# The difficulty to distinguish natural and human related seismicity in a complex tectonically active area

Thomas Braun [1], Jens Heinicke[2] and Torsten Dahm[3]

[1] Istituto Nazionale di Geofisica e Vulcanologia, Seismological Observatory, Arezzo, Italy
[2] Sächsische Akademie der Wissenschaften zu Leipzig, Office TU Bergakademie Freiberg, Germany
[3] Institut für Geophysik, Universität Hamburg, Germany

## Abstract

Human operations, such as mining, fluid production and the construction of a barrier lake in a tectonically active area can play an important role of triggering seismic events. An interesting area to study those phenomena is the northern part of the Upper Tiber Valley, which is characterized by the presence of a Low Angle Normal Fault, the so called Alto Tiberina Fault (ATF). The recent seismic activity of this fault line reflects the geodynamic behaviour of the regional stress field. Close to this fault zone, a 4.8 km deep borehole PSS1 is located which will be reopened at the end of 2010 to extract $CO_2$. This will possibly lead to a change in the hydraulic equilibrium in this region with possible consequences for the overall local geodynamics. Crustal deformation and microseismicity could be induced by the extraction. Fluid pressure changes and their influence to the hydraulic conduits up to the natural fluid emissions sites (mofettes) will be investigated as part of an actively controlled forcing experiment on this fault. Further human activities like mining industry and the filling of water reservoirs influence the local stress field. The derivation of natural and human induced seismicity can be improved by a comprehensive analysis.

## Introduction

The Upper Tiber Valley is situated in the northern part of the Central Apennines and is setting of a number of geological phenomena typical forvolcanic areas, like $CO_2$ degassing, moderate earthquakes (M < 6) and a strong microseismicity. The major part of the recorded seismicity can be associated to a Low Angle Normal Fault (LANF) – the so called Alto Tiberina Fault (ATF, see Figures 1 and 2), but some of the recorded seismograms show signals similar to those recorded on active volcanoes. In the vicinity of the ATF human activity provides a number of candidates, capable to influence the seismic release in the area:

- a huge barrier lake with a dam height of 52 m (Figure 3) and a water holding capacity more that 150 million m3 is directly situated on the ATF and characterized by seasonal water level oscillation of up to 12 m (Fig. 4).

Fig. 3: The Montedoglio barrier lake

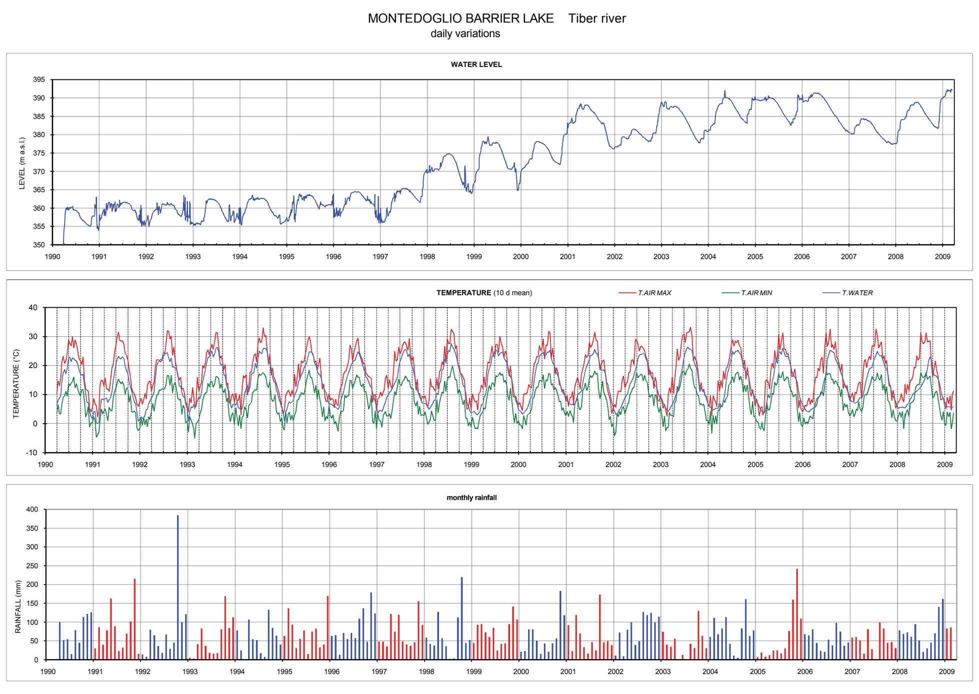


Fig. 4: Variation of water level, rainfall and air-temperature recorded at Montedoglio barrier lake between 1990 and 2009.

- a cement plant, quarries and decommissioned mines present in the area are in the direct vicinity of epicentres of tornillo-like seismograms and episodes of non-volcanic tremor (Figure 5).

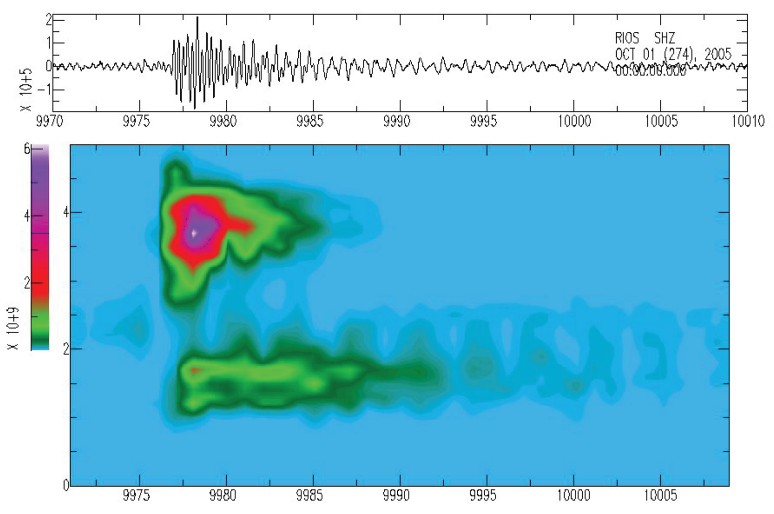

Fig. 5: Seismogram and spectrogram of tornillo-like signals, recorded in the study area.

- $CO_2$ extraction – also this candidate may influence the local stress regime: with the original scope to find methane, between 1982 and 1984 a perforation well has been sunk to a depth of 4800 m at a distance of about 5 km from the Montedoglio barrier lake, the so called PSS well. Instead of finding methane, carbon dioxide has been encountered, with the consequence, that the borehole was closed and sealed. In 2004 the well has been reopened and prepared for a future commercial use of carbon dioxide by a company that will start with continuous extraction from December 2010 on (Figure 6).

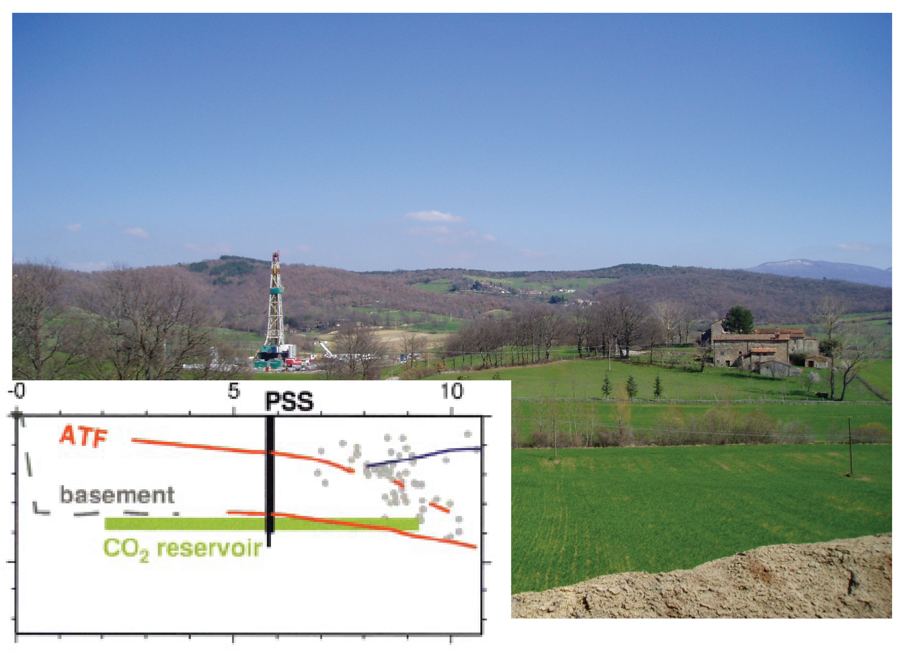


Fig. 6: Deep well drilling plant of the PSS borehole.

Since 2003 many field experiments as e.g. gas flux measurements and the installation of a webcam (Heinicke et al., 2006), different seismic network and array configurations (Braun et al., 2004; Piccinini et al., 2009) have been carried out to monitor the different geophysical phenomena.
Interesting in the near future will be the controlled extraction of $CO_2$ by a private company. In order to study its influence on the seismicity at July 2010 a small aperture seismic array (CAMI in Fig. 2 and Fig. 7) was installed in the vicinity of the well.
In 2011 the setup of a seismic network (S1-S8 in Figure 2) will complete the seismic monitoring capabilities in the area.

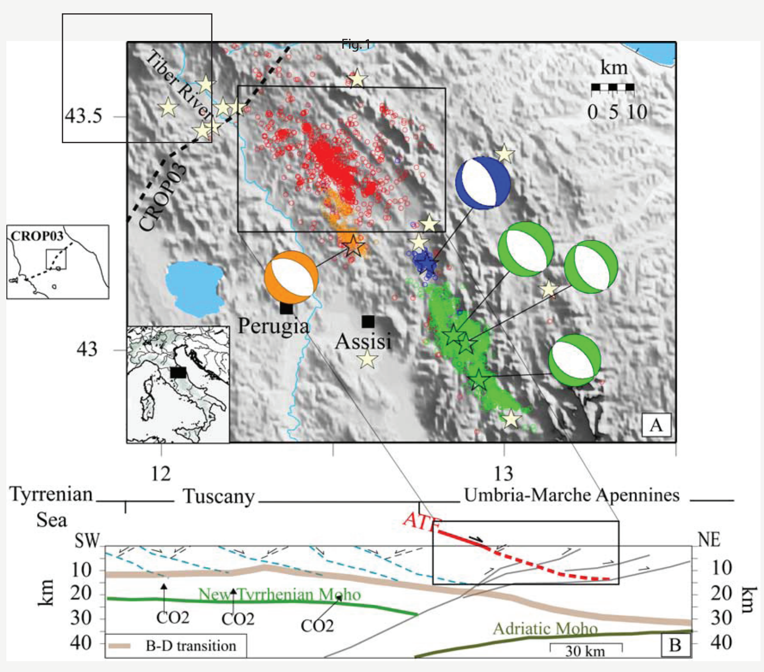


Fig. 1: The microseismicity located on the Alto Tiberina Fault (Chiaraluce et al. 2007). White stars indicate the strongest historical earthquakes.
Red symbols show the hypocenters of the earthquakes recorded during the 2000–2001 seismic survey. Orange, blue and green symbols indicate the aftershocks of the 1984 Gubbio (Mw 5.1), the 1998 Gualdo Tadino (Mw 5.1) and the 1997 Colfiorito sequence, respectively. Focal mechanisms of the three largest shocks: Mw 6.0, Mw 5.7, and Mw 5.6 from NW to SE, respectively) are plotted. Crustal-scale cross section interpretation of the CROP03 seismic profile running from the Tyrrhenian to the Adriatic coasts [Barchi et al., 1998; Collettini and Barchi, 2004]. The ATF is drawn in red, while other low-angle normal faults in the Tyrrhenian and Tuscany sectors are shown in blue. The rectangle in the upper left corner of the figure indicates the study area (Figure 2).

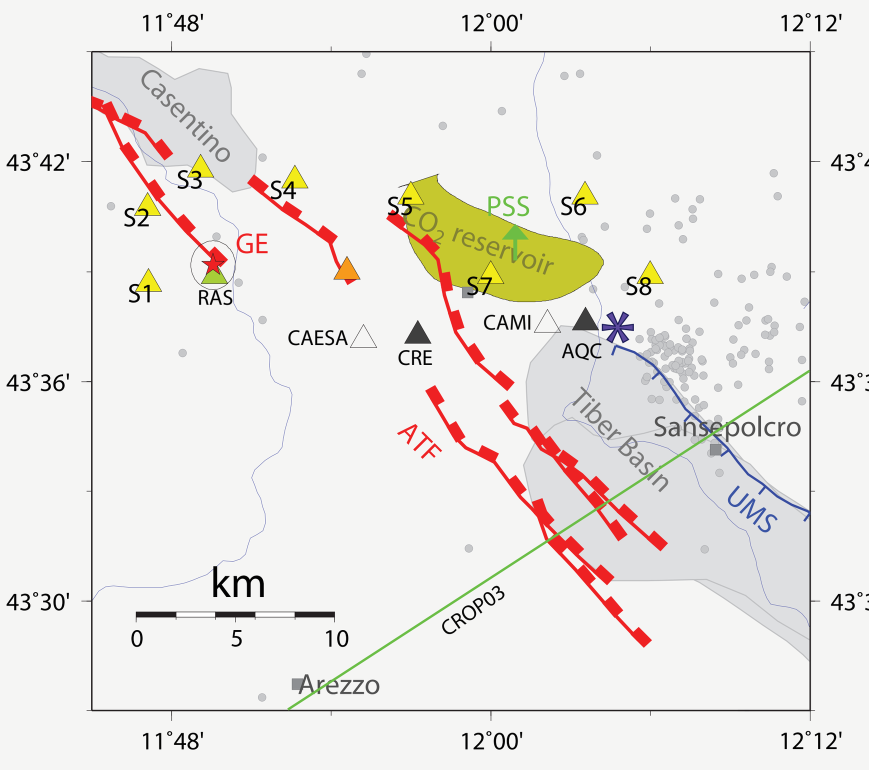


Fig. 2: Overview of the study area. The PSS borehole is indicated by a green asterisk, the $CO_2$ reservoir at ca. 4 km depth by the golden-filled polygon. The ATF (red faults) dip in NE, and its antithetic normal faults (blue faults, e.g. UMS) in SW. Instrumental micro-earthquakes are declared by small grey-filled circles. GE indicate the location Tornillo-like events. Coloured triangles give the location of permanent seismic stations.
Unfilled triangles indicate temporary array installations: CAESA (2005) and CAMI (2010). Other planned seismic stations are indicated by yellow triangles (S1-S8). Grey dots indicate the background seismicity. The blue asterisk indicates the Mw 4.6 main shock of the 2001 seismic sequence.


Fig. 7: Short aperture arrays installed in the study area during 2010.
The RAS-2010 array was located near the epicentre of the tornillo-like events (GE in Figure 2).
The CAMI-2010 array installed between near the mofettes (Figure 9), at half distance between the Montedoglio Barrier Lake and the PSS borehole.
Both arrays are composed of 8 stations, equipped with Earth Data Loggers and Gural CMG-3 ESP seismometers.

## Multiparameter studies of the influence of human activity to the geodynamic processes on site

Human related influences, as realized by the activities of cement plants, quarries or superficial mines may produce seismic signals, but will not directly have an impact on the mechanical behaviour of an active fault system at crustal depth. However, water level changes in a huge barrier lake, as the Montedoglio-Lake, or long term $CO_2$-extraction from the upper crust have the capability to directly influence the stress field at depth.
A large scale field experiment gives us the opportunity to study the overall influence of human activity at this LANF. Beginning from December 2010, the user of the $CO_2$ reservoir will re-open the PSS borehole and plans to produce 5 tons per hour of reservoir gases for commercial usage and trading. This production will lead to a pore pressure change and slow depletion of the reservoir formation, similar to many other gas fields under production. Since production volumes and pore pressure changes are relatively well known, we will consider the local depletion induced stress changes on the ATF and in the surrounding rock as driving forces to the system. We consider the geodynamic response of the ATF as result of a pore pressure perturbation by crustal fluids which influence the static stress regime in the reservoir. The installation of monitoring stations and seismic arrays even before the beginning of the $CO_2$-extraction is essential for estimating the background rate of the gas flux and seismicity. Seismic monitoring in the region is performed by INGV Arezzo since 2003.
The monitoring of the gas-flux measurements and continuous visual observation of the $CO_2$-mofettes has started during the last year, and will be improved within 2011. Water level changes in the nearby reservoir are measured since the beginning of filling in 2007. The purpose of the study is to compile and measure a reference dataset for the discrimination problem of natural and human related seismicity in a complex tectonic region, and to investigate possibly fluid migration in response to crustal stress changes.

## Tectonic setting of the study area

The Upper Tiber Valley is a Pliocene–Quaternary basin, bounded westwards by a Low Angle Normal Fault, the Alto Tiberina Fault, whose northern end has not been well determined. Barchi et al. (1998) analysed data from the seismic profile CROP03 and found the northernmost known part of the ATF in the area between Monterchi—Sansepolcro—Bocca Trabaria (see dashed line in Figure 1 and green line in Figure 2).
The ATF strikes SSE–NNW from Perugia in the South to the inadequately detected northern end at Sansepolcro (see Figure 2). The ATF was recognized by Boncio et al. (2000) as being part of the Etrurian Fault System. The same authors proposed a possible explanation for the prolongation of the fault: the northernmost edge of the ATF could be transected by a left lateral segment as a transition zone of the Casentino basin (NW). Fault scarps near Caprese Michelangelo (red lines in Figure 2), striking elements along the distribution of the fluid emission sites, and visible striking elements in the rock basement in a NW–SE direction, support this fault architecture. The ENE dipping of this low angle fault (<30°) was also detected in the CROP03 deep seismic reflection profile (Fig. 1 and Barchi et al. 1998). As confirmed by passive seismic observations (Piccinini et al., 2003), the easternmost of these LANFs, shows a strong microseismic activity with more than 3200 seismic events (ML < 3.2) in 8 months (red circles in Figure 1).
The topography of the ATF is well imaged up to the town of Sansepolcro (CROP03) by active and passive seismic observations. High-angle antithetic normal faults east of the ATF were also recognized in the CROP03. They are still active tectonic elements characterized by recent seismicity (Piccinini et al., 2009). Another hypothesis presumes that the northern part of the ATF continues to strike in a NNW direction. This opinion is based on stratigraphical data obtained from the deep borehole PSS (see Figure 2).

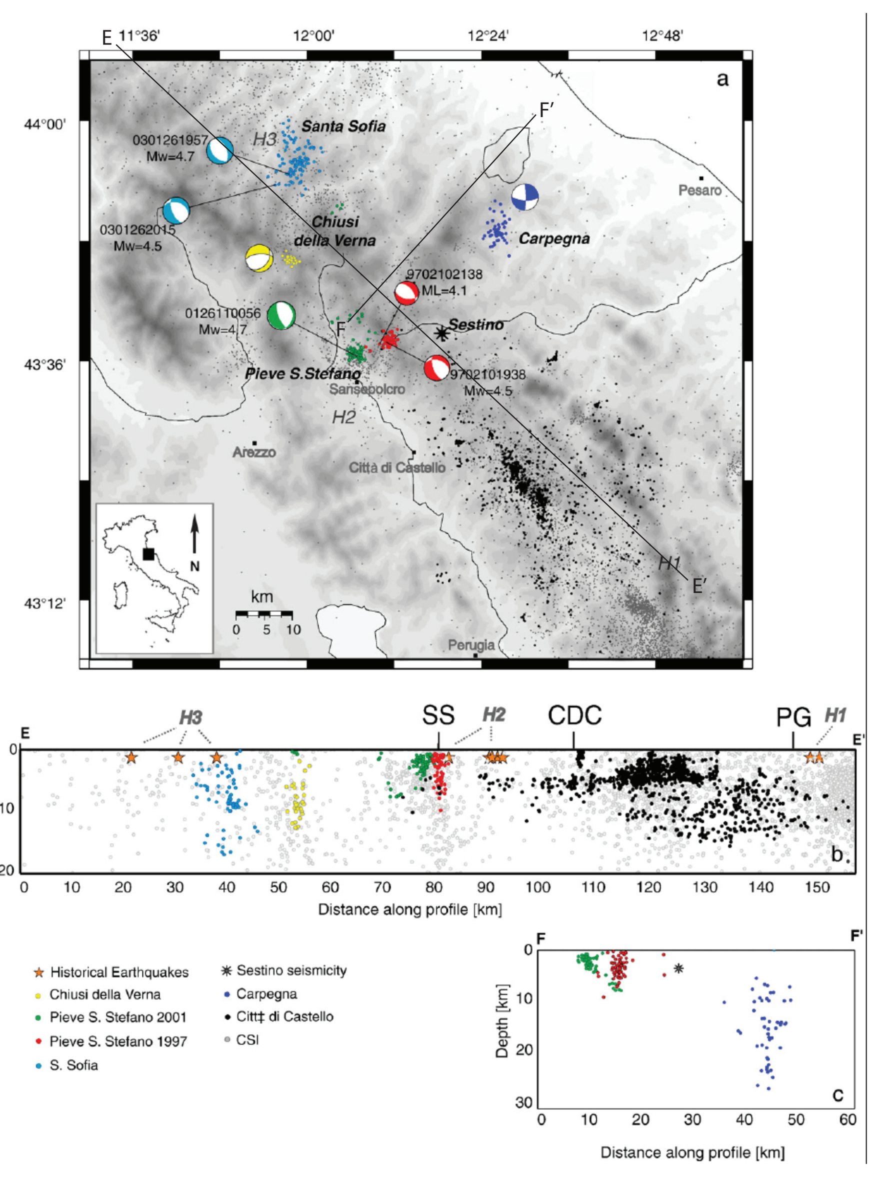


Fig. 8: (a) 1731 epicenters of the data set between 1997 and 2006 are represented by small dots (after Piccinini et al. 2009):
A) Pieve S. Stefano 1997 and 2001 (red and green), B) Carpegna (blue), C) Chiusi della Verna (yellow), D) Santa Sofia (light blue), the background seismicity around Città di Castello (black), and CSI catalogue seismicity (light grey). The Sestino seismicity is represented by a black asterisk.

(b) Cross-section showing the seismicity distribution in the Upper Tiber Valley along the NW–SE direction (E–E') and(c) SW–NE direction (F–F') are also shown. The fault plane solutions presented in the paper are plotted by colored beach balls. In gray, we label the location of the historical seismicity (H1, H2 and H3) as discussed in the text.

## Variations in the fluid emission

Cold $CO_2$ gas emission sites in rainwater-filled pools, so called mofettes, are widely distributed all over Italy. Their gas reservoir is of magmatic and/or metamorphic origin. The $CO_2$ gas reservoir in the Upper Tiber Valley (Figure 2) is dominated by a metamorphic origin (Heinicke et al., 2006). Results from the PSS well investigation show that the main component of the supercritical fluid is carbon dioxide under a static pressure of 700 bars and a temperature of 120°C at depth.
The chemical composition of the fluid is $CO_2$=92.2%, $N_2$=7.6%, $CH_4$=0.03%t, $O_2$=0.01%, $H_2S$=<0.02%. Water exists in that fluid only as a minor component with a content of less than 0.5 per cent. The well known mofettes in that area near Caprese Michelangelo (CAMI) show the same chemistry and the same isotope signature as the crustal fluids. That means a transport path exist between reservoir and mofettes along a seismically active fault zone. Therefore, anomalous fluid emissions have been observed as long-term variations in the long-distance fluid transport process from the reservoir induced by the local tectonic settings. In the northern part of the Alto Tiberina Fault, a fault intersection was reactivated by a seismic sequence which started on 2001 Nov. 26, and continued for approximately four months. The magnitude of the main shock was Mw 4.6. The fluid transport was activated by this seismic crisis as a consequence of the improved transport conditions by increased fracture apertures as a result of the rupture process. A migration of the hypocentres towards the surface provides hints of a possible pore pressure diffusion process. The consequence is an increased fluid transport to the mofettes. The first indications of anomalous fluid expulsions at the mofettes of Caprese Michelangelo were detected 18 months after the seismic events.
The delay in the increased fluid release gives the opportunity to approximate the physical transport parameters like hydraulic diffusivity with 0.25 m2/s as a typical value for fracture zones. These results confirm also the critical stage of the local stress regime which could be influenced by pore pressure variations (Heinicke et al., 2006).

Fig. 9: A typical mofette showing strong $CO_2$ degassing.

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