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2012 EMILIA EARTHQUAKES

Soil-gas survey of liquefaction and collapsed caves during the Emilia seismic sequence

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1. Introduction

The epicentral area of the Emilia seismic sequence is located in the Emilia-Romagna Region (northern Italy), 45 km from the city of Modena (Figure 1). This area is sited within thrust-related folds of the Ferrara Arc, which represent the most external part of the northern Apennines. This sector is considered as having been active during late Pliocene to early Pleistocene times [Scrocca et al. 2007] and encompasses also the Mirandola and Ferrara seismogenic sources [e.g., Burrato et al. 2003, Boccaletti et al. 2004, Basili et al. 2008].

The main sedimentary infilling of the Po Plain is represented by Pliocene–Pleistocene alluvial deposits (alternating fluvial sands and clays) that overlie a foredeep clastic sequence, with a total average thickness of 2 km to 4 km [e.g., Carminati et al. 2010].

Soon after the mainshock, several liquefaction phenomena coupled to ground fractures were observed in the epicentral area (e.g., San Carlo, Ferrara). Soil liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction generally occurs in saturated unconsolidated sediments (e.g., sand, mud, and artificial fill) that lose their shear strength [Hazen 1920]. As a consequence, liquefied soil cannot support differential stress, thus causing ground failure and damage to the built environment.

Several soil measurements of gas fluxes (CO_2 and CH_4) and concentrations were performed on liquefactions and ground fractures located in the Finale Emilia (Modena) area (Via Fruttarola and Santa Bianca) and the Ferrara area (Renazzo and San Carlo) (Figures 1, 2) to determine whether these diffuse phenomena can be correlated with deep fluid migration through preferential leakage pathways linked to the earthquake.

To determine the possible leakage induced by the seismic stress during the Emilia sequence, collapsed caves in the epicentral area were also sampled. These collapse phenomena are linked to gas escape, and have been known since the 1970's in some tectonically active areas of the southern Po Plain [Bonori et al. 2000]. Individual phenomena occur as localized depressions of the soil in the shape of the cavity, or an 'inverted funnel', or as wide slits that are broad and up to few meters deep (Figure 3). Collapsed caves are considered as superficial events that are likely to have been triggered by compaction of organic-matter-rich soils (e.g., peat) [Castellarin et al. 2006]. Complex microbial (bacteria) reactions transform the peat, resulting in volume loss and a consequent slight ground subsidence. Collapsed caves generally develop in orchards, mainly due to the loss of cohesion of the soil, its extreme imbibition, or the transit of agricultural vehicles.

Collapsed caves reported in the literature and/or local press [e.g., Febo 1999, Martelli 2002] in the epicentral area were previously investigated by our research group in 2008, with several soil measurements of CO_2 and CH_4 fluxes. Immediately after the May 20, 2012, mainshock and during the Emilia seismic sequence, the collapsed caves were sampled again to determine any variations in these CO_2 and CH_4 fluxes. In this survey, newly formed collapsed caves were also found and measured (especially in the northern part of investigated area).

2. Methods

CO_2 and CH_4 fluxes were measured by the speed-portable 'closed dynamic' accumulation chamber 'time zero' method [e.g., Cardellini et al. 2003] using a West System instrument equipped with CO_2 and CH_4 infrared detectors. The recorded concentrations measured over time, combined with other parameters such as volume and surface of the accumulation chamber, allowed the calculation of the exhalation flux from the soil [e.g., Hutchinson et al. 2000].

Soil-gas samples were collected using a steel probe that was driven into the ground to a depth of 0.6 m to 0.8 m, to avoid the major influence of meteorological variables [e.g., Hinkle 1994]. The soil-gas concentrations (CO_2, CH_4, He)

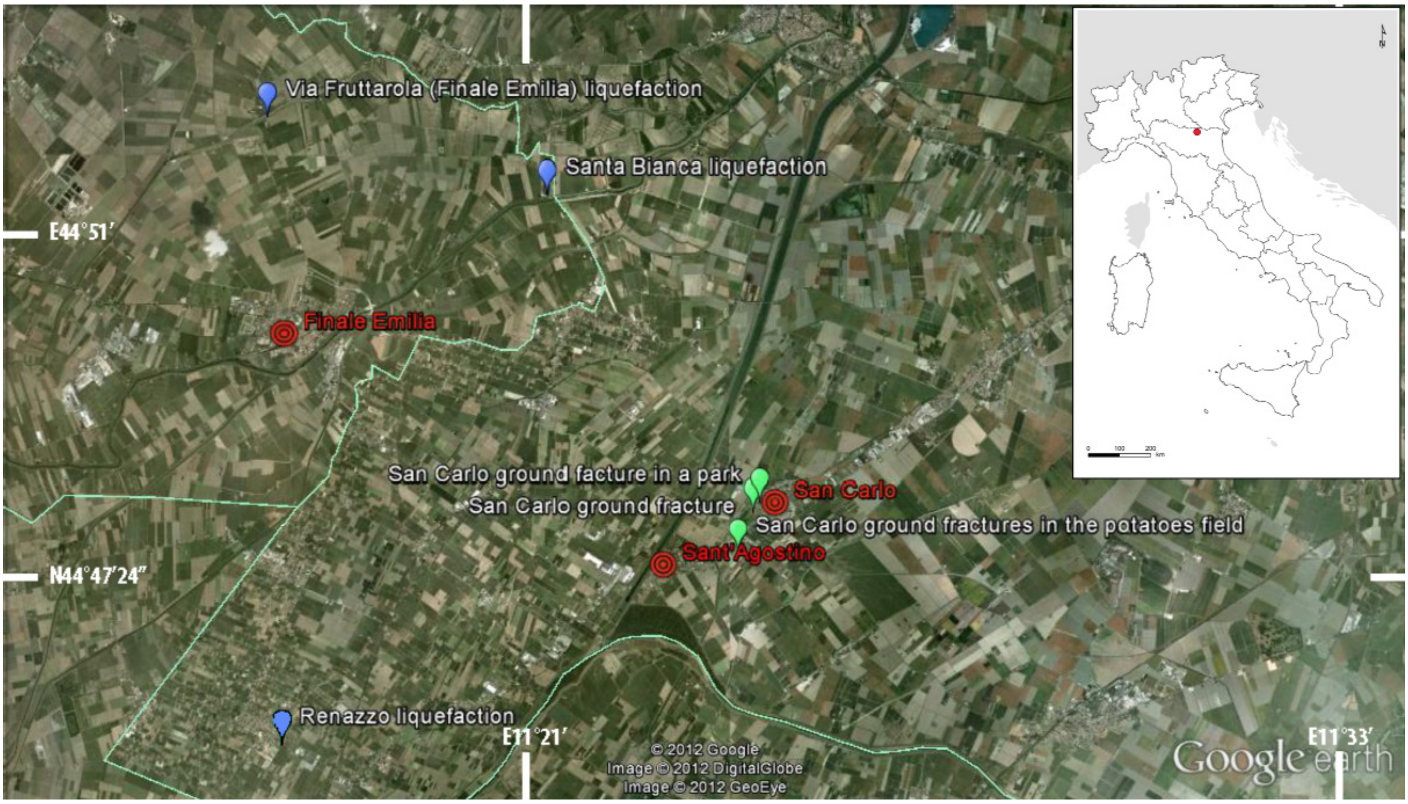

Figure 1. Location map of the sampled liquefactions (blue) and ground fractures (green). Geographic coordinates WGS 84.

were analyzed in the laboratory using a MicroGC Varian 4009 CP, equipped with thermal conductivity detectors. Radon was analyzed immediately in the field, due to its half-life (3.8 days), using a RAD7 Durridge alpha spectrometry instrument, at a depth of 70 cm.

3. Results and discussion

3.1. Soil liquefaction and ground fractures

In the epicentral area (e.g., San Carlo, Ferrara) soil liquefaction and sand blows were coupled to ground fractures that also showed noticeable horizontal and vertical displacements, and were observed at sites with young alluvium. A mixture of gray-colored fine particle materials and water bubbled up into streets, parks and fields, and even through the concrete floors of buildings.

The soil liquefaction and ground fractures followed two preferential alignments (N60W and N140W) which can be related both to the main directions of the buried fold axes and to paleo-river bed structures in the area.

Measurements of fluxes (ϕCO_2 and ϕCH_4) and soil-gas concentrations (CO_2, CH_4, He, ^{222}Rn), as well as the main statistical parameters, are reported in Tables 1 and 2, respectively. These data were compared both to previous soil-gas measurements performed by the authors in 2006 in the area between Rivara and Massa Finalese (Modena) (unpublished data), and to two case studies in central Italy [Annunziatellis et al. 2008] and in foredeep basins [Ciotoli et al. 2007].

The CO_2 concentrations after the May 20, 2012, earthquake decreased with respect to the Rivara 2006 ones, aligning with those reported in Annunziatellis et al. [2008].

The He and ^{222}Rn contents did not show any remarkable variations when compared to the 2006 data, and they were lower than the concentrations measured in other Italian sites [Ciotoli et al. 2007, Annunziatellis et al. 2008]. Negative He values (i.e., values lower than the atmospheric reference) constituted the bulk of our dataset. In spite of what was claimed by Reimer [1990] and Duddridge et al. [1991], negative anomalies did not appear to be linked to tectonic or morphological features. Several studies have reported He values below the air concentrations [e.g., Reimer 1980, Lombardi and Voltattorni 2010], which suggests a shallow origin of this gas. Therefore, negative He values can result from a disequilibrium between the soil gases and the atmosphere, as a consequence of differential mobility of the gaseous species involved [Ciotoli et al. 1999].

Radon is generally used as a tracer to provide a qualitative idea of gas transfer (velocity and flux), and its characteristics allow it to be used as a tool for mapping active faults in seismotectonic environments. In our samples, radon showed low values and was very similar to the Rivara data, indicating an absence of any deep fluid leakage.

CH_4 showed mean and median values clearly higher than the Rivara 2006 data (224.61, 6.01 and 14.65 ppmv/v, respectively). The highest CH_4 concentrations were measured for the ground fractures at San Carlo (890 ppm), and for the soil liquefaction in Via Fruttarola (434 ppm) and Renazzo (338 ppm).

San Carlo showed the highest CH_4 values, which were

Figure 2. A, B. Liquefactions with N60W direction observed in Via della Fruttarola–Finale Emilia (Modena) corn field and Santa Bianca (Modena), respectively. C. Sand blowout from a well in San Carlo (Ferrara). D, E. Ground fractures with a N140W direction observed in the San Carlo area (Ferrara) soon after May 20, 2012 (see Figure 1 for location map). Geographic coordinates UTM WGS 84 32N.

Sampling site – Emilia 2012	CO_2 (%v/v)	CH_4 (ppmv/v)	He (ppmv/v)	Rn (Bq/m^3)	ϕCO_2 (g/m^{2}day)	ϕCH_4 (g/m^{2}day)
Renazzo Liquefaction 01	6.03	337.80	3.69	-	30.669	4.569
Renazzo Liquefaction 02	1.57	68.73	3.69	-	18.257	2.541
Via Fruttarola Liquefaction 01	4.17	424.16	4.23	18400	2.856	1.719
Via Fruttarola Liquefaction 02	-	-	-	-	21.515	1.637
Via Fruttarola Liquefaction 03	-	-	-	-	15.733	1.259
Santa Bianca Liquefaction 01	-	-	-	-	6.439	3.389
Santa Bianca Liquefaction 02	-	-	-	-	10.760	0.00
San Carlo ground fracture in a park 01	0.73	38.60	4.43	1910	6.948	1.273
San Carlo ground fracture in a park 02	0.37	4.03	5.28	1700	8.017	2.105
San Carlo ground fracture 01	1.01	890.38	4.44	2520	4.599	3.457
San Carlo ground fracture 02	0.66	8.47	5.51	2120	2.301	0.00
San Carlo ground fracture 03					14.112	0.00
San Carlo ground fracture in the potato field 01	0.17	24.71	4.35	1920	77.283	1.782

Table 1. Measurements of fluxes and soil-gas concentrations for liquefactions and ground fractures in the Finale Emilia (Modena) area (Via Fruttarola and Santa Bianca), and in the Ferrara area (Renazzo and San Carlo), during 2012 earthquake sequence.

Data	N.	Mean	Median	Minimum	Maximum	Std. Dev.
Emilia 2012						
CO_2 (%v/v)	8	1.839	0.87	0.17	6.03	2.11
CH_4 (ppmv/v)	8	224.61	53.66	4.03	890.38	313.99
He (ppmv/v)	8	4.453	4.39	3.69	5.51	0.657
Rn (Bq/m^3)	6	4762	2020	1700	18400	6687
ϕCO_2 (g/m^2day)	13	16.88	10.76	2.301	77.283	19.90
ϕCH_4 (g/m^2day)	13	1.82	1.719	0.00	4.569	1.411
Rivara 2006						
CO_2 (%v/v)	24	2.31	1.59	0.11	7.21	2.06
CH_4 (ppmv/v)	24	6.01	0.15	0.00	134.62	27.40
He (ppmv/v)	24	4.99	4.98	4.69	5.44	0.17
Rn (Bq/m^3)	24	4854	2790	0	16400	5288
ϕCO_2 (g/m^2day)	231	21.27	13.76	0.43	211	26.19
ϕCH_4 (g/m^2day)	231	0.67	0.02	0.00	30.27	3.02
Italian data						
CO_2* (%v/v)	16301	1.93	0.83	0.03	100	6.09
CH_4*(ppmv/v)	11945	14.65	1.83	0.01	19396.14	263.10
He* (ppmv/v)	38060	5.48	5.31	1.20	315.22	2.95
Rn# (Bq/m^3)	2359	19100	12900	370	241200	22900

Table 2. Flux and soil-gas statistics for liquefactions and ground fractures in the epicentral area, compared both to previous soil-gas statistics obtained by the authors in 2006 in the area between Rivara and Massa Finalese (Modena) (unpublished data), and to the statistics obtained for two case studies in central Italy and in foredeep basins. *, soil-gas statistics taken from Annunziatellis et al. [2008]; #, radon data measured in foredeep basins from Ciotoli et al. [2007].

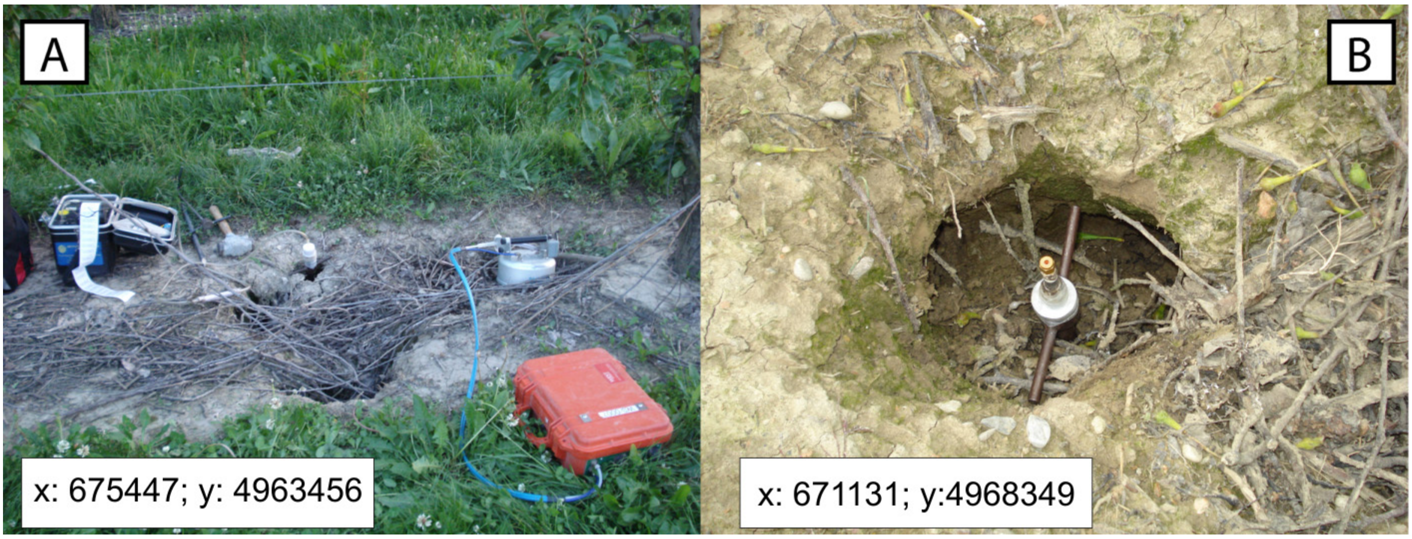

Figure 3. A, B. Soil-gas and flux measurements in collapsed caves. B. Detail of the steel probe driven into the collapsed caves to collect soil-gas samples. Geographic coordinates UTM WGS 84 32N.

not correlated with other pathfinder elements (e.g., ^{222}Rn and He) [Lombardi and Voltattorni 2010]. This might suggest a local anomaly, which would be likely to be due to surficial layer compression during the earthquake.

For Via Fruttarola and Renazzo liquefactions, the high CH_4, CO_2 and ^{222}Rn concentrations were correlated with each other (Table 1). Moreover, high values of ϕCO_2 and ϕCH_4 were well correlated with CH_4 at Renazzo. These positive correlations among various gaseous species support the theory that CO_2 acts as a carrier for trace gases like radon [Durrance and Gregory 1990, Hermansson et al. 1991, Etiope and Lombardi 1995, Quattrocchi et al. 1999, Beaubien et al. 2003, Ciotoli et al. 2005, Lombardi and Voltattorni 2010].

The $\delta^{13}C$ analyses were carried out only in the San Carlo sample (over the minimum of detection for the analyses: 450 ppm), which indicated a prevalent biogenic origin ($\delta^{13}C = -67.25‰$ vs. Pee Dee Belemnite [PDB] standard; $\delta D = -164.77‰$ vs. Standard Mean Ocean Water [SMOW]

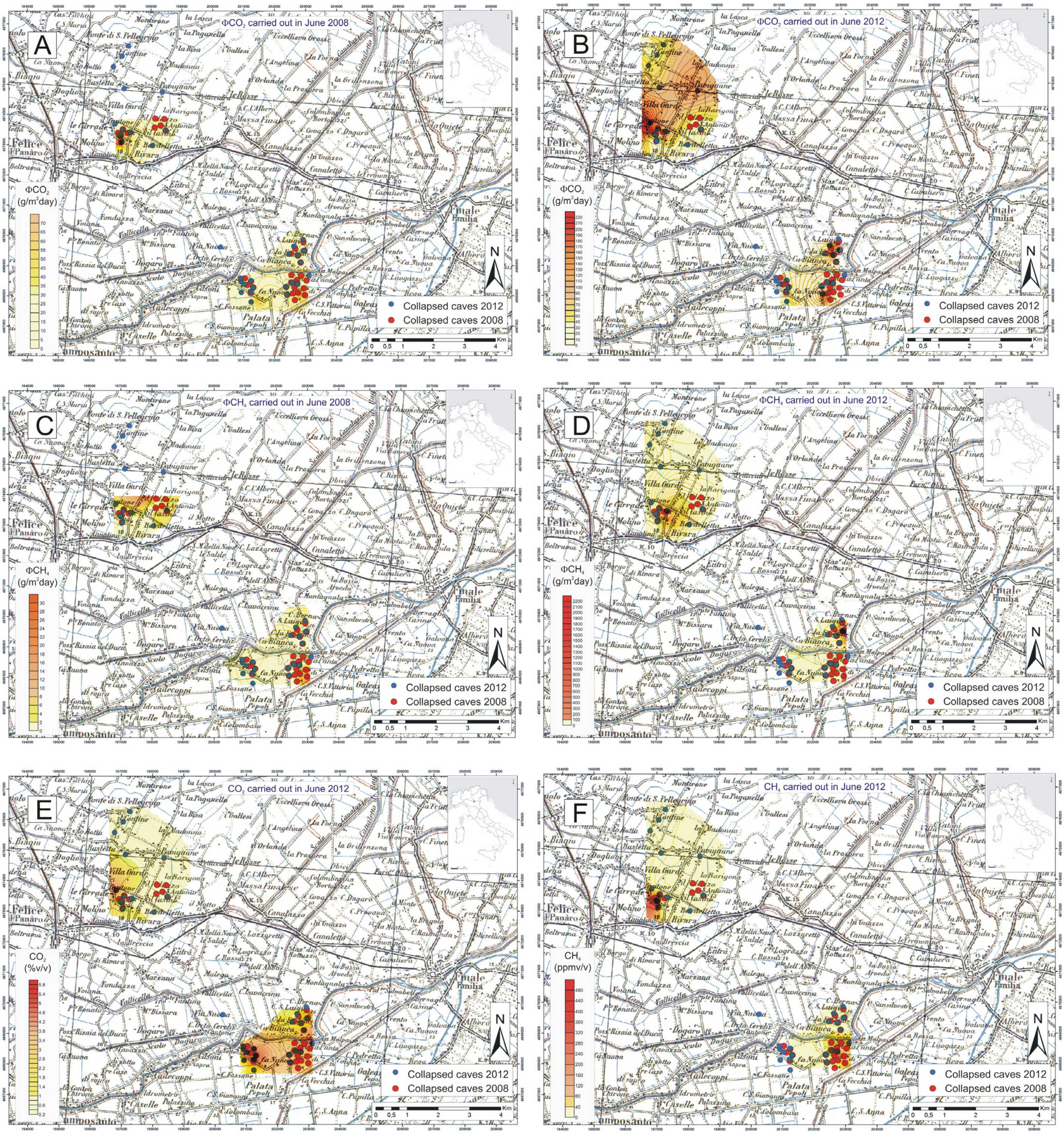

Figure 4. Collapsed cave contour maps in the Finale Emilia, Camposanto and Ponte San Pellegrino areas (Modena). A, B. ϕCO_2 measured in 2008 and 2012, respectively. C, D. ϕCH_4 measured in 2008 and 2012, respectively. E. CO_2 concentrations measured in 2012. F. CH_4 concentrations measured in 2012. Green dots, 2008 sampling points; red dots, 2012 sampling points. The areal distribution has different extents due to different numbers of sampling points in 2008 and 2012.

standard). The concentrations of lighter hydrocarbons were below the detection limit (2 ppm) in all of the samples, which suggested a low-temperature origin of CH_4 (i.e., shallow and biogenic production).

The flux measurements of CO_2 and CH_4 after the mainshock showed the same trends as the soil-gas concentrations. The ϕCO_2 values fit those measured in 2006, while the ϕCH_4 mean and median were higher.

The CO_2 values were within the typical range of vegetative exhalation of the cultivated soil [Baldocchi and Meyers 1991], minimizing its provenance from depth. The increased methane fluxes can be linked to the methane concentrations, and can be explained by the presence of peat layers in the most shallow strata.

3.2. Collapsed caves

Collapsed caves (Figure 3) in the epicentral area were sampled both in June 2008 and June 2012, with stable and dry weather conditions. The 2012 measurements were repeated in the same spot as those of 2008 when this still existed after four years, as well as in newly discovered collapsed caves.

All of the data were processed with a statistical approach using normal probability plots, to define the statistical populations for each parameter, and to compute the contour maps using experimental kriging (Figure 4).

The spatial distributions of the soil-gas concentrations and fluxes measured in 2008 and 2012 are shown in Figure 4. A comparison between the CO_2 fluxes of 2008 (Figure 4A) with those measured in 2012 (Figure 4B) shows a remarkable increase over time. The areal distribution of anomalous values is very similar, but the maximum CO_2 flux changed from 70 g/m^2day to 220 g/m^2day. The ϕCH_4 showed the greater variations, going from 30 g/m^2day to 2200 g/m^2day. These higher ϕCH_4 values in both 2008 and 2012 were in the southern part of the investigated area, close to the Panaro River (Ca' Bianca locality).

In the northern part of the study area (Villa Gardè locality), the anomalous CO_2 and CH_4 concentrations, which were higher than the Italian averages [Annunziatellis et al. 2008], corresponded to the maximum values of ϕCO_2.

In the southern part, a positive correlation was highlighted between the anomalous CH_4 concentrations and the maximum values of ϕCO_2. The highest CO_2 and CH_4 concentrations were found south of the Panaro River, between the Ca' Nuova and Palata Pepoli localities. The presence of anomalous values in collapsed caves close to the Panaro River suggests a surficial origin of these phenomena, which is likely to be due to redox processes in the alluvial sediments. Conversely, in the northern part of the investigated area, isotopic analyses aimed at determining the origin of the CH_4 were performed on a sample (CH_4 = 522.6 ppmv/v), which highlighted a prevalent shallow biogenic origin ($\delta^{13}C = -59.64‰$ vs. PDB; $\delta D = -153.39‰$ vs. SMOW). Therefore, the anomalous gas concentrations in collapsed caves is likely to be correlated to decomposition of shallow peat and/or lignite layers, which produce CH_4 through microbial activity [Bonori et al. 2000].

4. Conclusions and remarks

Soon after the May 20, 2012, mainshock (M_L 5.9) and during the Emilia seismic sequence of May-June 2012, geochemical field investigations were carried out into the epicentral area.

The soil-gas concentrations and flux measurements for liquefactions, ground fractures, and collapsed caves suggest a superficial origin of these phenomena. This is probably related to the stratigraphy of the shallowest layers of the Po Plain. The results gathered support the hypothesis that soil liquefactions are surficial phenomena [Bhattacharya et al. 2011] that affect only the shallowest layers of the ground (tens or hundreds of meters).

The results of the collapsed caves measurements show that the CO_2 had remained essentially constant with respect to the 2008 survey, while the CH_4 appeared to be higher after the seismic sequence. However, no hints of deep degassing can be inferred for the study area after the earthquake, as suggested by isotopical analyses carried out both on soil liquefaction and in collapsed caves.

The results obtained in this study constitute the starting point for subsequent geochemical surveys, which will be carried out over time, both on liquefactions and collapsed caves, to assess the temporal variations and to better understand the geochemical processes related to the seismic sequence.

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