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

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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 in 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 potential consequences for the overall local geodynamics. Crustal deformation and micro-seismicity 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 for volcanic areas, like CO_2 degassing, moderate earthquakes ($M \leq 6$) 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 Figs. 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 and a water holding capacity more that 150 million m^3 is directly situated on the ATF and is characterized by seasonal water level oscillation of up to 12 m.

- 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.
- CO_2 extraction – also this candidate influences 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-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.

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 array (CAMI in Fig. 2) was installed in the vicinity of the well. In 2011 the set up of a seismic network (S1-S8 in Fig. 2) will complete the seismic monitoring capabilities in the area.

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 Fig. 1 and green line in Fig. 2).

The ATF strikes SSE–NNW from Perugia in the South to the inadequately detected northern end at Sansepolcro (see Fig. 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 Fig. 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 ($M_L \leq 3.2$) 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 Fig. 2).

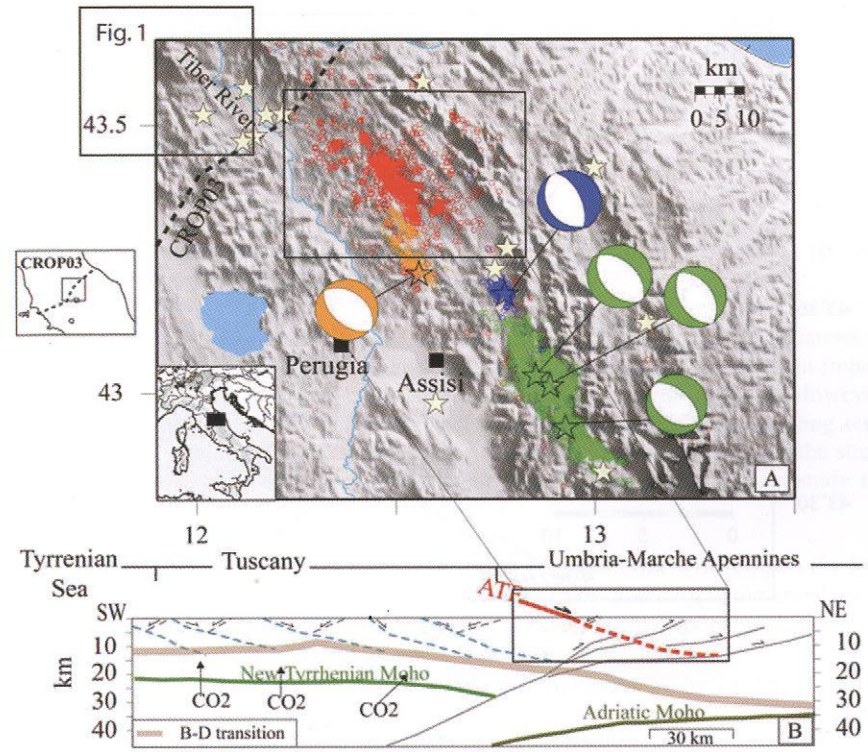

Figure 1: The microseismicity located on the Alto Tiberina Fault (Chiaraluce et al. 2007). White stars indicate the strongest historical earthquakes. Red symbols show the hypocenters of the earthquakes recorded during the 2000–2001 seismic survey. Orange, blue and green symbols indicate the aftershocks 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.

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 (Fig. 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

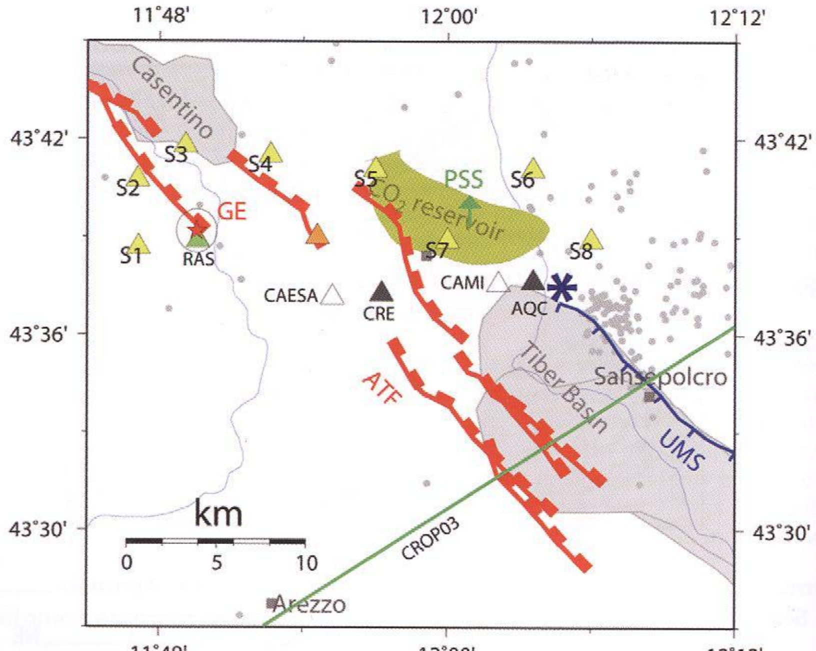

Figure 2: Overview to the study area. The PSS borehole is indicated by a green arrow, the CO_2 reservoir at ≈4km depth by the golden-filled polygon. The ATF (red faults) dip in NE, and its antithetic normal faults (blue faults, e.g. UMS) in SW. Instrumental micro-earthquakes are declared by small grey-filled 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.

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 November 26, and continued for approximately four months. The magnitude of the main shock was M_W 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 m^2/sec 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).

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.

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How to discriminate induced, triggered and natural seismicity

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Abstract

Human operations, such as mining, hydrocarbon production, fluid withdrawal or injection, drilling, hydro-fracturing and reservoir impoundments, can positively and negatively impact tectonic stresses, pore pressure, fluid migration and strain in the sub-surface. Earthquakes occurring in spatial and temporal proximity to such operations are immediately under suspicion to be triggered or induced. The **discrimination between natural, triggered, and induced earthquakes** is a difficult task, and clear rules and scientific methods are not well established or commonly accepted. The current practice to distinguish possible causes of earthquakes is not quantitative and individual cases are treated unequally, which often leads to questions on general liability. This situation has a negative drawback for private and public claimants and for companies performing the operations. Moreover, estimations of earthquake-related risk is still difficult.

Introduction and status quo

Figure 1 shows a number of significant earthquakes (M>3) in Germany and adjacent areas that are associated with geo-engineering operations· The events are related to different types of human operations, ranging from salt mining, coal mining, gas extraction to fluid injection associated with deep geothermal power generations. Some of the plotted events caused cessation of the mining or hydrothermal operations (Saarbruecken, Basel). Other operations as waste fluid injection, CO_2 sequestration or gas storage facilities may also induce or trigger seismicity. However, in the same way geo-engineering activities can bring fault zones close to failure, they can also bring them away from failure (for instance refilling of a gas reservoir or the decline of a water table in a mine). This means that the seismic risk in the vicinity of the operation point is reduced (Klose, 2010). Figure 1 indicates that operations affecting a larger area in the subsurface, such as salt mining, gas withdrawal or coal mining induced/triggered the strongest events with magnitudes up to Ml=5.5. However, the problem of the possible magnitude of a triggered earthquake is complex and additionally depends on the regional stress and pre-existing faults. Additionally, triggered/induced earthquakes typically occur within the uppermost 6 km of the crust and are often superficial. Therefore, even weak events with M<3 can be felt by the population and may pose a seismic hazard at the epicenter and are thus important for

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