Very slightly anomalous leakage of CO₂, CH₄ 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 CO₂ and CH₄ underground storage.

Quattrocchi Fa, Galli Ga, Gasparini A a, Magno La, Pizzino La, Sciarra .a, Voltattorni N a

Istituto Nazionale di Geofisica e Vulcanologia (INGV), UF “Fluid Geochemistry, Geological Storage, Geothermics”, Section Seismology and Tectonophysics, Via Vigna Murata 605, 00143, Rome, Italy.

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. The main-shock (Mₚ 6.3) occurred on April 6th at 1:32 (UTC). The earthquake was destructive and caused among 300 casualties. The hypocenter has been located at 42.35°N, 13.38° at a depth of around 10 km. The main shock was preceded by a long seismic sequence starting several months before (i.e., March, 30, 2009 with Mₚ 4.1; April, 5 with Mₚ 3.9 and Mₚ 3.5, a few hours before the main shock). A lot of evidences stress the role of deep fluids pore-pressure evolution – possibly CO₂ or brines - as occurred in the past, along seismically activated segments in Apennines. Our geochemical group started to survey the seismically activated area soon after the main-shock, by sampling around 1000 soil gas points and around 80 groundwater points (springs and wells, sampled on monthly basis still ongoing), to help in understanding the activated fault segments geometry and behaviour, as well as leakage patterns at surface (CO₂, CH₄, Radon and other geogas as He, H₂, N₂, H₂S, O₂, etc...), in the main sector of the activated seismic sequence, not far from a deep natural CO₂ reservoir underground (termomethamorphic CO₂ from carbonate diagenesis), degassing at surface only over the Cotilia-Canetra area, 20 km NW from the seismically activated area.

The 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. Mostly where the measured “threshold” magnitude of earthquakes (around 6), involve that the superficial effects could be absent

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or masked, our geochemical method demonstrated to be strategic, and we wish to use these methods in CO₂ analogues/CO₂ reservoir studies abroad, after done in Weyburn. The highlighted geochemical -slight but clear- anomalies are, in any case, not dangerous for the human health and keep away the fear around the CO₂-CH₄ bursts or explosions during strong earthquakes, as the L'Aquila one, when these gases are stored naturally/industrially underground in the vicinity (1-2 km deep). These findings are not new for these kind of Italian seismically activated faults and are very useful for the CO₂-CH₄ geological storage public acceptance: not necessarily (rarely or never) these geogas escape abruptly from underground along strongly activated faults.

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

The 2009-2010 L'Aquila seismic sequence is still slightly occurring along the central Apenninic Belt (August 2010), spanning more than one year period (Figure 1 a,b). The main-shock (Mₖ 6.3) occurred on April 6th at 1:32 (UTC). The earthquake struck a portion of central Apennine Belt and was felt in a wide part of central Italy, causing among 300 casualties and severely devastating the town of L'Aquila e surrounding villages (around 150,000 inhabitants, leaving 60,000 homeless). The hypocenter has been located at 42.35°N, 13.38°, at a depth of around 10 km (1,2,3) within the typical seismogenic tickness of Apenninic Belt. The main shock was preceded by a long seismic sequence starting four months before (i.e., March, 30, 2009 with Mₖ 4.1; April, 5, with Mₖ 3.9 and Mₖ 3.5, a few hours before the main shock). A lot of evidences (mainly Vₚ/Vₛ anomalous signals in the sequence) stress the role of deep fluids pore-pressure evolution – possibly driven by CO₂ or brines - in the seismogenic process, as occurred in the past along seismically activated segments in Apennines. (after 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 and figure 2). The aftershocks (more than 35,000) were characterised by moderate-magnitude events (seven with Mw around 5 and several with Mw 4.0 events occurred in the two weeks following the April 6 main-shock), with overall Apenninic direction distribution and normal fault focal mechanisms. The seismicity distribution, the GPS and DinSAR modeling (14, 15, 16) are in agreement to image a 15 km-long, 50°SE dipping normal fault as the seismogenic source, responsible of the April, 6 main-shock, along the so-called ”Paganica Fault” as defined in previous literature before (after 17, 18, 19, 20, 21) and along which the surface ruptures were observed focusing there our geochemical measurements too (22, 23, 24 and figure 1 b).

Among the historical earthquakes (mainly described in 20), those affecting the close seismogenic segments with respect the Paganica Fault were: i) the 1349, 1703, 1915 events on the North-Western side (Campotosto-Avezzano areas seismogenic segments), and ii) the 1461 (Mₖw 6.4), 1762 (Mₖw 5.9) and 1791 (Mₖw 5.4) events along the Middle Aterno Valley, on the East side of the Paganica Fault. While the Campotosto segment was activated during the 2009-2010 seismic sequence (and it is still active at the end of
August 2010), the Aterno Valley - S. Pio delle Camere fault segment remained, still now, "silent" and almost completely aseismic, before and after the April, 6 main-shock: on this dangerous quiescent fault segment, adjacent to the Paganica Fault one studied in the first days/months of the seismic sequence, we focus now our geochemical studies.

**Figure 1**: (a) The L'Aquila 2009-2010 seismic sequence area: the main shock (yellow star) and the two strongest aftershocks (green stars). The Southern one, in the Ocre area, activated a N-S complex seismic sub-sequence, along a complex stress-transfer fault-zone, where the role of fluids at depth is under study by INGV (Di Giovanbattista, 2010, after papers 1, 2; 13). The white box indicate the surface projection of the “Paganica Fault” plane activated by the main-shock. Bleu triangles are the strong motion stations (figure modified from paper 21). b) Tectonic ruptures, shaking effects and no-coseismic effects along the normal fault of the Abruzzo Region (figure modified from paper 23); along the tectonic coseismic ruptures our geochemical measurements in soil gases have been focused.

**Figure 2**: (a) Geological sketch map of the Abruzzo Region, with areas of anomalous deep-thermometamorphic CO₂ flux, from paper 8, along the NW normal seismogenic fault belt along the SW-NE profile (figure modified from paper 13). (b) The Cotilia CO₂-rich cold spring, 20 km far from epicentre, surveyed by INGV monthly, together with other 80 sites over the activated fault segments generating the 2009-2010 seismic sequence.
2. The Paganica activated fault segment and close the "silent" S. Pio delle Camere fault segment

Several different maps of the Paganica normal fault segment were published still now (see references inside paper 24) and after the L’Aquila 2009-2010 earthquakes (22, 23, 24). The NW-trending, SE dipping Paganica normal fault is a complex fault system extending from the Collebrincioni town to the NW to San Demetrio Ne’ Vestini town to the SE. Along with antithetic NW-SE trending 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 (15). The Southern boundary of this fault, in the Ocre-Fossa villages zone was affected by the April 7 Mw 5.3 aftershock and the consequent N-S-elongated micro-seismic sequence (see figure. 1 a) in the days after: is very intriguing for its role of fluids (possibly CO2, as postulated by previous papers 7, 8 or possibly connate/de-hydration brines as postulated by paper 5). The fluids are stored naturally at depth, affecting or triggering the seismogenic processes (Di Giovanbattista R. paper in preparation after paper 13). Fault planes at depth are less defined because it occur within a zone of extremely distributed deformation. At this Southern border of the Paganica Fault, starts the “S.Pio delle Camere” fault Western tip (Barisciano-S.Pio Camere-Navelli towns alignment): the temporal patterns of the 1461 and 2009 seismic sequences, located respectively along the S.Pio delle Camere and along the Paganica faults respectively, show remarkable 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+. One question remains: why the 2009-2010 seismicity stopped so abruptly at the W tip of the S. Pio delle Camere fault ? It is this fault in a preparing seismogenic process ? The degassing patterns monitoring in this last months could help to understand it ? Therefore this present paper is useful to define these patterns and where to locate the geochemical continuous monitoring stations as done elsewhere (25, 26).

3. Soil gas survey and groundwater sampling: strategies and methods

The objectives of the geochemical measurements in aquifers and soil gases (fluxes and concentrations) were: 1) to coadjuvate the INGV Emergeo Working Group and other collegues (22, 23, 24) finding i) hints of main-shock ruptures at surface; ii) fluids-related processes acting in the vicinity of the seismogenic segment, defining potentially “geochemical active faults (after paper 5 and references herein), i.e., by leakage, fluids squeezing at surface; heat flow; hints of frictional heating, radon as stress pathfinder; iii) hints of faults segmentation and transverse-tip lineaments of the main NW-SE activated segments, at the junction lines between them, where is foreseen the maximum geochemical anomalies, in occurrence of earthquakes if anomalous diffusion and advection occur (5, 9). 2) to verify the arising of abrupt burst or leaking of CO2 in occurrence of the strong seismic sequence, considering the not far deep-CO2 reservoir
uprising at Cotilia town (Rieti, figure 2 b), only 20 km NW far, in the frame of the CO2-rich ubelt described in papers 7 and 8 (figure 2 a). 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 CO2 Capture & Storage (CCS) technologies, in case of strong earthquakes in the vicinity of the storage sites. 3) to verify: i) permeability variations of the aquifers in the epicentral zone; ii) carbon balance variations (7, 8, 25, 26); iii) geotermometry variations; iv) WRI Processes variations linked to the seismic sequence (i.e., 6).

We discuss the results gathered by measuring fluxes (around 1000 sites) of CO2, CH4 and concentrations (around 100 sites) of radon, CO2, CH4, He, H2, N2, H2S, O2, and other minor geogas (i.e. light hydrocarbons), in the main sector of the activated seismic sequence. Our group was jointed daily to the EmerGeo Working Group (EWG): more than 400 observation sites (fractures mainly) have been surveyed in an area of ~ 900 km², part of which coupled by our 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: 1 m hollow steel probe with a conical point at the bottom and a sampling port on top is inserted to a depth of 0.5m below the ground surface. Two 50 cc samples of soil gas are extracted with a syringe for cleaning the probe, then a soil-gas sample is extracted and stored in an evacuated 25 mL steel cylinder for laboratory analysis (He, H2, O2, N2, CO2, CH4 and H2S) by means of a Perkin-Elmer AutoSystem XL gas chromatograph. A RAD7 Durridge® alpha spectrometer was used for Rn surveys. Other details are described in paper (26). Gas flux measurements have been performed in situ using the chamber technique The soil CO2 and CH4 fluxes were measured by a West System™ device assembled with portable online Li-COR® sensor model LI820, a customised trademark CH4 sensor and a PDA, to record the flux curve, as described in paper (26). We discuss in this paper only the results gathered by soil gas surveys, while the groundwater surveying will be discussed later: in any case no CO2/CH4-oversaturated waters were found in the studied area.

4. Results

We reported in table 1 the overall maximum and minimum values of fluxes and concentrations of geogas species, measured in soils along the two fault segments (see figure 4 c for their location and crossing area among the two). Along the Paganica fault area, the maximum flux of CH4 was measured around 300 grm⁻²day⁻¹ (in literature previous data are absent: the paper 27 taken in consideration only CH4 concentrations and not fluxes, along another quiescent seismogenic segment). After 1 month from the main-shock: the slight CO2: fluxes anomalies disappeared, while the CH4 fluxes passed from 300 to 3 grm⁻²day⁻¹. After 1 month, at Cava Sicabeton of Bazzano town - inside the Paganica fault Eastern tip depocenter, the gas-enriched ruptures in the soil, described in (24), disappeared: this fact stress that it is very important to perform soil gas surveying soon after the strong seismic event.
Figure 3: (a) Soil 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 (the red one in the lower part of the figure); b) studied profiles, with measuring points every 25 m, along the Paganica Fault (red line) activated by the April, 6,2009, L'Aquila earthquake. The green triangles are the surface ruptures appeared in the cosismic phase and evolved during the seismic sequence. c) CO2 flux values and peaks along the studied profiles, near the fault expression at surface: continuous monitoring station was installed where the maximum CO2 flux anomaly was discovered, in the vicinity of the co-seismically broken aqueduct, described by 22.23.24.

<table>
<thead>
<tr>
<th>Paganica Fault</th>
<th>CO2 (g/m²·day)</th>
<th>CH4 (g/m²·day)</th>
<th>Rn (Bq/m³)</th>
<th>He (ppm)</th>
<th>H2 (ppm)</th>
<th>CH4 (ppm)</th>
<th>CO2 (%v/v)</th>
</tr>
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<tbody>
<tr>
<td>I° Maximum Value</td>
<td>591</td>
<td>19.38</td>
<td>38900</td>
<td>10.31</td>
<td>5.68</td>
<td>642</td>
<td>8.23</td>
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<tr>
<td>II° valore massimo</td>
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<td>5.66</td>
<td>28500</td>
<td>7.70</td>
<td>5.53</td>
<td>215</td>
<td>7.56</td>
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<table>
<thead>
<tr>
<th>S. Pio delle Camere Fault</th>
<th>CO2 (g/m²·day)</th>
<th>CH4 (g/m²·day)</th>
<th>Rn (Bq/m³)</th>
<th>He (ppm)</th>
<th>H2 (ppm)</th>
<th>CH4 (ppm)</th>
<th>CO2 (%v/v)</th>
</tr>
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<tr>
<td>I° Maximum Value</td>
<td>321</td>
<td>4.25</td>
<td>13600</td>
<td>4.98</td>
<td>0.76</td>
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<tr>
<td>II° Maximum value</td>
<td>192</td>
<td>1.57</td>
<td>13400</td>
<td>4.83</td>
<td>0.34</td>
<td>1.46</td>
<td>1.48</td>
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Table 1: overall maximum and minimum values of fluxes and concentrations of geogas species measured in soil along the two fault segments grids.

We reported, in figure 3 c, CO2 flux profiles perpendicular to the Paganica fault (samples every 25 meters for two km long profiles). Around 230 measures were performed along the 10 profiles of figure 3 b. Maximum anomaly of CO2 flux (1500 g/m²·day) was few meters W from the Aqueduct rupture. CH4 flux signatures were found along one of the Paganica fault profile (T7), located close to the Eastern fault-tip. As regards the CH4 reservoir at depth and origin, we could mention that the closest deep drilling in the area is the Popoli 1 well (800 m deep), which encountered CH4 signature as free gas, at 730 m depth. The isotopic signature is not known (nor in paper 27), being probably biogenic (our samples had no enough CH4 volume for C isotopic values). In the Cava Sicabeton near the Bazzano town (depocenter of the Paganica Fault), we found relatively high flux...
of CO$_2$, but higher was found along a transverse lineament bordering the Eastern tip of the Paganica Fault, where the fractures are characterized to be 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). Here, the complexity of the fracture field is maximum as well as soil gas geochemical anomalies: this evidence is strongly correlated with the seismicity patterns of this sector, where the role of fluids and diffusivity at depth seem very special (Di Giovambattista R., INGV data-paper in preparation, after 13).

5. Discussion and conclusion

Our new geochemical measurements were used to update a GIS (Geographical Information System using ESRI ArcGIS) of the co-seismic effects associated to the earthquake with magnitude greater or equal to $M_w=5.5$) and their spatial and geometrical parameters. The geochemical data have been collected and critically discussed with respect $i)$ 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).

The work highlighted that geochemical measurements on soils are very powerful to discriminate the activated seismogenic segments, their jointing belt, as well as co-seismic depocenter of deformation: where the measured “threshold” magnitude of earthquakes (around 6), involves that the superficial effects could be absent or masked, our geochemical method demonstrated to be strategic, and we wish to use this method in CO$_2$ analogues/CO$_2$ reservoir studies, worldwide.

The highlighted geochemical anomalies are, in any case, not dangerous for the human health and keep away the fear around the CO$_2$-CH$_4$ bursts or explosions during strong earthquakes, as the L’Aquila one, when these gases are stored naturally underground in the vicinity (1-2 km at depth). These findings are not new for these kind of Italian seismically activated faults and they are very useful for the CO$_2$-CH$_4$ geological storage.
public acceptance: not necessarily (rarely or never) these geogas escape abruptly from underground along strongly activated faults.

The soil gas fluxes and concentration measurements highlighted that:

- No dangerous CO₂ fluxes in aquifers nor in soils have been measured or advised throughout the epicentral area or in the surrounding areas (including that of Cotilia-Canetra-Peschiera): strong earthquakes even if located in the vicinity or upon a Diffuse Degassing Structure (defined DDS in paper 25), very rarely involve uprisings of new dangerous fluxes of CO₂, CH₄ or radon indoor as well.

- Slight anomalies of CO₂-CH₄ and radon in soils have been found in correspondence of the depocenter of the coseismic deformation (25 cm max), recorded by DInSAR (paper 15), and where the GPS coseismic displacement vector was found maximum in the SE sector of the activated fault (paper 14), reaching in the first seismic days 2000 g/m²•day of CO₂ and 300 g/m²•day of CH₄ and 30,000 Bq/m³ respectively, compared to the regional background being 10, 0-1 g/m²•day and 500 Bq/m³ respectively. Geogas anomalies, in particular of CH₄ 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. The same measurements done inside the S. Pio delle Camere Fault depocenter are changing with time during 2010 suggesting change in diffusion/advection transport processes still ongoing. The study was useful to select the position of 4 geochemical continuous monitoring stations (since may 2009).

- The exact-punctual expression of rupture at surface of the Paganica Fault, geochemically studied in details by profiles (measures every 25 m) is well discriminable by the simple CO₂ and CH₄ flux measurements. The method is particularly useful when the magnitude of the event is not so large and in case of “blind” ruptures at surface not corresponding to “main walls on landscape”: new “research” paradigms to discover the “seismogenic” segments among the “active”, “secondary”, passive” and antithetic ones, is strongly necessary. This earthquake show (see Nature news, Katherine Sanderson and Walters et al., 2009) that it is dangerous to work on the assumption the faults associated with the largest topographic features are going to produce largest events”. The used experimental method could be exploited along other dangerous “silent” faults, “CO₂ analogues” o “CO₂ injection test sites”, adding information where geo-structural expressions of active faults at surface are hidden.

6. References