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

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Introduction

The epicentral area of the Emilia seismic sequence is located in the Emilia Romagna Region (Northern Italy), 45 km far away from the city of Modena (Figure 1). This area is sited within thrust-related folds of the Ferrara arc, representing the most external part of the Northern Apennines. This sector is considered being active during late Pliocene- 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 Po Plain is represented by Pliocene-Pleistocene alluvial deposits (alternating of fluvial sands and clays), overlying a foredeep clastic sequence, with a total average thickness of 2-4 km (e.g. Carminati et al., 2010).

Soon after the main shock 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 failures and also damage to the built environment.

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

In order to verify the possible leakage induced by the seismic stress during the Emilia sequence, also collapsed caves located in the epicentral area were sampled. These collapse phenomena, linked to gas escapes, were known since '70s 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, "inverted funnel" or wide slits, broad and deep up to few meters (Figure 3). Collapsed caves are considered as superficial events likely triggered by compaction of organic matter-rich soils (e.g. peat; Castellarin et al., 2006). Complex microbial (bacteria) reactions transforms the peat, involving volume loss and consequent slight ground subsidence. Collapsed caves are generally founded in orchards mainly due to the loss of cohesion of soil, its extreme imbibitions or transit of agricultural vehicles.

Collapsed caves reported by literature and/or local press (e.g. Febo, 1999; Martelli, 2002) in the epicentral area were previously investigated by our research group in 2008 throughout several soils measurements of CO_2 and CH_4 fluxes. Immediately after the 20th May 2012 main shock and during the Emilia seismic sequence, collapsed caves were sampled again to verify potential variations in CO_2 and CH_4 fluxes. In this survey, also newly formed collapsed caves were found (especially in the northern part of investigated area) and measured.

Methods

CO_2 and CH_4 fluxes were measured by 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, with other parameters such as volume and surface of the accumulation chamber, allow to calculate the exhalation flux from soil (e.g. Hutchinson et al., 2000).

Soil gas samples were collected using a steel probe driven into the ground to a depth of 0.6-0.8 m to avoid the major influence of meteorological variables (e.g. Hinkle, 1994). The soil-gas concentrations (CO_2, CH_4, He) have been analyzed in the laboratory using MicroGC Varian 4009 CP, equipped with TCD detectors. Radon was analyzed immediately in the field, due to its half-life (3.8 days), using a RAD7 Durridge® alpha spectrometry instrument at depths of 70 cm.

Results and discussions

Soil liquefaction and ground fractures

In the epicentral area (e.g. San Carlo, Ferrara) soil liquefactions and sand blows, coupled to ground fractures also with noticeable horizontal and vertical displacements, were observed in sites having young alluvium. A mixture of grey color fine particle materials and water bubbled up in streets, parks, fields and even through the concrete floors of buildings.

Soil liquefactions and ground fractures follow two preferential alignments (N60W and N140W) which could be related both to main directions of buried fold axes or paleo-river bed structures in that area.

Measurements of fluxes (ϕCO_2 and ϕCH_4) and soil gas concentrations (CO_2, CH_4, He, ^{222}Rn), as well as main statistic 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 foredeep basins (Ciotoli et al., 2007).

CO_2 concentration values after the 20th May earthquake decreases with respect to the Rivara 2006 ones, aligning with those reported in Annunziatellis et al. (2008).

He and ^{222}Rn contents don't show any remarkable variations if compared to 2006 data, resulting lower than concentrations measured in other Italian sites (Ciotoli et al., 2007; Annunziatellis et al., 2008). Negative helium values (i.e. values lower than the atmospheric reference) constitute the bulk of our dataset. In spite of what claimed by Reimer (1990) and Duddridge et al. (1991), negative anomalies do not seem to be linked to tectonic or morphological features. Several authors found He values below air concentrations (e.g. Reimer, 1980, Lombardi and Voltattorni 2010) suggesting a shallow origin of this gas. Therefore negative helium values can result from a disequilibrium between soil gases and the atmosphere, as a consequence of differential mobility of the involved gaseous species (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 shows low values and very similar to Rivara data, indicating an absence of a deep fluid leakage.

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

San Carlo shows the highest CH_4 value, uncorrelated with other pathfinder elements (e.g. ^{222}Rn and He; Lombardi and Voltattorni, 2010). This could suggest a local anomaly, likely due to surficial layers compression during the earthquake.

On Via Fruttarola and Renazzo liquefactions CH_4, CO_2 and ^{222}Rn high concentrations are correlated each other (Table 1). Moreover high values of ϕCO_2 and ϕCH_4 are well correlated with CH_4 at Renazzo. The positive correlation among various gaseous species, supports 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., 2003b; Ciotoli et al., 2005; Lombardi and Voltattorni, 2010).

$\delta^{13}C$ analysis were carried out only in the San Carlo sample (over the minimum of detection for the analyses: 450 ppm), pointing out a prevalent biogenic origin ($\delta^{13}C$ = -67.25 ‰ vs PDB; δD = -164.77 ‰ vs SMOW). Concentrations of lighter hydrocarbons are below the detection limit (2 ppm) in all samples, suggesting the low temperature (i.e. shallow and biogenic production) origin of CH_4.

Flux measurements of CO_2 and CH_4 after the main shock show the same trend than soil gas concentrations. ϕCO_2 values fit those measured in 2006, while ϕCH_4 mean and median are higher.

CO_2 values are within the typical range of vegetative exhalation of the cultivated soil (Baldocchi and Meyers, 1991), minimizing its provenience from depth. The increasing of methane fluxes can be linked to the methane concentration values, and be explained by the presence of peat layers in the most shallow strata.

Collapsed caves

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

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

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

In the northern part of studied area (Villa Gardè locality) the anomalous CO_2 and CH_4 concentration values, higher than Italian average values (Annunziatellis et al. 2008), correspond to the maximum values of ϕCO_2.

In the southern part, a positive correlation between anomalous CH_4 concentration values and the maximum values of ϕCO_2 is highlighted. The highest CO_2 and CH_4 concentration values are found south of the Panaro River, between 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, likely due to redox processes in the alluvial sediments. Conversely, in the northern part of the investigated area, an isotopic analyses aimed to determine the origin of methane was performed in a sample (CH_4 = 522.6 ppmv/v), highlighting a prevalent shallow biogenic origin ($\delta^{13}C$ = -59.64 ‰ vs PDB; δD = -153.39 ‰ vs SMOW). Therefore, anomalous gas concentrations in collapsed caves can be likely correlated to shallow peat and/or lignite layers decomposition producing CH_4 through microbial activity (Bonori et al., 2000).

Conclusion and remarks

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

Soil gas concentrations and flux measurements on liquefactions, ground fractures and collapsed caves suggest a superficial origin of these phenomena, likely related to stratigraphy of shallowest layers of Po Plain. Gathered results support the hypothesis that soil liquefactions are surficial phenomena (Bhattacharya et al., 2011) affecting only the shallowest layers of the ground (tens or hundreds of meters).

Results of collapsed caves measurements shows that CO_2 remain essentially unvaried with respect to 2008 survey. while CH_4 seems to be higher after the seismic sequence.

However, no hints of deep degassing can be inferred for the study area after the earthquake, like suggested by isotopical analyses executed both on soil liquefaction and in collapsed caves.

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

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References

Annunziatellis, A., S. E. Beaubien, S. Bigi, G. Ciotoli, M. Coltella, S. Lombardi (2008). Gas migration along fault systems and through the vadose zone in the Latera caldera (central Italy): Implications for CO_2 geological storage, Int. J. Greenh. Gas Con., 2, 353-372.

Baldocchi, D.D., T.P.Meyers (1991). Trace gas exchange above the floor of a deciduous forest, Evaporation and CO_2 flux. J.G.R. 96, 7271-7285.

Basili, R., G. Valensise, P. Vannoli, P. Burrato, U. Fracassi, S. Mariano, M. M. Tiberti, E. Boschi (2008). The Database of Individual Seismogenic Sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology, Tectonophysics, doi: 10.1016/j.tecto.2007.04.014.

Boccaletti, M., M. Bonini, G. Corti, P. Gasperini, L. Martelli, L. Piccardi, C. Tanini, and G. Vannucci (2004). Seismotectonic map of the Emilia- Romagna region, scale 1:250,000, Cons. Naz. delle Ric., Firenze, Italy.

Bhattacharya, S., M. Hyodo, K. Goda, T. Tazoh, C. A. Taylor (2011). Liquefaction of soil in the Tokyo Bay area from the 2011 Tohoku (Japan) earthquake, Soil Dynamics and Earthquake Engineering 31 (2011) 1618–1628.

Bonori O., M. Ciabatti, S. Cremonini, R. Di Giovanbattista, G. Martinelli, S. Maurizzi, G. Quadri, E. Rabbi, P. V. Righi, S. Tinti & E. Zantedeschi (2000). Geochemical and geophysical monitoring in tectonically active areas of Po valley (Northern Italy). Case histories linked to gas emission structures, Geogr. Fis. Dinam. Quat. 23, 3-20.

Burrato, P., F. Ciucci, and G. Valensise (2003). An inventory of river anomalies in the Po Plain, northern Italy: Evidence for active blind thrust faulting, Ann. Geophys., 46, 865–882.

Cardellini, C., G. Chiodini, F. Frondini, D. Granieri, J. Lewicki, L. Peruzzi (2003). Accumulation chambre measurements of methane fluxes: application to volcanic-geothermal areas and landfills. Appl. Geochem., 18, 45-54.

Carminati, E., D. Scrocca, and C. Doglioni (2010), Compaction-induced stress variations with depth in an active anticline: Northern Apennines, Italy, J. Geophys. Res., 115, B02401.

Castellarin, A., E. Rabbi, S. Cremonini, L. Martelli, F. Piattoni (2006). New insights into the underground hydrology of the eastern Po Plain (northern Italy), Boll. Geof. Teor. Appl. 47, 271-298.

Ciotoli, G., G. Etiope, M. Guerra, S. Lombardi (1999). The detection of concealed faults in the Ofanto Basing using the correlation between soil-gas fracture surveys. Tectonoph. 301, 321-332.

Ciotoli, G., S. Lombardi, S. Morandi, F. Zarlenga (2005). A multidisciplinary statistical approach to study the relationships between helium leakage and neo-tectonic activity in a gas province: The Vasto Basin, Abruzzo-Molise (central Italy). AAPG Bull., 88(3), 355–372.

Ciotoli, G., S. Lombardi, A. Annunziatellis (2007). Geostatistical analysis of soil gas data in a high seismic intermontane basin: Fucino Plain, central Italy, J. of Geoph. Res. 112, B05407.

Duddridge, G.A., P. Grainger, E. M. Durrance (1991). Fault detection using soil gas geochemistry. Q.J. Eng. Geol., 24, 427–435.

Etiope, G., S. Lombardi (1995). Evidence for radon transport by carrier gas through faulted clays in Italy. J. Radioanal. Nucl. Chem., 193(2), 291– 300.

Febo, C. (1999). Caratteri Idrogeologici e Idrochimici di Dettaglio delle Falde Acquifere Superficiali della Zona di Finale Emilia–MO. – Bachelor thesis,Tutor E. Rabbi.

Hazen, A. (1920). Transactions of the American Society of Civil Engineers 83: 1717–1745.

Hinkle, M. (1994). Environmental conditions affecting concentrations of He, CO_2, O_2 and N_2 in soil gases. Appl. Geochem., 9, 53– 63.

Hutchinson, G.L., G. P. Livingston, R. W. Healy, R. G. Striegl (2000). Chamber measurement of surface atmosphere trace gas exchange: numerical evaluation of dependence on soil, interfacial layer and source/sink properties, J.G.R. 105 (D7), 8865-8875.

Lombardi, S., N. Voltattorni (2010). Rn, He and CO_2 soil gas geochemistry for the study of active and inactive faults, Appl. Geoch. 25, 1206–1220.

Martelli, L. (2002). Indagine relativa ai fenomeni di scavernamento in atto nella Provincia di Bologna. Relazione Conclusiva all’Amministrazione Provinciale, Settore Ambiente, Servizio Assetto Idrogeologico.

McCarthy, J.H., G.M. Reimer (1986). Advances in Soil Gas Geochemical Exploration for Natural Resources: Some current Examples and Practices. J. Geoph. Res., 91, B12, 12,327-12,338.

Reimer, G.M. (1980). Use of soil-gas helium concentrations for earthquake prediction: Limitations imposed by diurnal variation. J. Geophys. Res., 85, 31 07-3114.

Reimer, G.M. (1990). Reconnaissance techniques for determining soil-gas radon concentrations: An example from Prince Georges County, Maryland, Geophys. Res. Lett., 17, 809–812.

Scrocca, D., E. Carminati, C. Doglioni, and D. Marcantoni (2007). Slab retreat and active shortening along the central-northern Apennines, in Thrust Belts and Foreland Basins: From Fold Kinematics to Hydrocarbon Systems, Frontiers in Earth Sciences, edited by O. Lacombe et al., pp. 471– 487, Springer, Berlin.

Table 1

Measurements of fluxes and soil gas concentrations on liquefactions and ground fracture in the Finale Emilia (Modena) area (Via Fruttarola and Santa Bianca) and Ferrara area (Renazzo and San Carlo) during 2012 earthquake sequence.

Sampling site – Emilia 2012	CO_2 (%v/v)	CH_4 (ppmv/v)	He (ppmv/v)	Rn (Bq/m^3)	ϕCO_2 (g/m^2day)	ϕCH_4 (g/m^2day)
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 2

Flux and soil gas statistics for liquefactions and ground fractures in the epicentral area, compared both to previous soil gas statistics performed by the authors in 2006 in the area between Rivara and Massa Finalese (Modena) (unpublished data) and statistics of two case studies in central Italy and foredeep basins.

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

*: Soil gas statistics are taken from Annunziatellis et al. (2008); #: radon data measured in foredeep basins from Ciotoli et al. (2007).

Figure Captions

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

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 N140W direction observed in San Carlo area (Ferrara) soon after 20th May (see location map in Figure 1). Geographic coordinates UTM WGS 84 32N.

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

Figure 4. Collapsed caves 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 concentration measured in 2012, F: CH_4 concentration measured in 2012. Green dot = 2008 sampling points; red dot= 2012 sampling points. Areal distribution has different extent due to a different numbers of sampling points in 2008 and 2012.

Figure 1

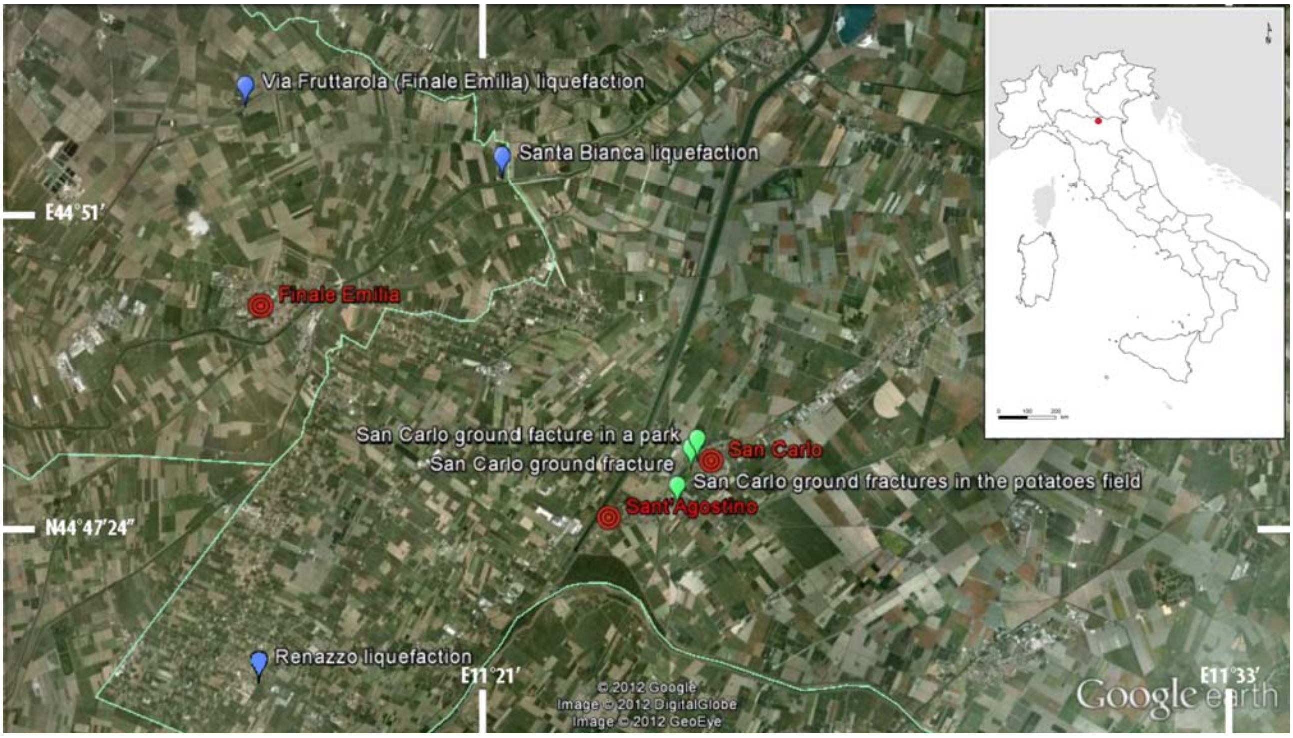
Via Fruttarola (Finale Emilia) liquefaction
Santa Bianca liquefaction
E44°51′
Finale Emilia
San Carlo ground facture in a park
San Carlo ground fracture
San Carlo
San Carlo ground fractures in the potatoes field
Sant'Agostino
N44°47′24″
Renazzo liquefaction
E11°21′
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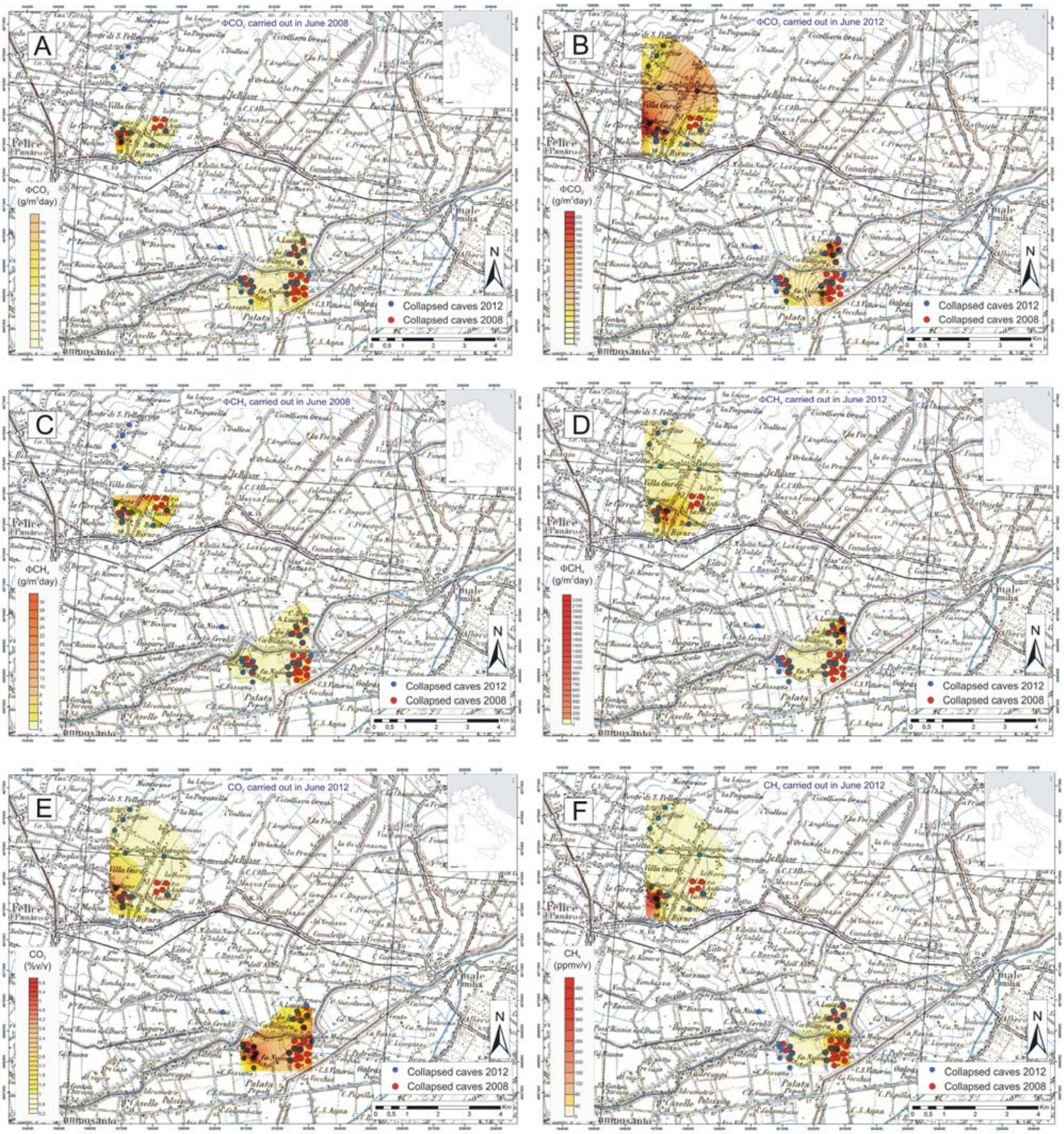
Image © 2012 GeoEye
Google earth
E11°33′

Figure 2

Figure 3

Figure 4



A
ΦCO_2 carried out in June 2008
ΦCO_2 (g/m²day)
B
ΦCO_2 carried out in June 2012
ΦCO_2 (g/m²day)
C
ΦCH_4 carried out in June 2008
ΦCH_4 (g/m²day)
D
ΦCH_4 carried out in June 2012
ΦCH_4 (g/m²day)
E
CO_2 carried out in June 2012
CO_2 (%v/v)
F
CH_4 carried out in June 2012
CH_4 (ppmv/v)
Collapsed caves 2012
Collapsed caves 2008
N
Km