SEISMIC ANISOTROPY AND MICRO-SEISMICITY IN THE UPPER CRUST AT NORTH OF GUBBIO BASIN (CENTRAL ITALY): RELATION WITH THE SUBSURFACE GEOLOGICAL STRUCTURES AND THE ACTIVE STRESS FIELD

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Introduction. During the months of April and May 2010, a seismic sequence (here named "Pietralunga seismic sequence") took place in the north-eastern part of the Gubbio basin (northern Apennines); this area is well known to be interested by a continuous background micro-seismic activity. The sequence was recorded both by the INGV National Seismic Network, and by the stations installed by the Project "AIRPLANE" (financially supported by MIUR-Italian Ministry of Education and Research) with the aim of investigating the seismogenetic processes in the Alto Tiberina Fault (ATF) system region.

In this work we present the anisotropic results at four stations: ATFO, ATPC, ATPI, ATVO located around the northern termination of the Gubbio basin that well delimit both the seismic sequence and the whole 2010 seismicity (about 2500 events).

The study of seismic anisotropy has provided useful information for the interpretation and evaluation of the stress field and active crustal deformation. Seismic anisotropy can yield valuable information on upper crustal structure, fracture field, and presence of fluid-saturated rocks. Moreover, the large number of seismic waveforms recorded especially during the Pietralunga sequence allows us also to study the spatio-temporal changes of anisotropic parameters to better understand its evolution and the possible correlation to the presence and migration of fluids.

Shear wave splitting and analysis code. When a shear wave propagates in an anisotropic medium splits into two components with orthogonal directions of polarization and different velocities, one faster respect the other, that are called respectively fast and slow components. This phenomenon is known as shear wave splitting or seismic birefringence.

Crampin and Lovell (1991) proposed as main sources of anisotropy:

- the presence of parallel aligned fluid filled micro-cracks;
- the influence of important parallel structural features, like majors faults or fractures;
- the presence of parallel aligned anisotropic minerals, like olivine or phyllosilicates;
- the propagation through horizontally-stratified structures like finely-layered sedimentary sequences.

In the Earth’s crust, especially in sedimentary rocks, the main source of anisotropy seems to be related to the presence of vertical parallel micro-cracks (Crampin and Peacock, 2008), and the active stress field defines their geometry and orientation. The Extensive Dilatancy Anisotropy model (EDA; Crampin, 1993) is the hypothesized distribution of stress-aligned fluid filled micro-cracks pervading most rocks in the Earth's crust. The geometry of the cracks and the aligning stress field can be monitored by analysis of the waveforms of shear waves propagating through the rock mass. In this view the polarization of the direction of leading (faster) split shear wave is parallel to the direction of the current maximum horizontal stress (S_{Hmax}). Moreover, as illustrated in the Anisotropic-Poro-Elasticity model (APE; Zatsepin and Crampin, 1997) the study of the anisotropic parameters temporal variations could be the result of a change in the active stress field, with a consequently re-orientation of the micro-cracks, caused by a migration of fluid. The analysis of the temporal series could hence give inferences on an important and intriguing phenomenon, the role of the fluid in the seismogenic processes. The shear wave-splitting phenomenon has been widely observed along the Apennine (Margheriti *et al.*, 2006; Piccinini *et al.*, 2006; Pastori *et al.*, BGTA in press).

Shear wave splitting is described by two parameters, the fast shear wave polarization direction, indicated as *fast direction* (φ), and the lag of the slow arrival, called *delay time* (δt). To evaluate these parameters we used a semi-automatic code, called Anisomat+ (Piccinini *et al.*, Computers and Geosciences under revision) that runs under MathLab platform and is able to retrieve crustal anisotropy parameters from three-component seismic recording of local earthquakes using the cross-correlation technique. The analysis procedure consists in choosing an appropriate frequency range, that better highlights the signal containing the shear waves, and a time window on the seismogram centred on the S arrival (the temporal window contains at least one cycle of S wave).

The horizontal components of the seismogram are rotated for steps of one degree in a range of 180° and for each degree of rotation the two orthogonal components are shifted in time for steps of 0.01 s within a time window analysis and for every of these steps the cross-correlation coefficient is computed. The angle of rotation and the temporal shift corresponding to the maximum cross-correlation coefficient are respectively the *fast direction* and the *delay time* for the event-station couple analyzed.

Geological setting and dataset. In the northern termination of the Gubbio basin, during the

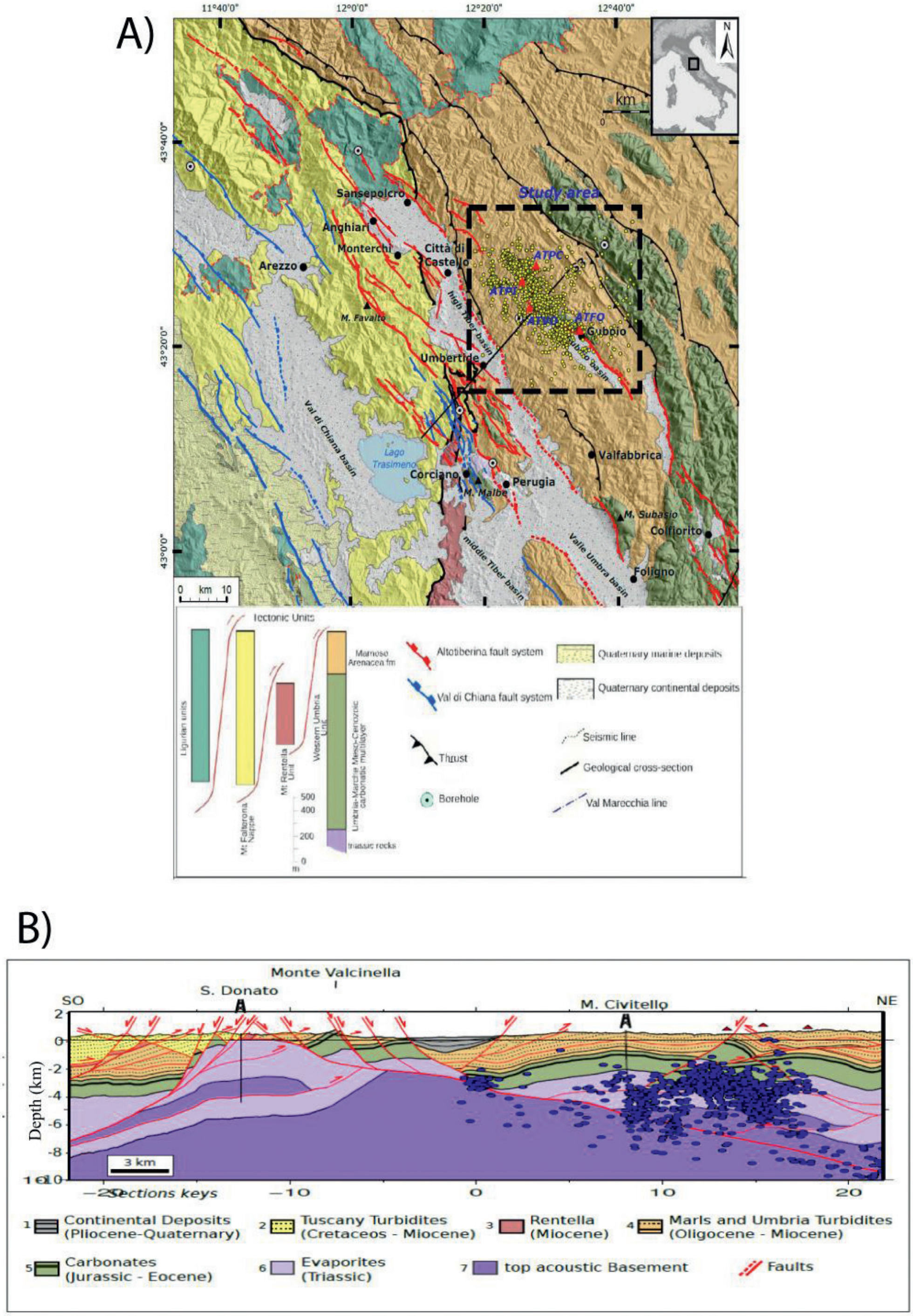

Fig. 1 - Localization of the studied area with the principal lithological and structural features. Yellow circles represented the epicentres of the earthquakes enucleated during the 2010. Red triangle represented the stations that have recorded the data used for shear wave splitting analysis (modified after Mirabella *et al.*, 2011).

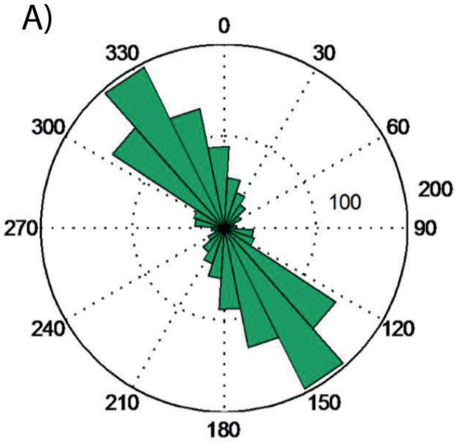

Fig. 2 - Frequency plots rose diagrams for A) the *fast direction* (919 measurements) B) the *null* results (1154 measurements) obtained at the 4 stations. The length of the petals is proportional to the number of the results for each direction. In the A) plot a NW-SE dominant fast polarization is clearly showed and is in agreements to the main geological structures and also to the active stress field [S_{hmin} is oriented NE-SW, see Mariucci *et al.* (2008)].

2010, an intense background micro-seismicity, about 2500 events with a mean magnitude M=1.5, occurred (Fig.1 A). In the period between the months of April and May an increase of the seismicity rate, with the culmination of the April 15 mainshock M=3.8, was recorded ("Pietralunga seismic sequence"). The most of the events are concentrated between 2 and 7 km depth, a second volume is delimited from 7 and 14 km containing less hypocenters than the upper zone, and finally after a gap from 14 to 18 km some seismicity occurs up to 20 km depth. According to Amato *et al.* (2010) part of that clusters on shallow high-angle normal faults above the ATF, and shows a clear migration pattern both along strike from SE to NW. The along-strike migration to NW is clear from April 14 (M3.8 main shock) to April 19, with a pause and another step on April 26-28 show a clear migration both along strike (at about 0.5 km/day) and in depth. This pattern has strong similarities with that observed in previous large normal faulting events in the Apennines, and is likely related to fluid migration. It is worth to note, however, that during the Pietralunga sequence no comparably large fault was ruptured.

Several researchers suggest that deep fluids play a key role in triggering earthquakes (Collettini, 2002; Chiodini *et al.*, 2004; Antonioli *et al.*, 2005) and control the spatio-temporal evolution of seismicity (Miller *et al.*, 2004; Antonioli *et al.*, 2005).

The hypocenters have been also projected on the S3 seismic profile (Fig. 1B) in order to correlate them with the known geological structures in the area and to have an idea in which lithologies they enucleate. From the cross-section it is possible to observe that the seismicity is structurally-controlled by the presence of an important low angle normal fault, the Alto Tiberina Fault (ATF; Barchi *et al.*, 1998) that possibly with its movements generates the most of the seismicity on the hangingwall (Chiaraluce *et al.,* 2007). The Gubbio basin, located above the ATF hangingwall, is a half-graben, delimited by a major SW-dipping normal fault: in this area the most important geological structures strike in NW-SE direction and the active stress field data reveal indeed that the minimum horizontal stress is generally oriented NE-SW (Collettini *et al.*, 2003; Mariucci *et al.*, 2008).

We analysed the dataset recorded at 4 stations (ATFO, ATPC, ATPI, ATVO) divided in two subsets, the first includes the whole 2010 local earthquakes, while the second only the events recorded during the seismic sequence (April-May). The seismic anisotropy results are used, on the whole dataset, to characterize the studied area to retrieve information on upper crustal structure, fracture field and the active stress field, and on the subset containing only the events

Tab. 1 - Average results of the anisotropic parameters at total and singular stations for the entire 2010 seismicity.

Stazione	Numero risultati	Direzione *fast* media (°)	Varianza direzione *fast*	*Delay time*	Varianza *delay time*	*Delay time* normalizzato	Varianza *delay time* normalizzato
ATFO	52	330	34	0.047	0.018	0.0056	0.0035
ATPC	475	322	21	0.050	0.017	0.0081	0.0028
ATPI	384	348	30	0.046	0.017	0.0073	0.0025
ATVO	8	118	26	0.057	0.014	0.0075	0.0057
TUTTE	919	330	27	0.048	0.017	0.0076	0.0029

of the Pietralunga sequence to better understand the complex process of diffusion/migration of fluids in the focal volume, in fact, according to Crampin and Gao (2010) through the splitting parameters temporal variations it seems possible to evaluate the presence, migration and state of the fluid in the seismogenic volume.

Results and discussion. In this work the results of the semi-automatic analysis at the northern area of the Gubbio basin are presented. We obtained 919 measurements of anisotropic parameters at the 4 stations for the entire 2010 seismicity (Tab. 1). The parameters defining the *fast direction* are quite stable and robust and indicate a NW-SE dominant polarization direction (Fig. 2A). This direction is parallel to the principal structural features in the area. In fact both thrust faults, inherited by the former tectonic regime, and direct faults, present tectonic regime expression, are oriented NW-SE. This is in agreement with the theory proposed by Zinke and Zoback (2000) that considers the shear wave splitting in the upper crust caused by the parallel aligned principal structural features and claims the *fast direction* results parallel to this alignment. The results obtained are also in agreement with the theory of Crampin and Peacock (2008), as mentioned, these authors consider the principal shear wave splitting cause the presence of fluid-filled micro-cracks aligned parallel to the maximum horizontal stress. Indeed in our region the *fast polarization direction* is parallel to the micro-cracks and, consequently, results orthogonal respect the current minimum horizontal stress (Mariucci *et al.*, 2008).

Fig. 2B shows also the frequency plot of the *null* measurements for the 4 stations, in it are clearly defined two main orthogonal directions, NW-SE and NE-SW. A measure is defined *null* when the original seismograms show linearly polarized S waves and the methods find δt close or equal to zero. Following Schutt *et al.* (1998), a *null* splitting measurement occurs in an anisotropic medium, when the initial polarization of the shear wave is parallel to the fast or slow directions of the anisotropic media. Although nulls do not provide any information on the delay time, they can be used to constrain the orientation of the anisotropy axis. In this work, we consider null those events with a delay time lower or equal to 0.02 s (two samples in our seismograms).

The average *delay* time for the whole results is about 0.05 s. Delay time is supposed to be directly proportional to the density and to the aspect ratio of the micro-cracks and to the thickness of the anisotropic layer. This average result is compared to a previous study of crustal seismic anisotropy proposed by Pastori *et al.* (BGTA in press) in the same area, the comparison show a robust agreement both for the average fast directions and for the average delay time values.

In literature several authors (Gao and Crampin, 2010; and reference therein) suggest that

Tab. 2 - Average results of the anisotropic parameters at total and singular stations for the Pietralunga seismic sequence.

Stazione	Numero risultati	Direzione *fast* media	Varianza direzione *fast*	*Delay time*	Varianza *delay time*	*Delay time* normalizzato	Varianza *delay time* normalizzato
ATFO	5	336	6	0.038	0.004	0.0058	0.0020
ATPC	321	323	20	0.049	0.015	0.0081	0.0024
ATPI	182	358	29	0.045	0.014	0.0073	0.0025
ATVO	2	116	19	0.070	0.011	0.0080	0.0011
TUTTE	510	331	27	0.048	0.015	0.0078	0.0025

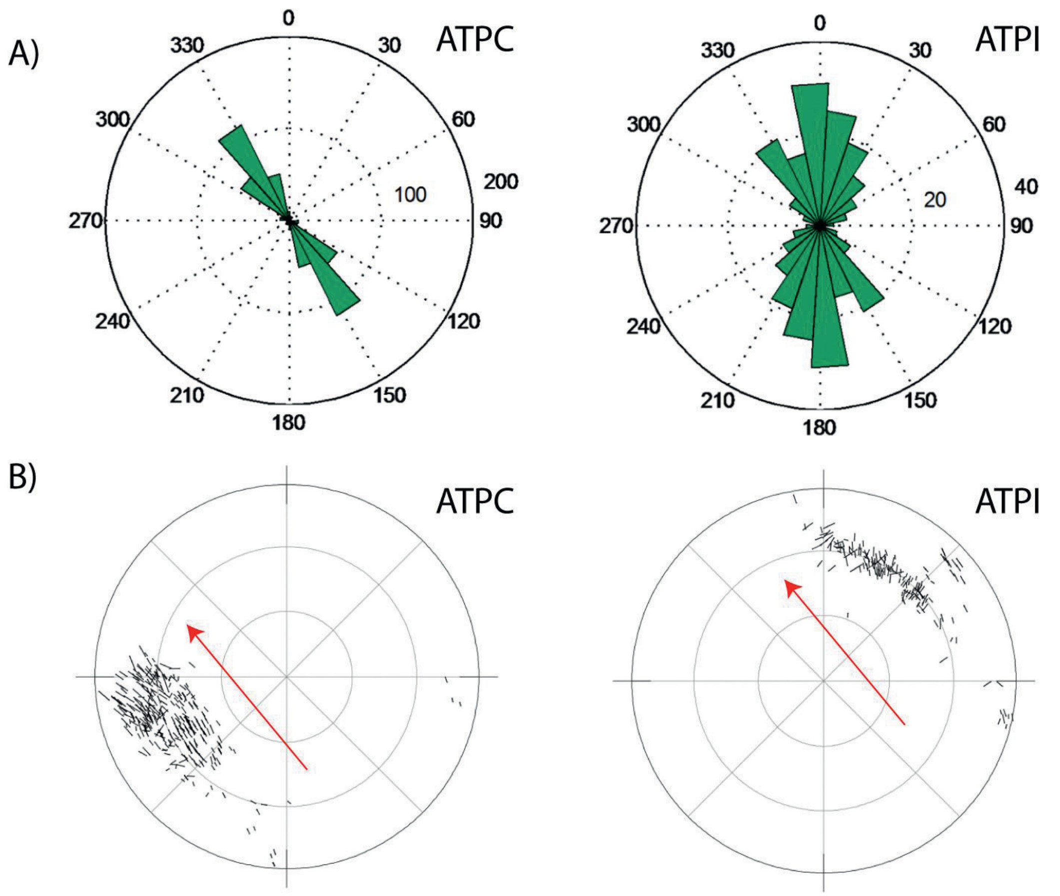

Fig. 3 – A) Rose diagrams and B) equal area plots for the ATPI and ATPC station analysed during the Pietralunga seismic sequence. The dominant fast orientation strikes NW-SE and roughly NNW-SSE for ATPC and ATPI respectively, in according to the total results for the whole 2010 recordings. The equal-area plots show each measurement projected according to it back-azimuth and incidence angles. They show a NE-SW rotation (more clear at station ATPI), especially after the 15 April M=3.8 mainshock, that comes back to an Apenninic direction at the end of May. The red arrows represent the direction of the seismicity migration.

eventually it might to be possible to monitor dilatancy process related to earthquake occurrence by analysing shear waves recorded above small earthquakes occurring in the region interested by these process. There are several ways in which changes of stress may alter the configuration of micro-cracks, changes 1) in the orientation of the crack 2) in crack density 3) of pore-fluid pressure (Crampin, 1987).

To understand if the anisotropy during the Pietralunga sequence was changing in relation to stress changes we analysed the anisotropic parameters in time, for this period we obtained 510 pairs of anisotropic parameters (Tab. 2, Fig. 3). Analyzing the *fast direction* temporal series we have pointed out a variation of this parameter during the seismic sequence time, especially at two stations: ATPC and ATPI that are located over the sequence hypocenters.

In Fig. 3A the rose diagrams show a dominant fast orientation strikes NW-SE and roughly NNW-SSE for ATPC and ATPI respectively, in agreement with the total results for the whole 2010 recordings. In detail, during the SE-NW migration of the hypocenters the fast directions (Fig. 3B) are characterized at station ATPI by a rotation from the initial NW-SE orientation to NE-SW direction around the occurrence time of the M=3.8 April 15 mainshock, and than at the end of May back to the NW-SE direction. In literature this phenomena, known as *90°-flip* of fast direction (Crampin *et al.*, 2002; Angerer and Crampin, 2002; Teanby *et al.*, 2004) and is related to the presence of high-pressure fluid in the rock volume that could be the cause of geometry and orientation micro-crack variations.

The next steps of our work will be the construction of a 3D model of the area interested by the earthquakes in order to better understand which are the volumes of the crust, the lithologies and the structures sampled by the ray paths showing anisotropy. This will allow us to resolve the ambiguity between temporal and spatial variation, to better understand the influence of the lithologies and of the structural features on the shear wave splitting parameters, and to understand how the stress is distributed in the volume of the crust interested by the earthquakes.

Conclusion. The whole dataset recorded during the 2010 allows us to carry out a robust shear wave splitting study in Italy, this considerable number of results made also possible the analysis of the spatio-temporal variations of the anisotropic parameters. These parameters can be related to different causes, such as the active crustal stress field and the pre-existing crustal structure and tectonic style. Moreover, they provide information about the presence and migration of fluids at depth.

The dominant fast direction strikes NW-SE like the orientation of the main geological structures and of the horizontal maximum stress. This result is in agreement to the anisotropic interpretation proposed by Zinke and Zoback (2000) and EDA-APE models (Crampin, 1993; Zatsepin and Crampin, 1997), so the results at are not conclusive on which of the two competing models better explain average fast direction. To understand which interpretative model of seismic anisotropy better fit our results and to know the role of the fluids in the seismogenic processes, the spatio-temporal variations of anisotropic parameters are taken into account.

A possible connection between the temporal variations of the anisotropic parameters and the possible stress change (in term of pore-pressure changes, stress and fracture field variation, fluid migration) related to the occurrence of the mainshock M=3.8 on April the 15 is observed as predicted by EDA-APE model.

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