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The contribution of fluid geochemistry to define the structural pattern of the 2009 L'Aquila seismic source

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Abstract

Field investigations performed in the epicentral area within the days following the April 6, 2009 L'Aquila earthquake (M_w 6.3) allowed several researchers to detect evidence of coseismic ground rupturing. This has been found along the Paganica Fault and next to minor synthetic and antithetic structures. Although a lot of geo-structural and geophysical investigations have been recently used to characterize these structures, the role of the different fault segments – i.e. as primary or secondary faults – and their geometrical characteristics are still a matter of debate. In light of this, we have here integrated data derived from fluid geochemistry analyses carried out soon after the main-shock with field structural investigations. In particular, we compared structural data with CO_2 and CH_4 flux measurements, as well as with radon and other geogas soil concentration measurements (see details in Voltattorni et al., this issue). Our aim was to better define the structural features and complexities of the activated Paganica Fault. Here, we show that, in the near rupture zone, "geochemical signatures" could be a powerful method to detect earthquake activated fault segments, even if they show subtle or absent geological-geomorphological evidence and are still partially "blind". In detail, a clear degassing zone was identified just along the San Gregorio coseismic fracture zone – i.e., the surface deformation related to the "blind" San Gregorio normal fault. Indeed, CO_2 and CH_4 flux maximum anomalies were aligned along the Northern sector of the San Gregorio fault, in the Bazzano industrial area. This area also corresponds to the depocenter of the maximum coseismic deformation highlighted by DInSAR analysis (ATZORI ET AL., 2009). Here, maximum radon concentration values in soil gases were also found. As a whole, these results corroborates the hypothesis of BONCIO ET AL. (2010) who suggested that the San Gregorio fault probably represents a synthetic splay of the Paganica Fault, being thus connected with the main seismogenic fault at depth.

Moreover, another maximum in CO_2 flux anomaly has been measured along the southernmost tip of the earthquake rupture zone, close to the San Gregorio village. Minor or absent soil gas and flux anomalies were instead located along antithetic structures as the Bazzano and Fossa faults, while some anomalies in CO_2 flux or radon concentration in groundwater have been found within transfer zones, such as the step-over zone between the central segment of the Paganica fault and the San Gregorio fault and in the zone which separates the Paganica fault from the *i)* Middle Aterno Valley-Subequana Valley and *ii)* Barisciano-S. Pio delle Camere-Navelli fault systems.

Our results corroborate the power of fluid geochemistry in investigating the structural features of active tectonic structures, being particularly helpful in discerning blind faults. More specifically, our data suggest that the youngest fault splays, as in the case of the San Gregorio fault, may represent preferential sites for degassing.

1. Introduction, method and rationale

Seismogenic sources responsible for earthquakes with a magnitude equal to or minor than about 6.0 commonly lack of clear and undoubted coseismic surface geological-geomorphological evidence (e.g. COPPERSMITH & YOUNGS, 2000; MICHETTI ET AL., 2000; VALENSISE & PANTOSTI, 2001, HALLER & BASILI, 2011 and references therein). In this perspective, several authors argued that the fluid geochemistry approach may help the classical geologic field methods to discriminate the surface expression of some "blind" activated faults (QUATTROCCHI, 1999; QUATTROCCHI ET AL., 2000), both created by recent earthquakes or by historical ones (SALVI ET AL., 2000; PIZZINO ET AL., 2004).

In the investigated case, geological and geophysical studies indicate that the April 6, 2009 M_w 6.3 earthquake ruptured part of a NW-SE extensional tectonic structure, i.e. the Paganica Fault (hereafter PF), dipping toward the SW, with the city of L'Aquila lying a few kilometers away on the hanging wall (Fig. 1). Surface faulting occurred along some sectors of the PF, with a continuous extent of some-km-long surface open cracks and vertical dislocations or warps (i.e., about 9 km, according to Falcucci et al., 2009; about 13 km, according to Boncio et al., 2010; more than 2.5-6 km, according to EMERGEO WORKING GROUP, 2010; and about 19 km, according to GALLI ET AL., 2010). On the other hand, the aftershock area is extended for a length of more than 35 km and included major aftershocks and thousands of minor events.

Since *i)* the "origin" of some sets of ground fractures detected along the PF and other surrounding normal fault strands is still a matter of debate (i.e., whether they represent the evidence of primary synthetic and antithetic normal faulting or are due to secondary effects triggered by ground shaking), and *ii)* some parts of the surface rupture zone have not geological/geomorphological expression (e.g., cut through an alluvial plane and have no evident fault scarps), we here show how fluid geochemistry investigations, i.e., gas concentrations and geogas fluxes surveying, may contribute to decipher the complex structural framework related to the 2009 seismic event.

In particular, soil gas concentrations as well as CO_2 and CH_4 flux measurements have been performed in an area of 24 km^2, over an irregular sampling grid, covering almost all the main fault segments (see Fig. 1 for location). Moreover, detailed measurements were performed along ten profiles crossing the PF. The soil CO_2 and CH_4 fluxes (Φ_{CO2} and Φ_{CH4} respectively, expressed in [g/m^2d]) were measured by means of a West System™ chamber (CHIODINI ET AL., 1995, 1998; 2000, BROMBACH ET AL., 2001; CARDELLINI ET AL., 2003) that has an assured low rate of mixing, pressure equilibration between the inside and the outside of the chamber and real time (PDA memorization) measurements with a portable on-line Li-COR, model LI820. The error caused by the interference of the H_2O signal (generated by the humidity, normally cut by a Magnesium Perchlorate drier), has been evaluated to be lower than 1%. Main descriptive statistics of flux measurement results are reported in Table 1 of VOLTATTORNI ET AL. (this issue), where also detailed mapping was inserted.

This soil gas surveying was parallel to regional groundwater surveying started soon after the main-shock and lasted during the entire L'Aquila seismic sequence, for more than one year.

Hence, by applying a geochemical-geological approach the main focus of this work is a better understanding of the role, location and behavior of the: *i)* PF and its related segments; *ii)* synthetic splays; *iii)* secondary antithetic faults, as the Bazzano and Fossa NE-dipping faults; *iv)* transfer zones between the major fault segments (i.e., oblique transfer faults and step-over zones). During our analysis and interpretation, we also considered the information provided by the aftershocks location, DInSAR and GPS inverse modeling technique (ANZIDEI ET AL., 2009; ATZORI ET AL., 2009; CIRELLA ET AL., 2009; BRIOLE ET AL., 2009; AVALLONE ET AL., 2009; CHELONI ET AL., 2009; DI LUCCIO ET AL., 2010), in order to enhance the basic knowledge of geogas transport processes associated to the activated faults, particularly in occasion of moderate-strong earthquakes, as the 2009 one was.

2. Structural framework of the 2009 L'Aquila rupture zone: the Paganica fault

Discrete zones of several-km-long surface faulting and fracturing observed shortly after the April 6, 2009 earthquake has evidenced that the seismic event ruptured the PF (e.g., FALCUCCI ET AL., 2009; BONCIO ET AL., 2010; EMERGEO WORKING GROUP, 2010; GALLI ET AL., 2010). Geological investigations performed after the quake defined a long-term surface expression of the

PF (Fig. 1) as being made of three main NW-SE trending segments, each one about 1-to-3-km long, displaying a dextral en-echelon arrangement. Coseismic reactivation of this partly already known Quaternary normal fault (e.g., BAGNAIA ET AL., 1992) has also been supported by seismological, GPS, DinSAR and GPR data (e.g., ANZIDEI ET AL., 2009; ATZORI ET AL., 2009; CHIARABBA ET AL., 2009; WALTERS ET AL., 2009; ROBERTS ET AL., 2010).

2.1 The PF central segment

The most continuous zone of faults and fractures, about 6.3-km-long, was mapped in the Paganica village area, where down-to-the-SW coseismic throw, ranging between 1 cm to 10-15 cm, and fracture opening, varying between 0.5 and 12 cm, have been measured. These ground fractures are extensively described in BONCIO ET AL. (2010) and by the EMERGEO WORKING GROUP (2010).

The fault segment has been responsible for the displacement of continental (alluvial fan, fluvial and slope-derived) deposits dated between the Middle Pleistocene and the Late Holocene (e.g. GALLI ET AL., 2010). A flight of fault scarps, carved both on the limestone bedrock and on the mentioned deposits, represent the surface expression of the fault branch. Many outcrops in the area of Paganica showed several synthetic shear planes displacing the continental sequences. Sets of ground cracks were detected along the whole segment, most of which organized in parallel and *en echelon* arranged strands several tens of metres long.

2.2 The San Gregorio fracture zone

The San Gregorio fracture zone has been interpreted by BONCIO ET AL. (2010) as the SE-continuation of the PF rupture, being part of the main tectonic structure. A right stepping step-over zone, 1.4-1.7 km wide, separates the PF central segment from the San Gregorio rupture zone (overlap ~1.3 km, Fig. 1). An about N-S trending fault plane occurs along this transfer zone, where FALCUCCI ET AL. (2009) observed N-S oriented ground cracks, i.e. aligned with this transfer fault, crossing with NW-SE trending fractures, i.e. aligned with the main segments of the PF (Fig. 2).

Along the ~4.5 km San Gregorio fracture zone, linear fissures with cm-size apertures and echelon cracks, generally without appreciable vertical slip, were found (Fig. 3a). Fissures ubiquitously cut the ground surface and human-made structures (such as gravel and asphalt roads), buildings and reinforced concrete walls. Basing on its average orientation, the San Gregorio fracture zone can be in turn subdivided in a “southern segment”, that strikes 130°-140°, a “central segment”, that strikes 110°, and a “northern segment”, that strikes 130°-140°. Along the northern segment, where a long fissure crossed an irrigation channel (close to the Sicabeton quarry), a vigorous degassing, which disappeared in few days, has been observed on April 10, 2009 (BONCIO ET AL.,

2010) (Figs. 3b) (the degassing was not dangerous for human health; see discussion in Quattrocchi et al., 2009; 2010). Such evidence suggested that widening of the fractures during coseismic and immediate postseismic deformation was accompanied by fluid circulation and expulsion. Close to the northernmost portion, the San Gregorio fracture zone strikes near and parallel to a set of paleo-fissures dipping steeply to the SSW observed along the walls of a large building excavation. The paleo-fissures cut Upper Pleistocene alluvial fan gravels and are filled by alluvial pink-yellowish sand, which can be probably referred to the end of the Late Pleistocene, and brown Holocene organic soil, indicating that pieces from the overlying sedimentary units have fallen into the fissures at the time of fissuring. This suggests the reactivation of a Late Pleistocene-Holocene pre-existing fracture zone, during the April 6, 2009 earthquake.

Geological, geophysical and shallow well-logs investigations performed after the earthquake indicate that the San Gregorio fracture zone strikes parallel to a previously unrecognized blind fault, buried by a thin cover of late Quaternary deposits, synthetic to the PF: the San Gregorio Fault (hereafter SGF) (Fig. 3c). In particular, two boreholes located in the footwall of the SGF reached the limestone bedrock at a depth of 20-30 m below a cover layer of alluvial gravels. A borehole located in the hanging wall, instead, penetrated the limestone bedrock at 190 m depth, indicating an abrupt deepening of the bedrock across the SGF. The central and northern segments of the San Gregorio coseismic fracture zone were located in the hanging wall of the SGF, at a distance of 60-90 m from the fault trace (Fig. 3c), whereas the southern segment was located in the footwall of the SGF, at a distance of 140-150 m from the fault trace.

As a whole, these observations indicate that the San Gregorio rupture zone probably represents the surface defomeation related to the coseismic activation of the blind SGF.

3. Correlation between geochemical anomalies and structural pattern

A comparison between the overall geochemical measurements and the pattern of the coseismic surface ruptures allowed us to discuss different geochemical anomalies, both for the near-fault and off-fault areas.

For the near-fault case, we distinguished the following sectors: 1) the area across the central segment of the PF, which exhibits a morphological signature (i.e., fault scarp carved on the Quaternary sedimentary sequences), with evident surface ruptures as a consequence of the mainshock; 2) the area across the San Gregorio rupture zone, which is within the "depocenter" of the coseismic ground deformation, as highlighted by InSAR (ATZORI ET AL., 2009) and GPS data (ANZIDEI ET AL. 2009; CIRELLA ET AL. 2009; BRIOLE ET AL. 2009; AVALLONE ET AL. 2009; CHELONI

ET AL., 2009); 3) antithetic faults, as the Bazzano and Fossa faults; and 4) areas of secondary faulting (i.e., step-over and normal-oblique transfer zones).

3.1. Geochemical anomalies along the central segment of the PF (sector 1)

Detailed CO_2 and CH_4 flux measurements (one measurement every 25 or 50 meters) have been performed throughout 2 km-long profiles crossing the scarp related to this fault branch (Fig. 4a). A total of 210 measures were performed along 10 profiles, validating the statistical results for the entire sampling population. Results from each profile highlight, as expected, a stronger degassing close to the surface fault rupture, due to the maximum renewed fractured exposition of rocks after the mainshock (Fig. 4b). Maximum anomaly of CO_2 flux (around 1500 [g/m^{2}d]) was found few meters W from the water pipeline which ruptured owing to the main-shock (Fig. 4b and inset)..

An higher than background CH_4 flux signature was found along one of the PF profile (T7). The origin of the CH_4 signature is not known isotopically (the gas amount was not enough to provide reliable C isotope analyses of the CH_4 component of the soil gas): this Apennine area is affected by slight CH_4 underground, as highlighted by the drilling performed during the '70 of the deep well named "Popoli 1" (800 m deep), which encountered CH_4 as free gas at 730 m depth.

The overall maximum and minimum values of fluxes measured in soils along this fault segment are reported in table 1 of VOLTATTORNI ET AL. (this issue).

3.2. Geochemical anomalies along the San Gregorio rupture zone (sector 2)

The maximum anomalies of soil fluxes and concentration in the near-fault field were found along the San Gregorio rupture zone (Fig.5). In particular, the maximum anomalies were in *i)* Rn concentration (see VOLTATTORNI ET AL., this issue, for the regional background comparison), *ii)* CH_4 flux (up to 300 [g/m^{2}d]) and *iii)* CO_2 flux (max values up to 2000 [g/m^{2}d]) (Fig. 5a-c). These values were measured along the Northern segment of the San Gregorio rupture zone, near the Sicabeton quarry, where a relatively vigorous degassing has been observed on April 10. Although the CO_2 and CH_4 flux anomalies disappeared after 1 month, such evidence suggests that the widening of the fractures during coseismic and immediate post-seismic deformation was accompanied by a slight but not absent “breath” as signature of enhanced fluid circulation and expulsion, i.e., by co-seismic mechanisms, as “seismic pumping” (see QUATTROCCHI, 1999 and references therein, for the Umbria-Marche 1997-98 seismic sequence). This slight degassing disappeared in few days after the main-shock and it could be advised only by sophisticated geochemical instrumentation.

At the Southeastern tip of the SGF, the anomalous values were not absent as well: the maximum anomalous values of CO_2 flux were found around 590 [g/m^{2}d] in the graben bounded by the SGF, to the east, and the Fossa antithetic fault, to the west, with the highest values centered near the San Gregorio village (Fig. 5c).

3.3 Geochemical anomalies along secondary structures: distinct behavior between antithetic and transfer fault segments (sectors 3 and 4)

As exposed in paragraph 2.2, a step-over zone separates the central segment of the PF from the SGF where two intersecting sets of coseismic ground fissures – NW-SE and N-S trending – were identified by FALCUCCI ET AL. (2009). The N-S set, although rather discontinuous, occurred at the base of a pre-existing N-S striking fault dipping to east and showing a normal-to-transtensive kinematics, which displaces Middle Pleistocene fluvial deposits at the hanging wall (FALCUCCI ET AL., 2009). Based on this evidence, FALCUCCI ET AL. (2009) suggested that such E-dipping, N-S striking structure may correspond to an oblique transfer fault between the PF and SGF segments. Anyhow, we discovered a quite clear anomaly in soil gases and fluxes in correspondence of this transfer zone/fault (Fig. 5).

On the other hand, almost absent geochemical anomalies have been observed along tectonic structures antithetic to the PF, suggesting their passive role (or even non-activation) in the overall coseismic deformation. Random radon and CO_2 flux anomalies are located along the NE-dipping Bazzano antithetic fault (Fig. 5).

3.4. Geochemical anomalies in the off-fault area

The observation of high radon content in groundwater, as measured from April 2009 to February 2011 in the area of the Ocre Mts. (Rocca di Cambio, S. Martino D'Ocre, S. Felice D'Ocre), around 5-10 km to the SSE of the PF, might suggest the occurrence of geochemical anomalies far from the 2009 ruptured fault zone. Indeed, although we do not know the background radon content (i.e., before the 2009 earthquake), it is to note that the location of the overall groundwater radon anomaly, NE-SW and N-S trending, corresponds with a wide zone interposed between the PF and the two sub-parallel Quaternary fault systems occurring to the South, i.e. the "Middle Aterno Valley-Subequana Valley" (FALCUCCI ET AL., 2011 and references therein) and "Barisciano-S.Pio delle Camere-Navelli" (DI BUCCI ET AL., 2011) fault systems (Fig. 6) – the current activity of the latter is still under debate (MESSINA ET AL., 2011) –, to the S and to the SE of the PF, respectively. This wide zone also contains a ~N-S trending cluster of aftershocks (Fig. 6) – probably associated to pore pressure evolution in triggering their occurrence (CHIARABBA ET AL.,

2009; 2010; DI LUCCIO ET AL., 2010; CALDERONI ET AL., 2010) – coinciding with an hypothesised – i.e., based on geological and seismological data – structural "threshold" occurring south of the PF (GIACCIO ET AL., 2011; GORI ET AL., this issue; PASTORI ET AL., in press).

Hence, the radon groundwater values, associated with the N-S trending cluster of aftershock, may indicate the presence of a "structural boundary" between the PF and the mentioned fault systems.

4. Discussion and Conclusions

Geochemical surveying performed within the epicentral area soon after the 2009 earthquake, mostly consisting in CO_2 and CH_4 fluxes measurements as well as by soil gas concentration analyses and radon measures in groundwater, provided a complex pattern of geochemical anomalies which shows a good correlation with the coseismic ground ruptures mapped by several authors (e.g., FALCUCCI ET AL., 2009; BONCIO ET AL., 2010; EMERGEO WORKING GROUP, 2010; GALLI ET AL., 2010). Although the detected geochemical anomalies show clustered patterns, they generally fall along (or very close to) the trace of the central PF segment, along the SGF, and along transfer zones/structures between these faults.

As expected, geochemical measurements along several transects crossing the trace of the central segment of the PF, where the most prominent and continuous evidence of surface faulting were mapped, provided a strict correlation between degassing and the trace of ground coseismic ruptures, with peak values of about 1500 [g/m^2 d] of CO_2 flux.

Moreover, an evident geochemical signature characterised the San Gregorio rupture zone, where the blind SGF occurs. Considering the map distance between the PF and the SGF and their dip as deduced by seismological and subsurface data - i.e., ~50° and ~70° respectively- the fault strands should join at depths of 3.0-3.5 km, therefore representing splays of a single deep seismogenic fault at depths (Fig. 7). Such deep rooted nature of the "San Gregorio conduit" is constrained by our geochemical data which suggest fluids enhanced circulation and differential expulsion, as a sort of slight "seismic pumping" (e.g., Sibson literature of the 70s-80s of the past century, see references in QUATTROCCHI, 1999) observed and measured during the co-seismic and post-seismic deformation.

Also, our experimental data showed that gas flux and soil gas anomalies were found in the downthrown block of conjugate normal faults, thus suggesting that also secondary faults, both transfer tectonic structures and antithetic planes branching from the main fault, can have enhanced the vertical permeability during the seismic sequence (Fig. 7).

From a structural and seismotectonic point of view, our results highlight that fluid geochemistry can represent a powerful method in constraining the fault geometry and complexities allowing *i)* to discriminate the "deep-rooted nature" of coseismic surface breakages, *ii)* to detect splays of the causative fault of a seismic event that are characterised by a subtle (or even absent) surficial geomorphic expression, particularly in cases of moderate magnitude earthquakes, and *iii)* to make inferences about the boundaries between different tectonic structures affecting a certain area. In particular, as for the latter point, the occurrence of diffuse radon anomalies, probably also in groundwater, in the sector that separates the PF from the adjacent Quaternary fault systems to the south, might suggest the presence of a complex N-S segment-boundary zone, where the aftershocks of the first days after the mainshock were concentrated in the Ocre Mts sector, well correlated with the N-S seismic anisotropy anomaly highlighted by PASTORI ET AL., (in press).

Hence, as a whole, the results achieved with our investigation suggest that the structural-geochemical multidisciplinary approach should be used systematically after an earthquake during field investigations as well as to investigate historical paleo-earthquake fault zones. Moreover, considering the clear relations between structural patterns and fluid geochemistry, we feel that this approach might provide useful information about fault segmentation also during the inter-seismic period. This might help in constraining the fault segmentation of particularly complex or poorly known fault systems, with implications in terms of improvement of databases of seismogenic sources (e.g., DISS database for Italy; BASILI ET AL., 2008), including the "Composite Seismogenic Sources" (HALLER & BASILI, 2011).

Furthermore, the fact that the SGF – which is still partially "blind" and without clear geomorphic expression – showed higher geogas degassing compared to the PF — which, in contrary, is characterized by a ~50 m wide fault zone and an evident fault scarp (BONCIO ET AL., 2010; GALLI ET AL., 2010) — indicates that younger splays that branch from the main seismogenic fault may be preferential site of degassing. Similar evidence of relative higher gas anomalies (^{222}Rn in that case) along the youngest active normal faults (characterised by fresh, open fractures) has been described for the Crati Graben faults system of Southern Italy (i.e., TANSI ET AL., 2005).

The good correlation among the maximum values of Rn, CH_4 and CO_2 along the SGF (in particular at the Sicabeton quarry) and the evidence of their strong decrease in one month after the mainshock also suggests that *i)* carbon dioxide could be suitable radon-carrier to the surface (PINAULT AND BAUBRON, 1997; QUATTROCCHI, 1999; 2010 A; MANCINI ET AL., 2000, and *ii)* coseismic fracturing and pore-pressure transients provided time-dependent high-permeability changes of the fault zone.

In this perspective, it is worth noting that, although there is not clear and unambiguous evidence of the role of fluids at depth by our geochemical data collected at surface during a yearly period since the April 6, 2009 main-shock, the correlation in this area of anomalous gas concentrations with large post-seismic deformation evidenced by GPS and seismic data (ANZIDEI ET AL., 2009; BRIOLE ET AL., 2009) might correborates the role of deep fluids pore-pressure evolution – possibly CO_2 or brines – in triggering seismicity (after QUATTROCCHI 1999, FRIMA ET AL. 2005; MILLER ET AL., 2004; CHIARABBA ET AL. 2009; BIANCHI ET AL., 2010; CALDERONI ET AL., 2010), as occurred during the Umbria Marche 1997-1998 seismic sequence (QUATTROCCHI, 1999 and references herein; MILLER ET AL., 2004).

Lastly, this work provides good hints for both the location of geochemical sampling grids and the location of continuous monitoring stations to investigate hydro-geochemical transients associated to seismicity, as well as possible, despite improbable, earthquake forerunners, taking into consideration exclusively a multiparametric and multidisciplinary approach, still almost completely lacking in the literature (QUATTROCCHI ET AL., 2000 a,b).

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Figure captions

Figure 1. Structural framweork of the epicentral area of the April 6, 2009 L'Aquila seismic event. The black rectangle (labelled as Fig. 5) indicates the area (24 km^2) covered by fluid geochemistry investigations.

Figure 2. Transverse fault (about N-S oriented) located between the central segment of the PF and the adjacent San Gregorio Fault segment. The two sets of ground fractures are marked in the inset with black (N-S trending set) and white (NW-SE trending set) arrows.

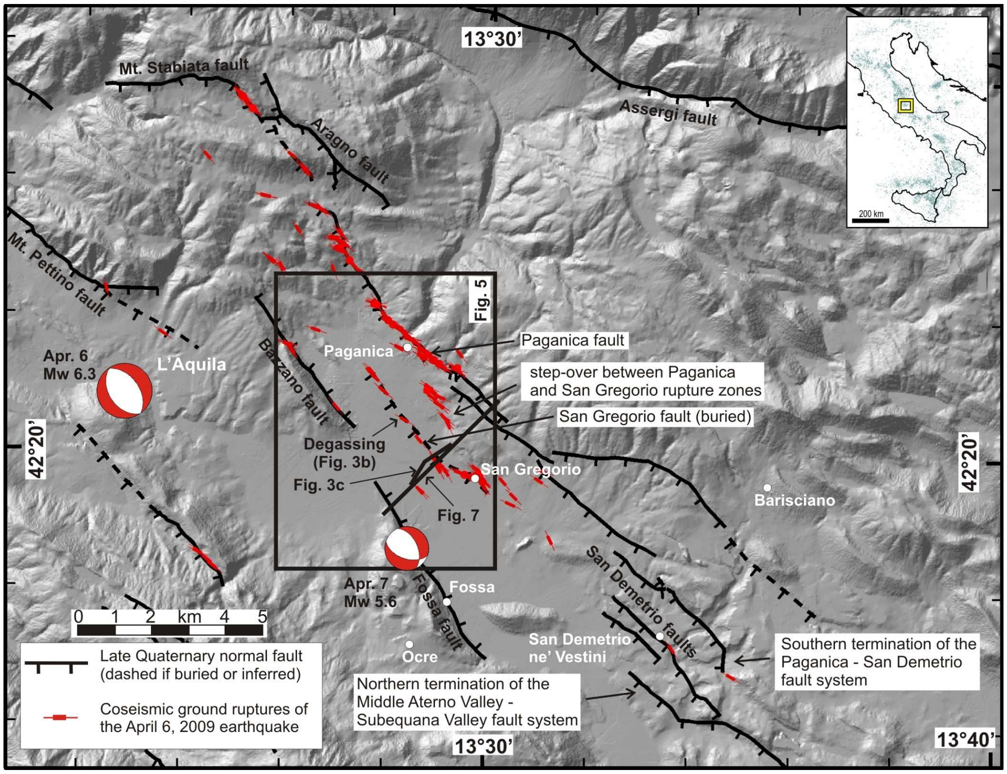
Figure 3. a) Open fissures along the San Gregorio rupture zone at the Sicabeton quarry; b) bubbles nucleated by degassing where the northern segment of the San Gregorio rupture zone crossed an irrigation channel (see Fig.1 for location); c) geologic cross section across the SGF constrained by well data (location in Fig. 1; modified from BONCIO ET AL., 2011). SGRZ: San Gregorio rupture zone.

Figure 4. Soil gas profiles measuring every 25 or 50 m the CO_2 and CH_4 fluxes, crossing the Paganica Fault, during the first days/weeks after the April 6 mainshock. The red line is the trace of the surface breakages along the Paganica Fault. A paleo-slip event in the "Aqueduct" sector of the Paganica Fault, inset.

Figure 5. ^{222}Rn concentration, CO_2 and CH_4 flux distribution maps. The highest radon and Φ_{CH4} values (a and c, respectively) were along the Northern segment of the San Gregorio rupture zone, close to the Sicabeton quarry, where a higher degassing was observed on April 10. The maximum CO_2 flux value (2000 g/m^{2}d) was measured in south-eastern sector of the studied area (b).

Figure 6. (a) Dissolved Rn in groudwater, marked by green circles; the purple circle comprises the anoumalous Rn content in the Ocre Mts. area; red lines, the Paganica Fault, yellow line, the Barisciano-San Pio delle Camere-Navelli fault; green line, the San Demetrio fault. (b) Aftershock sequence folowing the April 6, 2009 mainshock; the purple circle highlight the about N-S trending aligneament of aftershock at the souther tip of the Paganica fault.

Figura 7. Schematic geologic cross-section illustrating the correlation between the area of geochemical anomalies at surface and the possible degassing pathway along the major coseismic activated structures (see the text for more explanation and Fig. 1 for location). Considering a fault dip of ~50° for the PF (CHIARABBA ET AL., 2009) and ~70° for the SGF (BONCIO ET AL., 2011) the SGF should join at depth with the PF, hence representing a younger splay branching from the main seismogenic fault. In this hypothesis the later activation of the SGF (and related transfer zones) may be responsible for increased permeability at the faults intersection at depth and recent narrowing of the L'Aquila basin at surface. (SGRZ: San Gregorio rupture zone).



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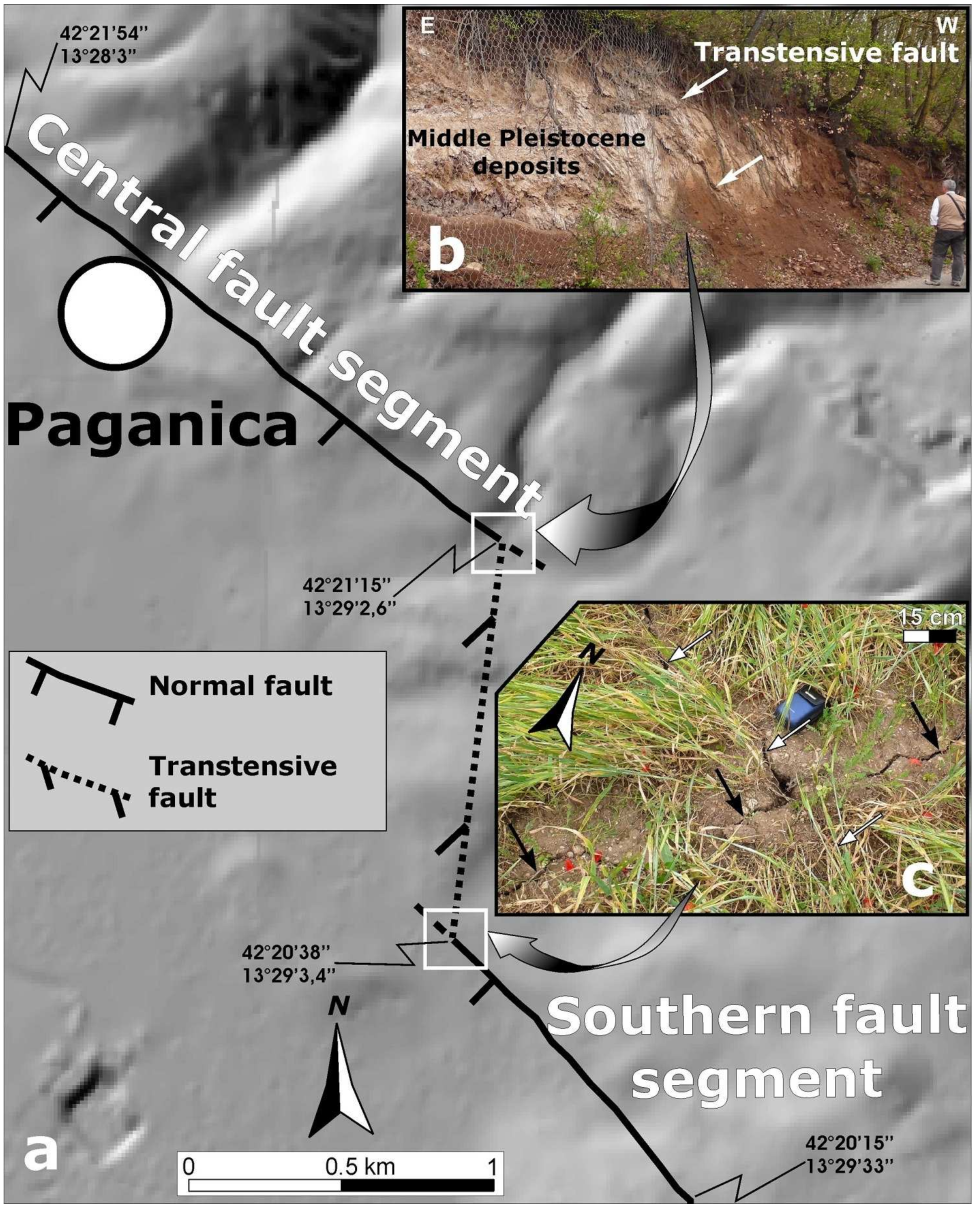

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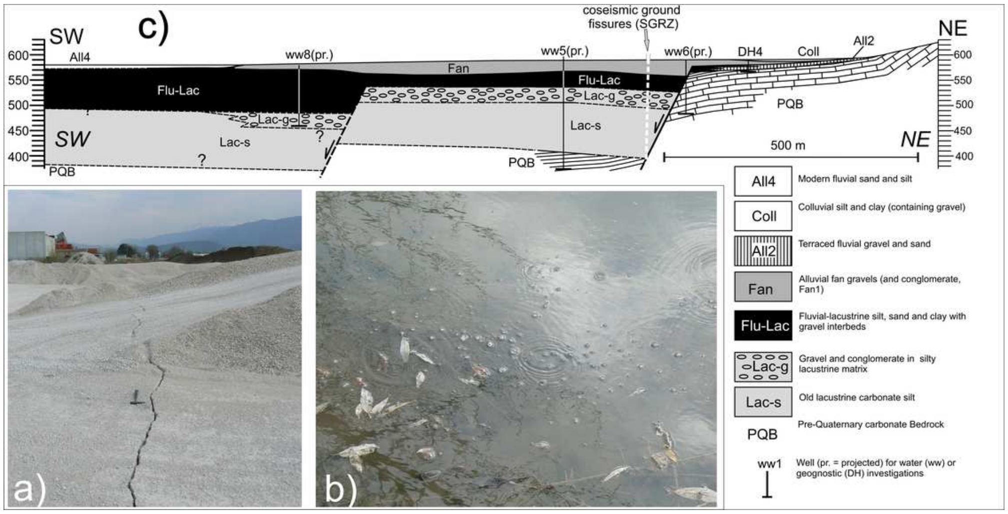

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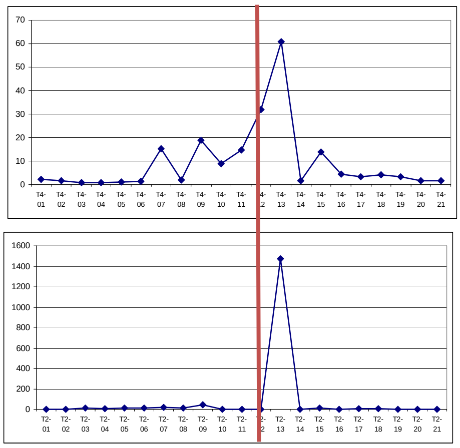
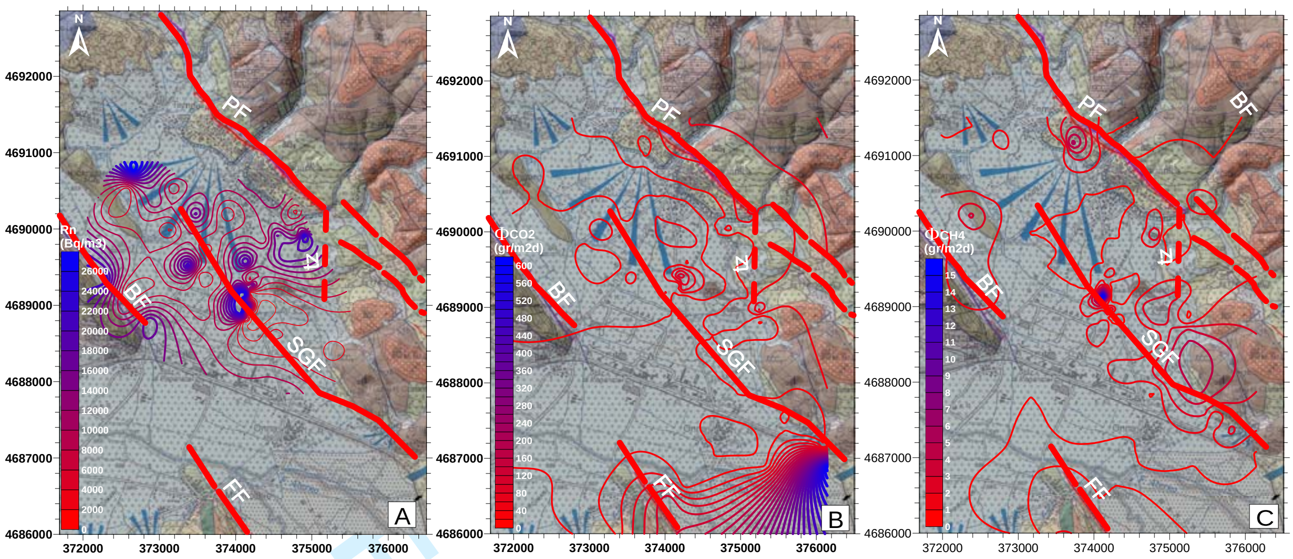
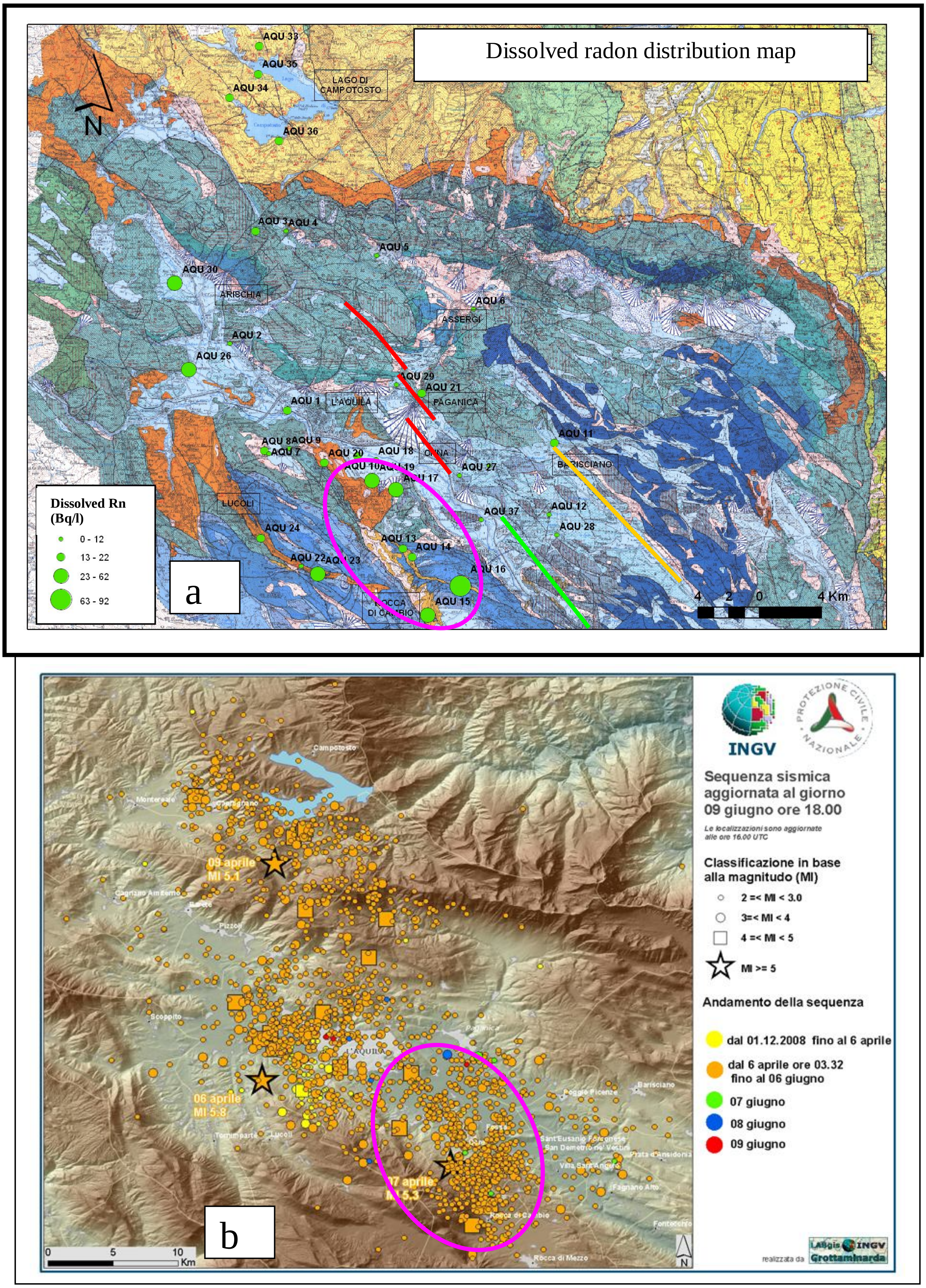
T4-11

T2-11




N
PF
BF
SGF
FF
Rn (Bq/m3)
26000
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
ΦCO2 (gr/m2d)
ΦCH4 (gr/m2d)
4692000
4691000
4690000
4689000
4688000
4687000
4686000
372000
373000
374000
375000
376000
A
B
C


Dissolved radon distribution map
N
AQU 33
AQU 35
AQU 34
LAGO DI CAMPOTOSTO
AQU 36
AQU 3
AQU 4
AQU 5
AQU 30
ARISCHIA
AQU 6
ASSERGI
AQU 2
AQU 26
AQU 29
AQU 21
PAGANICA
AQU 1
L'AQUILA
AQU 11
AQU 8
AQU 9
AQU 7
AQU 20
AQU 18
AQU 27
AQU 17
LUCOLI
AQU 37
AQU 12
AQU 24
AQU 13
AQU 14
AQU 28
AQU 22
AQU 16
AQU 15
Dissolved Rn (Bq/l)
0 - 12
13 - 22
23 - 62
63 - 92
a
4 2 0 4 Km
Campotosto
Montereale
09 aprile
Ml 5.1
Cagnano Amiterno
Pizzoli
Scoppito
L'AQUILA
06 aprile
Ml 5.8
Lucoli
Paganica
Barisciano
Poggio Picenze
7 aprile
Ml 5.3
Fagnano Alto
Rocca di Cambio
Rocca di Mezzo
b
0 5 10 Km
N
INGV
PROTEZIONE CIVILE NAZIONALE
Sequenza sismica aggiornata al giorno 09 giugno ore 18.00
Le localizzazioni sono aggiornate alle ore 16.00 UTC
Classificazione in base alla magnitudo (Ml)
2 =< Ml < 3.0
3=< Ml < 4
4 =< Ml < 5
Ml >= 5
Andamento della sequenza
dal 01.12.2008 fino al 6 aprile
dal 6 aprile ore 03.32 fino al 06 giugno
07 giugno
08 giugno
09 giugno
realizzata da
LABgis INGV Grottaminarda

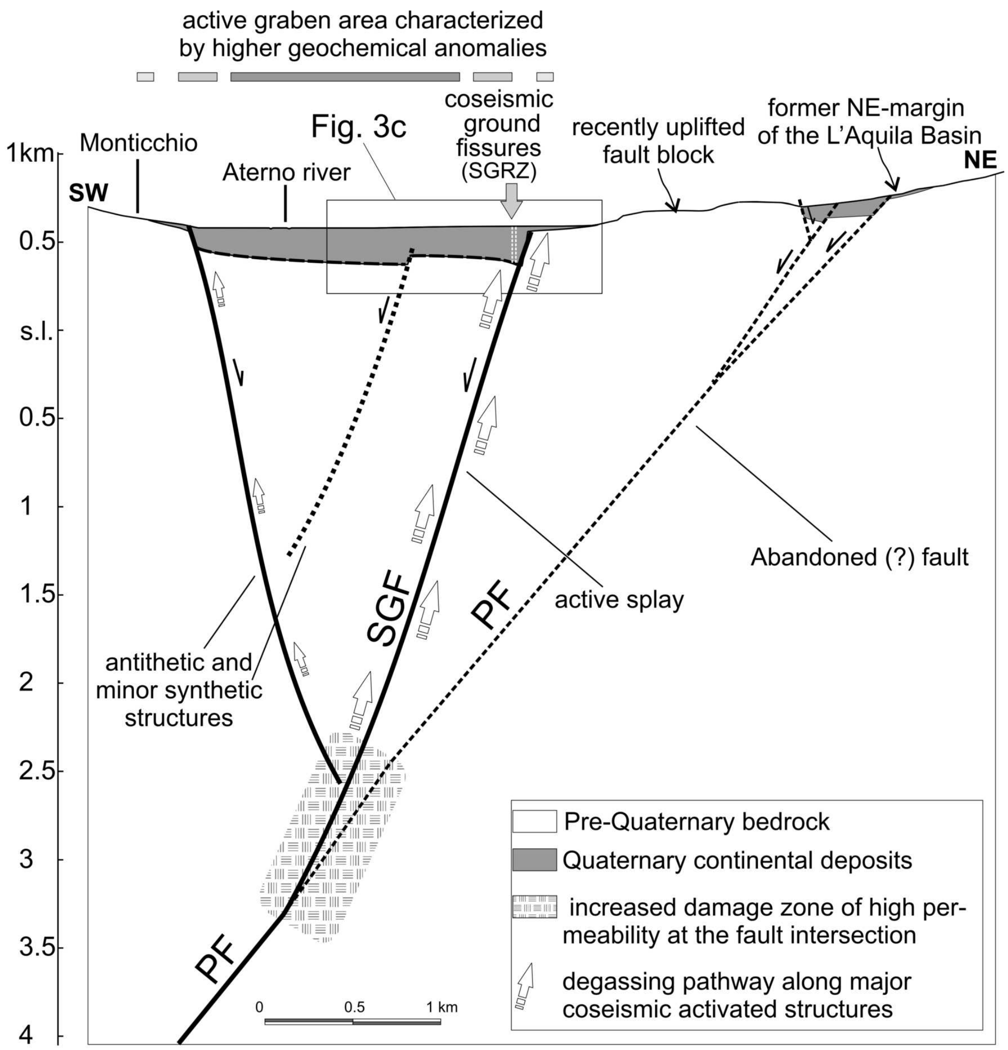


Fig. 7

150x176mm (300 x 300 DPI)