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Very slightly anomalous leakage of CO_2, CH_4 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_2 and CH_4 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_2 reservoir is present (termomethamorphic CO_2 from carbonate diagenesis), to study leakage patterns at surface (CO_2, CH_4, Radon and other geogas as He, H_2, N_2, H_2S, O_2, 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_2 analogues/CO_2 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_2-CH_4 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, 13.38°, 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 4.1; 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_2 or brines - in the seismogenic process (Figure 3). The aftershocks (more than 35.000) were characterised by moderate-magnitude events (between Mw 5 and 4.0), with Apenninic direction and normal fault focal mechanisms. Seismicity distribution, GPS and DinSAR modelling 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, 1703, 1915 events in the North-Western area (Campotosto-Avezzano), and *ii)* 1461 (Maw 6.4), 1762 (Maw 5.9) and 1791 (Maw 5.4) events in the Eastern area (along the Middle Aterno Valley).

Campotosto segment has been activated during the 2009-2010 seismic sequence (and it is still active at the end of August 2010), while the Aterno Valley - S. Pio delle Camere fault segment is "silent" yet. On this dangerous quiescent fault segment (adjacent to the Paganica Fault) we focused also our geochemical studies.

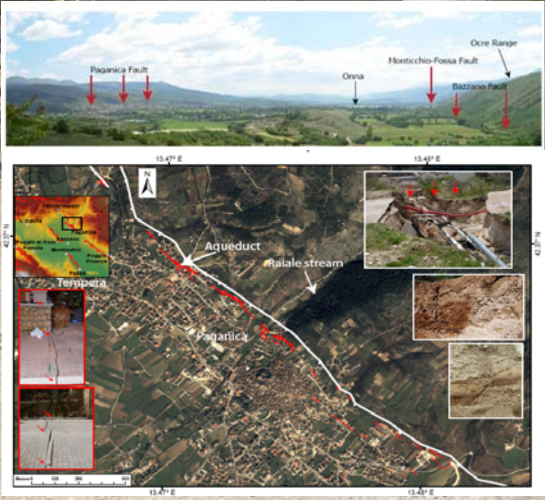


Figure 1: *Location of the studied area.*

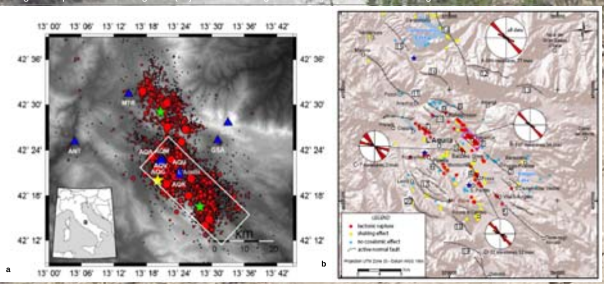


***Figure 2:* a)** *L'Aquila 2009-2010 seismic sequence area: the main shock (yellow star) and the two strongest aftershocks (green stars). White box indicates the surficial projection of the "Paganica Fault" plane. Bleu triangles are the strong motion stations;* **b)** *Tectonic elements, shaking effects and no-coseismic effects along the normal faults in the Abruzzo Region.*

2 - Paganica and S. Pio delle Camere fault segments

The NW Paganica normal fault, SE diping, 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 Aterno River Valley. The Paganica fault system forms a graben and control a depocenter, well highlighted by the cosismic DInSAR image soon after the April, 6 earthquake. The Southern boundary of this 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-Navelli 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+.

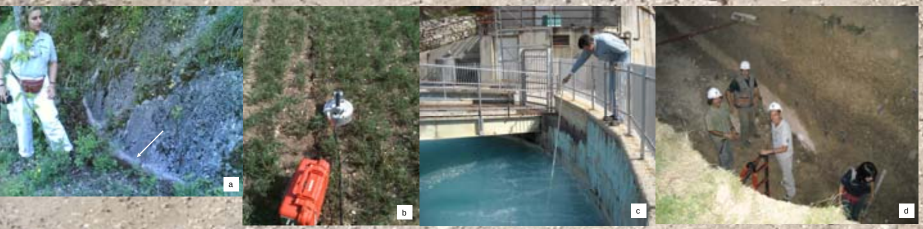


***Figure 3:* a)** *Paganica Fault plane. White arrow shows the fault throw;* **b)** *Shallow fractures observed during the geochemical measurements;* **c)** *the Cotilia CO_2-rich cold spring, 20 km far from epicentre, surveyed monthly by INGV; d) trench executed by INGV to find the Paganica fault plane.*

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_2 leakages in occurrence of strong seismic sequences, taking into account the deep-CO_2 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_2 Capture & Storage (CCS) technologies, in case of strong earthquakes close storage sites; **3)** to evaluate variations of geochemistry, carbon balance, geothermometry and WRI Processes in the aquifers linked to the seismic sequence.

We show the results by CO_2 and CH_4 fluxes measurements (around 1000 sites) and radon, CO_2, CH_4, He, H_2, N_2, H_2S, O_2 and light hydrocarbons concentrations points (around 100 sites) in the main sector of the seismic sequence. An area of ~ 900 km^2 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_2, O_2, N_2, CO_2, CH_4 and H_2S) by means of a *Perkin-Elmer AutoSystem XL* gas chromatograph. A *RAD7 Durridge® alpha* spectrometer was used for Rn surveys. Gas flux measurements have been performed in situ using the accumulation chamber technique (*West 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_4 flux is around 300 gm-2day^{-1}, after 1 month the CH_4 fluxes decrease from 300 to 3 gm^{-2}day^{-1} and CO_2 fluxes anomalies disappeared. Soil gas surveys carried out at Cava Sicabeton 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.

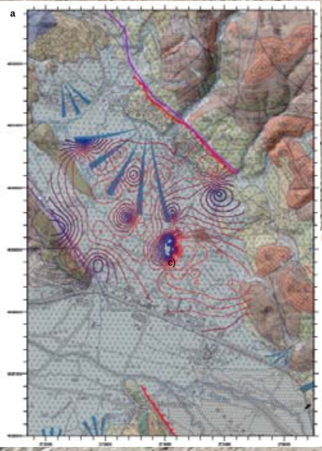
In Figure 4 b are reported CO2 flux measurement profiles perpendicular to the Paganica fault (one samples every 25 meters per two km). Around 230 measures were performed along the 10 profiles of Figure 4 b. Maximum anomaly of CO2 flux (1500 g/m2day) was few meters W from the Aqueduct rupture. CH4 flux measurements were carried out along one of the Paganica fault profile (T7), located close to the Eastern fault-tip. In the Cava Sicabeton, near the Bazzano town (depocenter of the Paganica Fault), we found relatively high flux of CO2. The highest values was found along a transverse lineament bordering the Eastern tip of the Paganica Fault, where the fractures are oriented in the NW-SE, NE-SW and N-S direction in the San Gregorio and Fossa area (while the Paganica fault zone has 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	ϕCO_2	ϕCH_4	Rn	He	H_2	CH_4	CO_2
	(g/m^2day)	(g/m^2day)	(Bq/m^3)	(ppm)	(ppm)	(ppm)	(%v/v)
I° Maximum value	591	19.38	38900	10.31	5.68	642	8.23
II° valore massimo	127	5.66	28500	7.70	5.55	215	7.56

S. Pio delle Camere Fault *October 2009*	ϕCO_2	ϕCH_4	Rn	He	H_2	CH_4	CO_2
	(g/m^2day)	(g/m^2day)	(Bq/m^3)	(ppm)	(ppm)	(ppm)	(%v/v)
I° Maximum value	321	4.25	13600	4.98	0.76	1.95	2.02
II° Maximum value	192	1.57	13400	4.83	0.34	1.46	1.48

S. Pio delle Camere Fault *August 2010*	ϕCO_2	ϕCH_4
	(g/m^2day)	(g/m^2day)
I° Maximum value	156	3.27
II° Maximum value	118	3.12

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



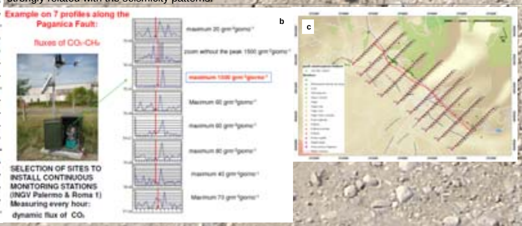


***Figure 4*: a)** *Radon maximum anomaly at Sicabeton Cave of Bazzano, inside the Paganica fault Eastern tip depocenter. The white dotted line is the start of the "transfert"-complex zone, where the seismicity disappear completely after the April 7, event Mw 5.6, at the border of the S. Pio delle Camere fault system in front of the antithetic Fossa Fault (in the lower part);* **b)** *Flux measurement profiles (one points every 25 m) along the Paganica Fault (red line). The green triangles are the fracture surface evidence of the cosismic phase and evolved during the seismic sequence;* **c)** *peaks of CO_2 flux values along the studied profiles, near the fault expression at surface: continuous monitoring station was installed where the maximum CO_2 flux anomaly was discovered, close to the co-seismically broken aqueduct during the earthquake. Continuous monitoring station was installed where the maximum CO_2 flux anomaly was discovered, close to the co-seismically broken aqueduct during the earthquake.*

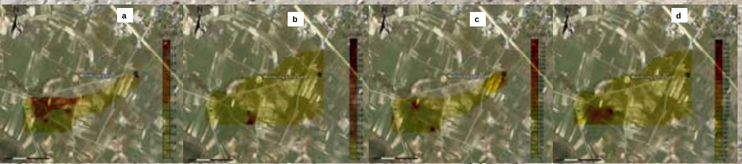
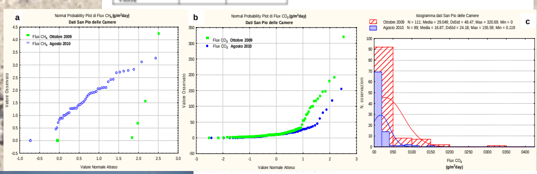


***Figure 5:* a-b)** *isoconcentration maps of CH_4 fluxes measured in August 2010 and October 2009;* **c-d)** *isoconcentration maps of CO_2 fluxes measured in August 2010 and October 2009.*



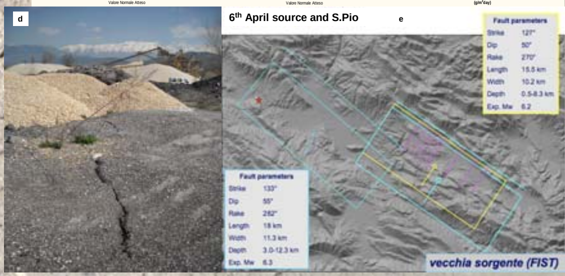


***Figure 6:* a)** *Normal Probability Plot of the CO_2 flux measurements in the depocenter of the S. Pio delle Camere fault, soon after the paroxysmal phase of the L'Aquila seismic sequence (October, 2009) and during a subsequent survey, far from this seismic phase (August, 2010);* **b)** *Normal Probability Plot of the CH_4 flux data. Both these gas species, during the August 2010 survey, show variation of anomalous transport process in the "silent" fault area;* **c)** *Histogram of CO_2 flux measurements carried out in October 2009 and August 2010;* **d)** *Fracture in Sicabeton 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_2 and CH_4 flux and soil gas measurements have been collected and discussed with respect to: *i)* the InSAR deformation; *ii)* coseismic 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_2 analogues/CO_2 reservoir studies, worldwide.

The soil gas fluxes and concentration measurements highlighted that:

1) Nor dangerous CO_2 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 Degassing Structure, very rarely involve uprising of dangerous CO_2 and CH_4 fluxes or radon indoor.

2) Slight anomalies of CO_2-CH_4 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 g/m^2day of CO_2, 300 g/m^2day of CH_4 and 30,000 Bq/m^3 of Rn have been measured, while regional background is 10, 0-1 g/m^2day and 500 Bq/m^3, respectively. The shallow fractures in the Paganica Fault have been studied with CO_2 and CH_4 flux measurements profiles (one point every 25 m). Geogas anomalies, in particular of CH_4 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_2 analogues" or "CO_2 injection test sites", adding information where geo-structural expressions of active faults at surface are hidden.