

# very slightly anomalous leakage of CO<sub>2</sub>, CH<sub>4</sub> and radon along the main activated faults of the strong L'Aquila earthquake (Magnitude 6.3, Italy).

## Implications for risk assessment monitoring tools & public acceptance of CO<sub>2</sub> and CH<sub>4</sub> underground storage.

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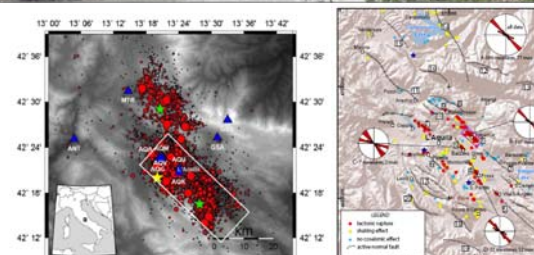
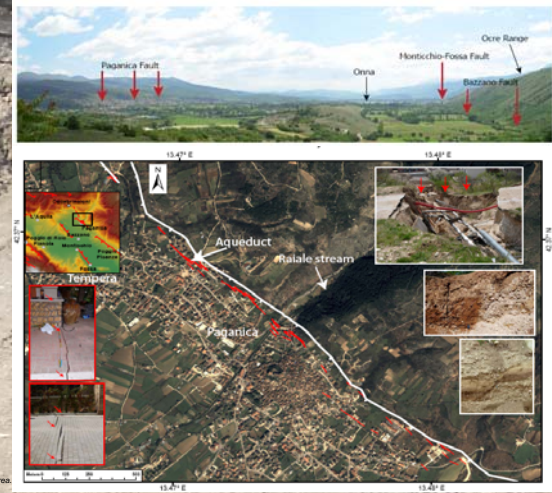
### Abstract

The 2009-2010 L'Aquila seismic sequence is still slightly occurring along the central Apenninic Belt (August 2010), spanning more than one year period. After the main-shock (Mw 6.3), occurred on April 6th at 1:32 (UTC), INGV geochemical group started to survey the seismically activated area. We sampled around 1000 soil gas points and flux measurements and around 80 groundwater points (springs and wells), to understand geometry and behaviour of the activated fault segments. In addition, we sampled groundwaters in Cotilia-Canetra area (20 km NW from the seismically activated area) where a deep natural CO<sub>2</sub> reservoir is present (ferromethamorphic CO<sub>2</sub> from carbonate diagenesis), to study leakage patterns at surface (CO<sub>2</sub>, CH<sub>4</sub>, Radon and other geogas as He, H<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>S, O<sub>2</sub>, etc.).

Results of this work highlighted that geochemical measurements on soils are very powerful to discriminate the activated seismogenic segments at surface, their jointing belt, as well as co-seismic depocenter of deformation. Our geochemical method demonstrated to be strategic, also in presence of earthquakes with magnitude around 6, and we wish to use these methods in CO<sub>2</sub> analogues/CO<sub>2</sub> reservoir studies abroad. Moreover, measured geochemical anomalies have not caused hazard for the human health, suggesting that these gases can be safely stored naturally/industrially (1-2 km deep) without dangerous leakage. Therefore, these results can be very useful also for the CO<sub>2</sub>-CH<sub>4</sub> geological storage public acceptance: not necessarily (rarely or never) deep geogas uplift abruptly from underground along activated faults.

### 1 - The 2009-2010 destructive seismic sequence in the Abruzzo Region

The 2009-2010 L'Aquila seismic sequence is occurring along the Apenninic Belt (Central Italy), for more than one year (Figure 2 a,b). The main-shock (Mw 6.3) occurred on April 6th at 1:32 (UTC) causing about 300 casualties and devastating the L'Aquila town and close villages. The hypocenter has been located at 42.35°N, 13.33°E at a depth of around 10 km. Before the main shock a long seismic sequence was occurred for four months (i.e. March, 30, 2009 with Mw 4.4, April, 5, with Mw 3.9 and Mw 3.5, a few hours before the main shock). Vp/Vs anomalous signals in the earthquake sequence suggest an important role of deep fluids pore-pressure evolution – possibly driven by CO<sub>2</sub> or brines – in the seismogenic process (Figure 3). The aftershocks (more than 35,000) were characterized by moderate-to-gradate events (between Mw 3 and 4.0), with Apatinic direction and normal fault focal mechanisms. Seismicity distribution, GPS and DiNSAR modeling suggest the presence of a 50SE normal fault of 15 km as the seismogenic source (Paganica Fault, responsible of the April 6 main-shock). Historical earthquakes affecting seismogenic segments close to the Paganica Fault are: i) 1349 – Mw 5.5 events in the North-Western area (Capitosto-Avazzano), and ii) 1784 (Mw 5.4) – 1785 (Mw 5.4) events in the East area (along the Middle Aeno Valley). Capitosto segment has been activated during the 2009-2010 seismic sequence (it is still active at the end of August 2010), while the Aeno Valley – S. Pio delle Camere fault segment is "silent" yet. On this dangerous quiescent fault segment (adjacent to the Paganica Fault), we focused our geochemical studies.



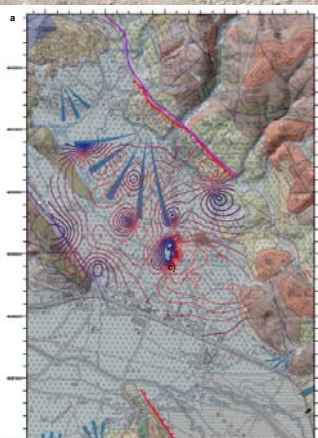
### 2 - Paganica and S. Pio delle Camere fault segments

The NW Paganica normal fault, SE dipping, is a complex fault system with antithetic NW-SE faults (Bazzano and Fossa Faults), on its hanging-wall, which bound the SW side of the Middle Aeno River Valley. The Paganica fault system forms a graben and control a depocenter, well highlighted by the cosimic DiNSAR image soon after the April 6 earthquake. The S. Pio delle Camere fault, in the Ocre-Fossa zone, was affected from Mw 5.3 aftershock in the April 7 and the subsequent N-S micro-seismic sequence (see Figure 2 a). In the Southern border of the Paganica Fault, begins the S. Pio delle Camere' fault Western tip (Barisciano-S. Pio Camere-Navello alignment); the temporal patterns of the 1461 and 2009 seismic sequences, located along the S. Pio delle Camere and the Paganica faults respectively, show significant similarities. Indeed, the two main-shocks were preceded by significant foreshocks which occurred 7-10 days before the main-shocks. Moreover, both main-shocks were shortly (1-2-hours) followed by a high energy aftershocks and the rest of the sequence evolved for about two months with several M4+.

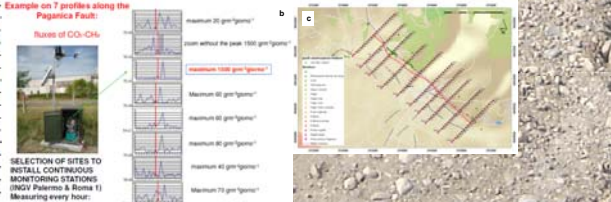


### 3 - Soil gas survey and groundwater sampling: strategies and methods

The aims of the geochemical measurements in aquifers and of soil gases (fluxes and concentrations) were: 1) to study the fluid processes acting close to the seismogenic segment and defining geochemically active faults; 2) to verify the CO<sub>2</sub> leakages in occurrence of strong seismic sequences, taking into account the deep-CO<sub>2</sub> reservoir at Cotilia town, only 20 km NW far away (Figure 3 c). This task is mainly addressed to a carbon mass balance and to exclude leakage and seepage dangerous for the health, with the final purpose to enhance the "public acceptance" of the newly exploited CO<sub>2</sub> Capture & Storage (CCS) technologies, in case of strong earthquakes close storage sites; 3) to evaluate variations of geochemistry, carbon balance, geochemistry and WRI Processes in the aquifers linked to the seismic sequence. We show the results by CO<sub>2</sub> and CH<sub>4</sub> fluxes measurements (around 1000 sites) and radon, CO<sub>2</sub>, CH<sub>4</sub>, He, H<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>S, O<sub>2</sub> and light hydrocarbons concentrations points (around 100 sites) in the main sector of the seismic sequence. An area of ~ 900 km<sup>2</sup> have been surveyed by INGV with more than 400 monitoring sites (fractures mainly) part of which are coupled by geochemical measurements in soils. Most of the surface effects have been mapped also as regards the presence/absence at surface of deep fluids uprising including false alarms (hot water, gas pools/fluxes, vapours, etc.). Soil gas samples were collected from shallow point sources, with a steel probe to a depth of 0.6m below the ground surface. After a preliminary cleaning of the system, soil-gas sample is extracted and stored in a pre-evacuated 50 mL steel cylinder for laboratory analysis (He/Ne, H<sub>2</sub>, O<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>S) by means of a Parkin-Elmer AutoSystem XL gas chromatograph. A RAD7 Durringer alpha spectrometer was used for Rn surveys. Gas flux measurements have been performed in situ using the accumulation chamber technique (Wesf System™).



**4 - Results**  
Table 1 shows the maximum and minimum values of fluxes and concentrations of geogas species, measured in soils along the two fault segments. Along the Paganica fault area, the maximum CH<sub>4</sub> flux is around 800 gm<sup>-2</sup>day<sup>-1</sup>; after 1 month the CH<sub>4</sub> fluxes decrease from 300 to 3 gm<sup>-2</sup>day<sup>-1</sup> and CO<sub>2</sub> fluxes anomalies disappeared. Soil gas surveys carried out at Cava Scabaton of Bazzano town - inside the Paganica fault Eastern tip depocenter - show gas-enriched along the soil fractures that disappeared after one month. This fact underlines that it is very important to perform soil gas surveying soon after the strong seismic event. In Figure 4 a are reported CO<sub>2</sub> flux measurement profiles perpendicular to the Paganica fault (one samples every 25 meters for two km). Around 230 measures were performed along the 10 profiles of Figure 4 b. Maximum anomaly of CO<sub>2</sub> flux (1500 gm<sup>2</sup>day) was few meters W from the Aqueduct. CH<sub>4</sub> flux measurements were carried out along one of the Paganica fault profile (T7), located close to the Eastern fault-tip. In the Cava Scabaton, near the Bazzano town (depocenter of the Paganica Fault), we found relatively high flux of CO<sub>2</sub>. The highest values was found along a transverse lineament bordering the Eastern tip of the Paganica Fault, where the fractures are oriented NW-SE, NE-SW and N-S direction in the San Gregorio and Fossa area (while the Paganica fault zone base simple NW-SE fractures mainly). In these areas the complexity of the fracture field and soil gas geochemical anomalies are strongly related with the seismicity patterns.

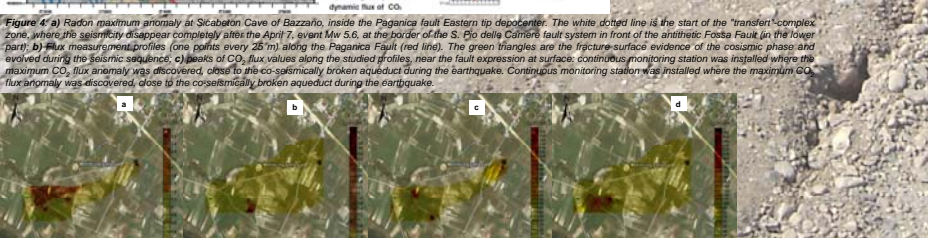


Paganica Fault	CO <sub>2</sub>	CH <sub>4</sub>	Rn	He	H <sub>2</sub>	CH <sub>4</sub>	CO <sub>2</sub>
F <sup>1</sup> Maximum	591	19.38	18900	10.31	5.68	942	8.23
F <sup>1</sup> Minimum	127	5.66	26500	7.70	5.55	111	7.56

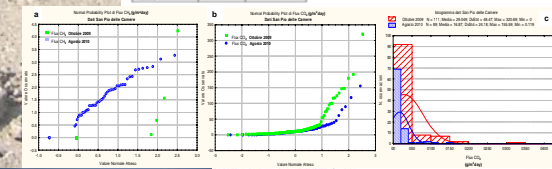
  

S. Pio delle Camere Fault	CO <sub>2</sub>	CH <sub>4</sub>	Rn	He	H <sub>2</sub>	CH <sub>4</sub>	CO <sub>2</sub>
F <sup>2</sup> Maximum	331	8.25	11600	4.98	0.76	1.97	2.02
F <sup>2</sup> Minimum	192	1.57	13400	4.83	0.34	7.46	1.48

**Table 1:** overall maximum and minimum values of fluxes and concentrations of geogas species measured in soil along the two fault segments grids.



**Figure 5:** a-b) Isoconcentration maps of CH<sub>4</sub> fluxes measured in August 2010 and October 2009. c-d) Isoconcentration maps of CO<sub>2</sub> fluxes measured in August 2010 and October 2009.



**Figure 6:** a) Normal Probability Plot of the CO<sub>2</sub> flux measurements in the depocenter of the S. Pio delle Camere fault, soon after the paroxysmal phase of the L'Aquila seismic sequence (October, 2009) and during a subsequent survey, far from this seismic phase (August, 2010). b) Normal Probability Plot of the CH<sub>4</sub> flux data. Both these gas species, during the August 2010 survey, show vibration of anomalous transport process in the "silent" fault area. c) Histogram of CO<sub>2</sub> flux measurements carried out in October 2009 and August 2010. d) Fracture in Scabaton Cave of Bazzano; e) Location of the Paganica Fault (red star) and the S. Pio delle Camere "silent" fault complex.

### 5 - Discussion and conclusion

Geochemical data of CO<sub>2</sub> and CH<sub>4</sub> flux and soil gas measurements have been collected and discussed with respect to: i) the InSAR deformation; ii) seismicity slip data from GPS network; iii) joint sectors among activated segments; iv) surface fracture field along and close to many previously mapped active faults (INGV Catalogue of Strong Historical earthquakes). This work highlighted that geochemical measurements on soils are very powerful to discriminate activated seismogenic segments, their jointing belt, as well as co-seismic depocenter of deformation. Geochemical methods are here demonstrated to be strategic, and we wish to use them in CO<sub>2</sub> analogues/CO<sub>2</sub> reservoir studies, worldwide.

The soil gas fluxes and concentration measurements highlighted that: 1) Nor dangerous CO<sub>2</sub> fluxes in aquifers nor in soils have been measured or advised throughout the epicentral area nor in the surrounding areas (including that of Cotilia-Canetra-Peschiera). Strong earthquakes, even if located close to a Diffuse Depassing Structure, very rarely involve uprising of dangerous CO<sub>2</sub> and CH<sub>4</sub> fluxes or radon indicator. 2) Slight anomalies of CO<sub>2</sub>-CH<sub>4</sub> fluxes and radon in soils have been found in correspondence of the coseismic deformation depocenter and the GPS co-seismic displacement vector. In the first seismic days 2000 gm<sup>2</sup>day<sup>-1</sup> of CO<sub>2</sub>, 300 gm<sup>2</sup>day<sup>-1</sup> of CH<sub>4</sub> and 30,000 Bq/m<sup>3</sup> of Rn have been measured, while regional background is 10, 0-1 gm<sup>2</sup>day<sup>-1</sup> and 500 Bq/m<sup>3</sup>, respectively. The shallow fractures in the Paganica Fault were studied with CO<sub>2</sub> and CH<sub>4</sub> flux measurements profiles (one every 25 m). Geogas anomalies, in particular of CH<sub>4</sub> and Radon are also concentrated along a transverse NE-SW line at the Eastern tip border of the Paganica Fault, where the complex structural interaction with the S. Pio delle Camere Fault is located. Geochemical measurements carried out in S. Pio delle Camere fault depocenter have been changed during 2010, suggesting changes in migration processes still ongoing. Geochemical results allowed to select the site for 4 geochemical continuous monitoring stations. The used experimental method could be exploited along other dangerous "silent" faults, "CO<sub>2</sub> analogues" or "CO<sub>2</sub> injection test sites", adding information where geo-structural expressions of active faults at surface are hidden.