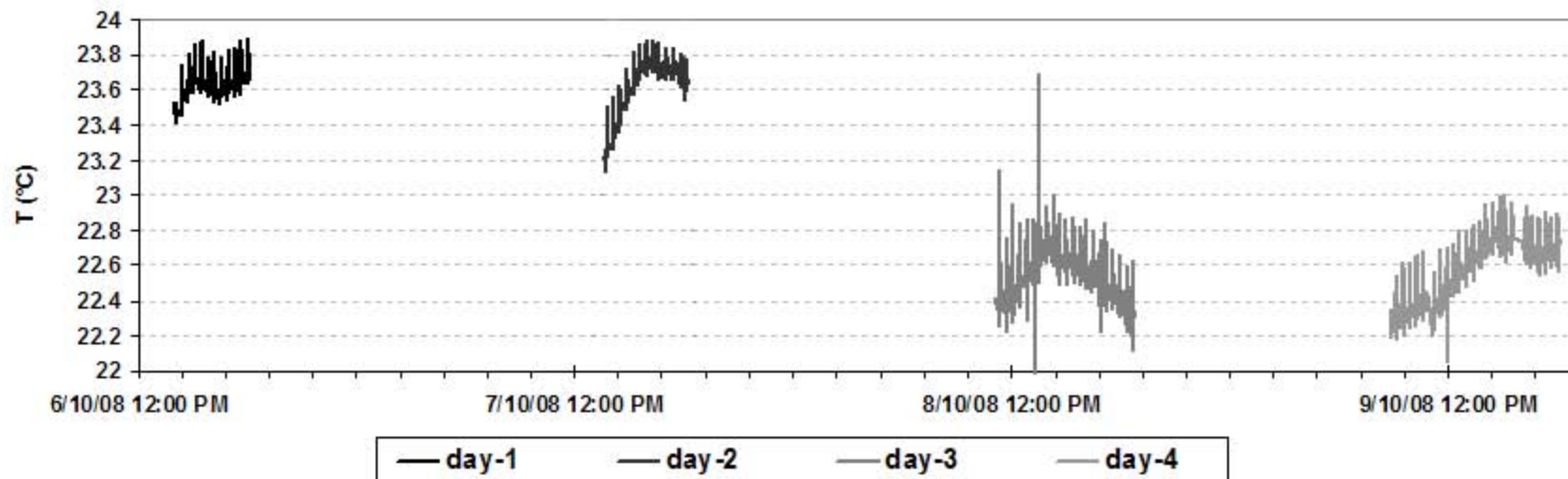
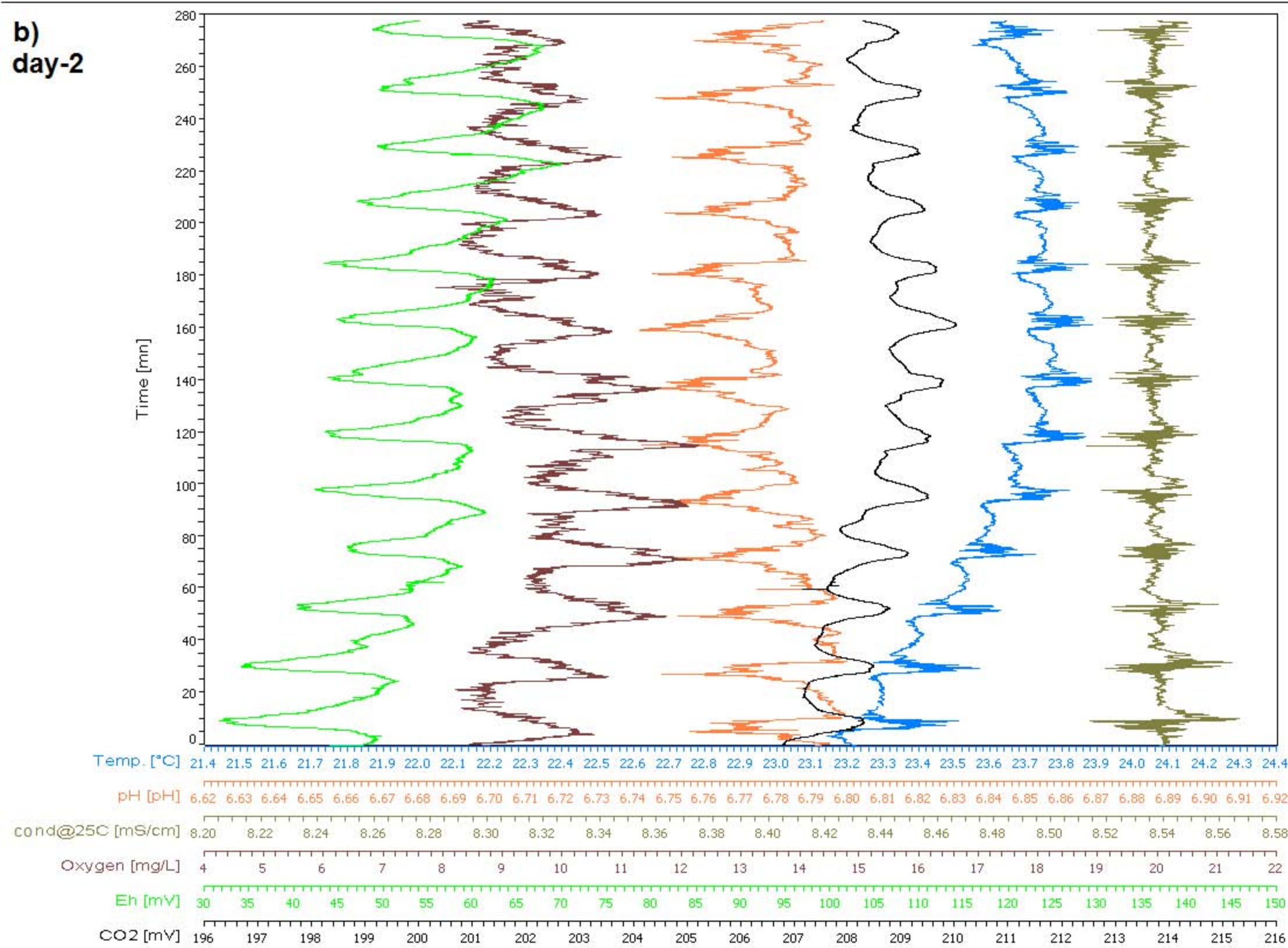
colorscale: sum of CO2 + radon + helium fitted in the 0 - 1 interval
greyscale: helium distribution in the same interval







a)

b)
day-2

| | CO ₂ (%) | CO ₂ (%) | CO ₂ (%) | ²²² Rn (Bq.m ⁻³) | ²²² Rn (Bq.m ⁻³) | ²²² Rn (Bq.m ⁻³) | ⁴ He (ppm) | ⁴ He (ppm) | ⁴ He (ppm) |
|----------------------------|---------------------|---------------------|---------------------|---|---|---|-----------------------|-----------------------|-----------------------|
| | all data | 1992 | 2006-2010 | all data | 1992 | 2006-2010 | all data | 1992 | 2006-2010 |
| nb. of measurements | 1058 | 504 | 554 | 913 | 503 | 410 | 917 | 431 | 486 |
| minimum | 0.05 | 0.08 | 0.05 | 144 | 148 | 144 | < 0.05 | 2.58 | < 0.05 |
| maximum | 100 | 91.40 | 100 | 2482000 | 1930000 | 2480000 | 17.68 | 17.68 | 9.83 |
| 1st quartile | 1.40 | 1.18 | 3.31 | 15800 | 17000 | 13800 | 5.19 | 5.24 | 5.04 |
| median value | 4.64 | 1.70 | 15.76 | 39800 | 37000 | 43200 | 5.24 | 5.30 | 5.22 |
| 3rd quartile | 24.08 | 5.10 | 47.00 | 80000 | 71000 | 97400 | 5.34 | 5.36 | 5.26 |
| mean value | 18.66 | 7.07 | 29.21 | 81700 | 57200 | 112000 | 5.30 | 5.42 | 5.19 |
| standard deviation | 27.23 | 13.48 | 31.90 | 189700 | 105000 | 250000 | 0.76 | 0.81 | 0.69 |
| coeff. of variation | 1.46 | 1.91 | 1.09 | 2.32 | 1.84 | 2.28 | 0.14 | 0.15 | 0.13 |

| Sample | T (°C) | pH | cond@25°C (μS.cm ⁻¹) | Eh (mV) | Ca (mg/l) | Mg (mg/l) | Na (mg/l) | K (mg/l) | Fe(III) (mg/l) | Mn (mg/l) | Sr (mg/l) | Li (mg/l) | HCO ₃ (mg/l) | Cl (mg/l) | SO ₄ (mg/l) | PO ₄ (mg/l) | NO ₃ (mg/l) | F (mg/l) | Br (mg/l) | SiO ₂ (mg/l) | δ ¹⁸ O (‰ VSMOW) | δD (‰ VSMOW) | <i>theoretical δD if belonging to LMWL</i> | ⁸⁷ Sr/ ⁸⁶ Sr | ¹³ C _{gas} open sys. |
|------------------------|-----------|------|-------------------------------------|------------|--------------|--------------|--------------|-------------|-------------------|--------------|--------------|--------------|----------------------------|--------------|---------------------------|---------------------------|---------------------------|-------------|--------------|----------------------------|--------------------------------|-----------------|--|------------------------------------|---|
| Chapelle 1 (2006) | 17.8 | 6.54 | 5210 | 338 | 237 | 121 | 776 | 81.9 | | | 3.74 | | 2288 | 717 | 146 | | 4.9 | | | | -8.3 | -57.4 | -53.3 | 0.712298 | -4.6 |
| Chapelle 1 (2007) | 16.6 | 6.63 | 4530 | 391 | 248 | 137 | 875 | 97.4 | | | 4.37 | 4.48 | 2465 | 806 | 155 | | 2.8 | 0.7 | 1.8 | | | | | | -5.1 |
| Chapelle 2 (2006) | 18 | 6.21 | 3070 | 336 | 196 | 117 | 304 | 34.5 | | | 2.5 | | 1276 | 298 | 192 | | 6.3 | | | | -7.5 | -53.7 | -46.9 | 0.712818 | -2.8 |
| Chapelle 2 (2007) | 16.6 | 6.33 | 3130 | 444 | 188 | 127 | 360 | 39.1 | | | 2.38 | 1.66 | 1483 | 340 | 202 | | 4.4 | 0.9 | 0.7 | | | | | | -3.4 |
| Chapelle 3 (2006) | 17.5 | 6.38 | 2730 | 340 | 178 | 104 | 266 | 34.6 | | 0.02 | 2.16 | | 1410 | 230 | 198 | | 8.3 | | | | -7.7 | -54 | -48.5 | 0.712035 | -3.7 |
| Chapelle 3 (2007) | 15.9 | 6.51 | 2410 | 420 | 184 | 126 | 301 | 40.7 | | | 2.30 | 1.52 | 1332 | 315 | 209 | | 4.6 | 1.0 | 0.6 | | | | | | -4.5 |
| Tennis (2006) | 29.2 | 6.48 | 7970 | 91 | 306 | 131 | 1493 | 163 | | 0.10 | 6.37 | | 3554 | 1495 | 101 | | | | | | -9.6 | -63.2 | -63.7 | 0.713388 | -3.9 |
| Tennis (2007) | 29 | 6.46 | 7970 | 140 | 295 | 135 | 1486 | 167 | | | 6.66 | 8.03 | 3515 | 1348 | 129 | | | 0.5 | 3.7 | | | | | | -3.9 |
| Tennis (2008) | 28.5 | 6.58 | 8440 | 138 | 301 | 133 | 1461 | 163 | 2.75 | | | | 3527 | 1370 | 111 | 0.4 | | 1.1 | | 107 | -9.5 | -62.8 | -62.9 | | -4.4 |
| Geyser Brissac (2006) | 24.6 | 6.65 | 8180 | 186 | 307 | 133 | 1497 | 163 | | 0.10 | 6.33 | | 4135 | 1429 | 100 | | | | | | -9.6 | -63 | | 0.713387 | -4.9 |
| Geyser Brissac (2007) | 23.5 | 6.62 | 7990 | 180 | 297 | 136 | 1485 | 167 | | | 6.88 | 7.99 | 3534 | 1355 | 126 | | | 0.4 | 3.7 | | | | | | -4.8 |
| Geyser Brissac (2008) | 23 | 6.57 | 8310 | 158 | 299 | 132 | 1447 | 162 | 2.80 | | | | 3562 | 1360 | 111 | 0.5 | | 1.1 | | 106 | -9.5 | -62.7 | -62.9 | | -4.6 |
| Petit Saladis (2007) | 21.6 | 6.58 | 8190 | 245 | 295 | 136 | 1498 | 168 | | | 6.29 | 8.13 | 3554 | 1344 | 125 | | | 0.5 | 3.5 | | | | | | -4.7 |
| Grand Saladis (2007) | 16.1 | 7.24 | 7920 | 386 | 125 | 139 | 1579 | 180 | | | 2.60 | 8.52 | 3124 | 1414 | 108 | | 11.0 | 0.4 | 3.9 | | | | | | -7.6 |
| old plant sp. (2008) | 29.3 | 6.7 | 8270 | 140 | 302 | 133 | 1457 | 164 | 2.41 | | | | 3147 | 1390 | 110 | 0.4 | | 0.8 | | 105 | -9.5 | -63 | -62.9 | | -4.9 |
| Valois sp. (2008) | 25.3 | 6.45 | 7840 | 105 | 298 | 129 | 1461 | 163 | 2.80 | | | | 3536 | 1370 | 109 | 0.4 | | 1.2 | | 106 | -9.5 | -62.9 | -62.9 | | -3.9 |
| terrace sp. (2008) | 18.6 | 6.45 | 8410 | 197 | 296 | 131 | 1459 | 163 | 2.44 | | | | 3566 | 1360 | 111 | 0.3 | | 1.2 | | 102 | -9.6 | -62.8 | -63.7 | | -4.1 |
| rainwater (08/10/2008) | 12.4 | 8.45 | 65 | 273 | 4.2 | 0.9 | 8.3 | 1.2 | 0.03 | | | | 24 | 6 | 2 | | 1.7 | | | 0.7 | -8.8 | -64.7 | -57.3 | | -9.2 |

| radon-222 (Bq.m ⁻³) DATA greater than 10 Bq.m ⁻³ and lesser than 10 ⁶ Bq.m ⁻³ | POINT 2 | POINT 4 | | | |
|--|---------------------|-------------------------------|-------------------------|---------------------|---------------------|
| | 06/10/08 → 28/01/09 | 06/10/08 → 28/01/09 | 26/02/09 → 01/09/09 | 11/09/09 → 16/03/10 | 06/10/08 → 16/03/10 |
| nb of meas. (hours) | 2728 | 2729 | 3869 | 740 | 7338 |
| hours of deployment | 2735 | 2735 | 4471 | 4459 | 11665 |
| Min. value | 60 | 30 | 50 | 1030 | 30 |
| Max. value | 2.69E+05 | 2.14E+05 | 9.09E+05 | 9.80E+05 | 9.80E+05 |
| 1st Quartile | 5820 | 20900 | 2410 | 5890 | 9640 |
| Median value | 28500 | 51700 | 4810 | 7500 | 16800 |
| 3rd Quartile | 102000 | 71500 | 13600 | 10700 | 12500 |
| Mean value | 56500 | 65300 | 28700 | 26300 | 31300 |
| std. dev. | 66400 | 57600 | 73600 | 93200 | 66100 |
| PEAK values: nb of meas. | 3 | 4 | 1 | | |
| PEAK values: Max. value | 8.57E+07 | 7.06E+06 | 1.24E+06 | | |
| Cycle analysis | no cycle | 7 - 10 - 22 hours 5.5 days | 15 - 25 - 39 - 74 hours | 24 - 58 hours | |

| DESCRIPTIVE | day 1 (7400 data) | | | | | day 2 (8300 data) | | | | | day 3 (13800 data) | | | | | day 4 (15800 data) | | | | |
|--------------------|-------------------|------|----------------|------|------|-------------------|------|----------------|------|------|--------------------|------|----------------|------|--------|--------------------|------|----------------|------|-------|
| STATISTICS | T° | EC | O ₂ | pH | Eh | T° | EC | O ₂ | pH | Eh | T° | EC | O ₂ | pH | Eh | T° | EC | O ₂ | pH | Eh |
| minimum | 21.15 | 8505 | 7.7 | 6.75 | 1.1 | 23.14 | 8512 | 7.9 | 6.74 | 31.6 | 21.98 | 7621 | 5.3 | 6.40 | -162.1 | 22.05 | 8477 | 5.9 | 6.43 | -61.4 |
| maximum | 23.89 | 9184 | 10.8 | 6.80 | 29.7 | 23.88 | 8567 | 12.3 | 6.80 | 70.1 | 23.66 | 8264 | 18.0 | 7.28 | 206.2 | 23.00 | 8639 | 14.5 | 7.81 | 128.9 |
| mean value | 23.62 | 8532 | 9.2 | 6.78 | 20.5 | 23.62 | 8537 | 9.7 | 6.78 | 54.2 | 22.54 | 8061 | 9.9 | 6.83 | 69.2 | 22.57 | 8535 | 9.2 | 6.84 | 57.7 |
| standard deviation | 0.16 | 37 | 0.5 | 0.01 | 7.1 | 0.16 | 4 | 0.9 | 0.01 | 7.4 | 0.13 | 72 | 1.1 | 0.03 | 12.4 | 0.17 | 7 | 0.9 | 0.02 | 15.0 |