CRUSTAL FRACTURING FIELD AND PRESENCE OF FLUID AS REVEALED BY SEISMIC ANISOTROPY: CASE HISTORY FROM SEISMOGENIC AREAS IN THE APENNINES

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During the last decades, 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. In fact seismic anisotropy is related to stress-aligned, fluid-filled micro-cracks (Fig. 1, EDA model, Crampin et al., 1984; Barkved et al., 2004).

Seismic anisotropy is an almost ubiquitous property of the Earth. The *Shear Wave Splitting* is the most unambiguous indicator of anisotropy but the automatic estimation of the splitting parameters presents difficulties because the effect of the anisotropy on the seismogram is a second order effect not very easily detectable. Various researchers developed automated techniques for the study of *Shear Wave Splitting*.

In the last three years, it was developed, tested and improved an automatic analysis code"*Anisomat_plus",* to calculate the anisotropic parameters, *fast polarization direction* (**f**) and *delay time*

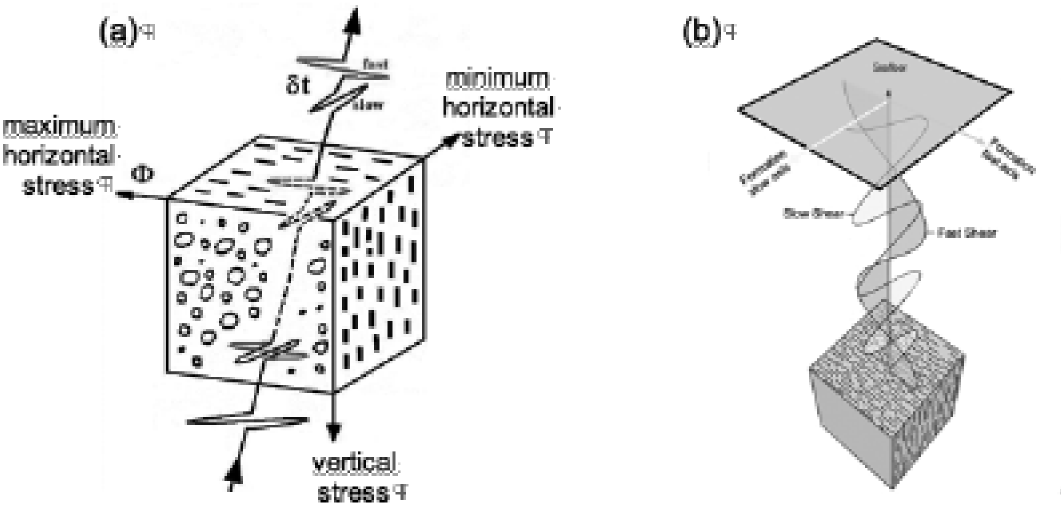

Fig. 1 – a) Simple schematics of shear wave splitting principles, as a direct or indirect result of the principal stress and the associated stress-aligned, fluid-filled cracks (Crampin and Lovell, 1991). An updated version of this classic diagrams, from the BGS Anisotropy Project in Edimburg, shows larger ‘cracks’, signifying not just aligned microcracks, but perhaps an aligned joint set, also assumed to be roughly parallel to maximum stress. b) A more comprehensive diagram of the principles of shear wave splitting (from Barkved et al., 2004). The fast particle motion is polarized in the average direction of fracture strike, while the slow particle motion is polarized perpendicular to the average fracture strike.

(**∂t**). “*Anisomat_plus”* is a set of MatLab scripts able to retrieve crustal anisotropy parameters from three-component seismic recording of local earthquakes. The code uses the horizontal component cross-correlation method, a mathematical operation that allows measuring the similarity of the pulse shape between two S-waves (Fig. 2). These two waves have similar shape, mutually orthogonal oscillation directions and travel with different velocities. 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 code was tested on three key areas selected because of their peculiar geological setting. For each area I used the anisotropic parameters resulting from the automatic computation, in order to determine the fracture field geometries in the portion of crust sampled by S waves. This led to define the strain field of the three areas.

In detail, the three study areas show the following geological features:

1) Val d’Agri basin: I investigated the upper crust trying to relate the anisotropy to the active structures and the stress field (there is still an open discussion about the location of the seismogenic source of 1857 earthquake) and to the changes in seismicity rate probably related to temporal evolution of pore pressure caused by fluid migration in the oil reservoir and by the water level oscillations of the Pertusillo artificial lake. It is important keep in mind that the Val d’Agri basin is the most important Mediterranean oil reservoir.

Fig. 3 shows the rose diagrams of the fast polarization directions at station having more than 10 measurements. These plots consider only *no-null* events and the length of rose petal is proportional to the number of measurements in the correspondent 10th interval, at each station. The lower inset shows the total fast directions at all stations.

I note a NW–SE dominant fast direction at most of the stations (AG04, AG09, AG13, AG14, AG18) whereas other measurements are slightly rotated in a more N100E direction (AG11 and

AG17) or strikes E–W (AG05). The remaining station, AG01, doesn't show a preferentially orientation. In the Val d'Agri I observe a dominant fast polarization direction striking NW–SE, perpendicular to the Shmin active stress indicators available for the region, such as borehole breakout data and *T*-axis of focal mechanisms (Cucci et al., 2004).This also agrees with those recently estimated by Valoroso et al. (2009).

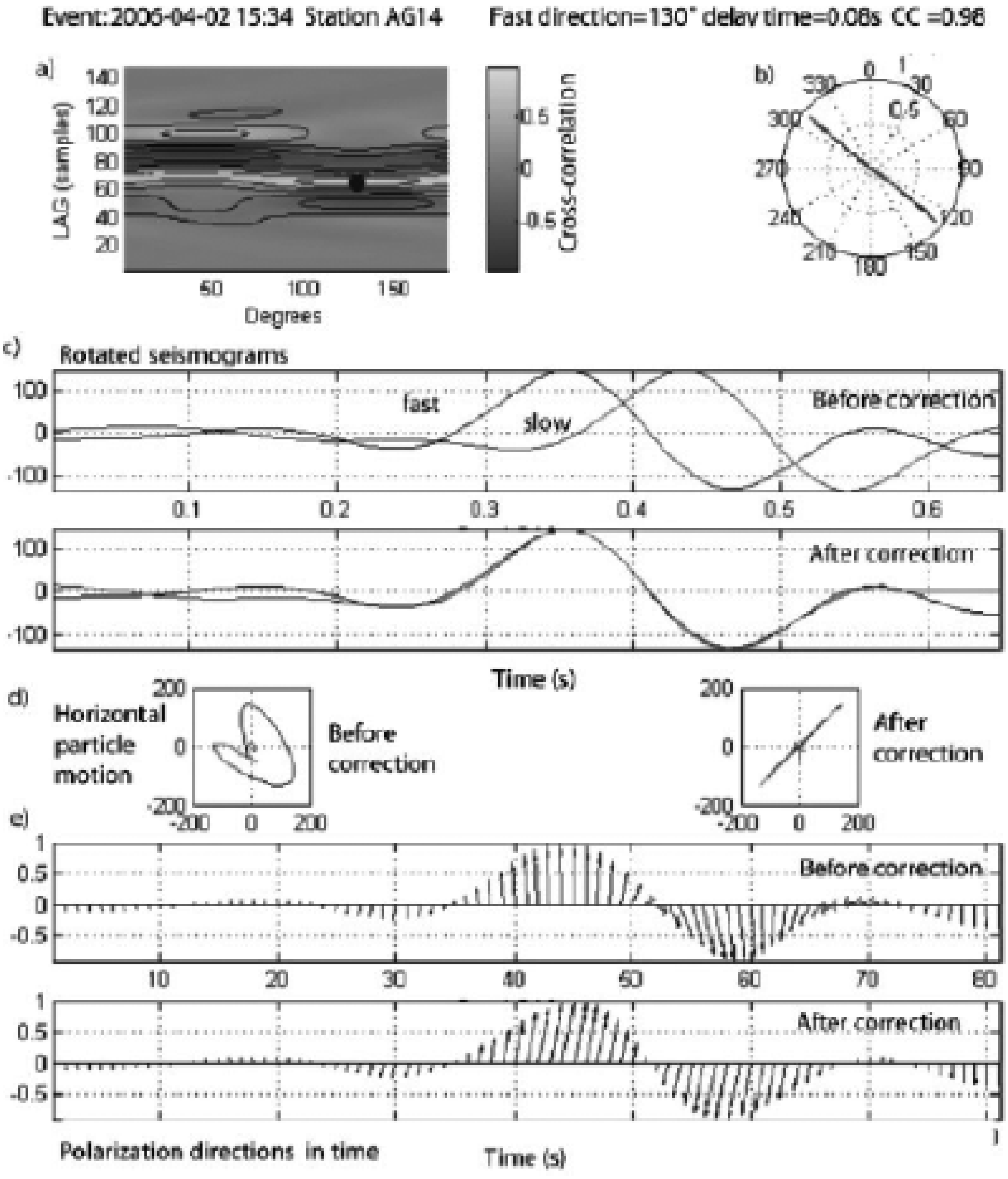

Fig. 2 - Example of shear wave splitting figure output obtained with cross-correlation code after-processing: (a) Estimation of cross-correlation value (black dots). (b) Circular plot showing the fast polarization direction. (c) Seismograms rotated into the fast and slow direction before and after correction. (d) Horizontal particle motion before and after correction. (e) polarization direction before and after correction (from Pastori et al., 2009).

I estimate an average normalized delay times for the region of 0.009 s km^{-1}. The estimated values for single station strongly vary, ranging from 0.002 to 0.012 s km^{-1}. I found greater values (above 0.01 s km^{-1}, at stations AG09, AG14, AG18) characterize stations located along the SW margin of the Val d'Agri basin, whereas lower values (below 0.01 s km^{-1}) characterize both the NE margin of the basin (sites AG04 and AG11) and station AG05 located to the SE of the Vallo di Diano basin, as shown by the colours in Fig. 3 representing the interpolated values of normalized delay times.

Furthermore I analysed the temporal variations of anisotropic parameters in order to explain if fluids play an important role in the earthquake generation process. The close association between anisotropic variations and Vp/Vs changes with the increase of seismicity rate in the shallow portion of the fault system supports the hypothesis that the background seismicity is influenced by the fluctuation of pore fluid pressure at depth (Valoroso et al., submitted). An increase in the pore pressure leads to a decrease in the strength on the fault due to lower values of effective normal stress over the fault surface (Bell and Nur, 1978). In this framework, fluid flow and pore pressure relaxation,

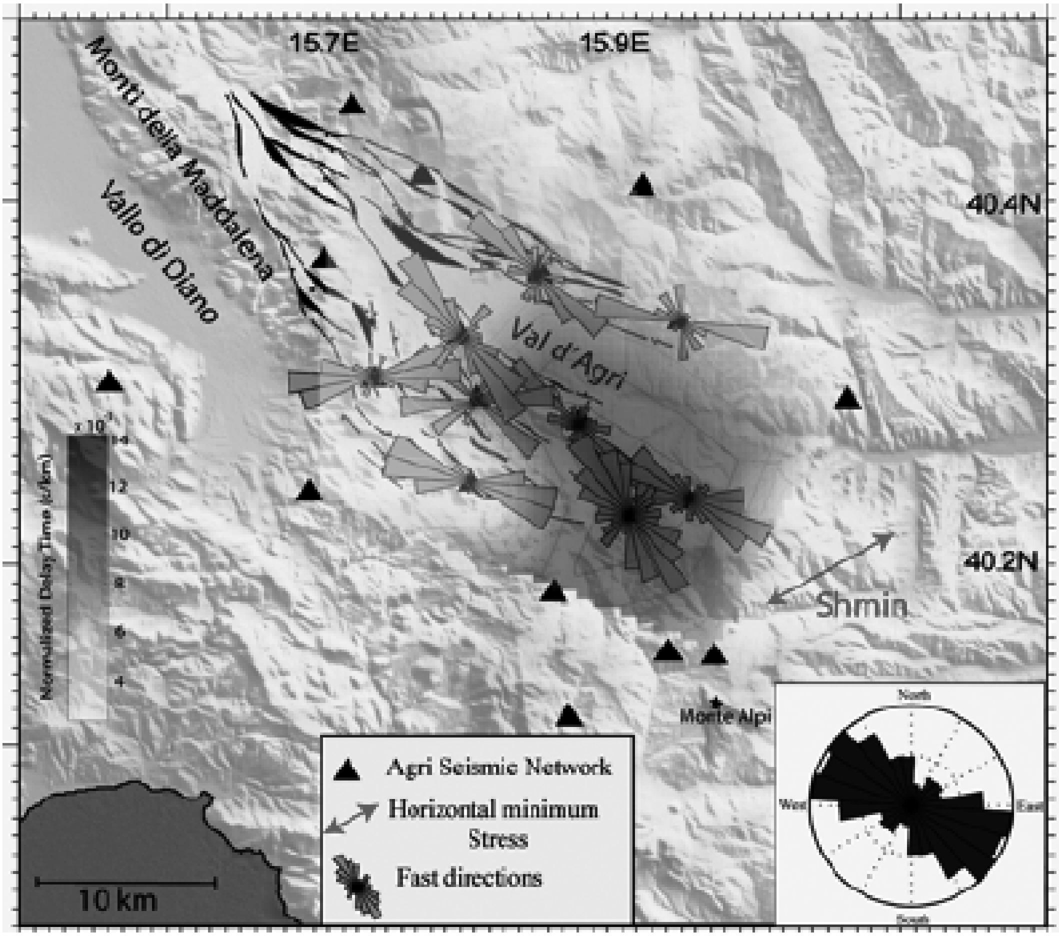

Fig. 3 – Rose diagrams of the fast polarization directions obtained with cross-correlation code; the size of the roses on the map is proportional to the number of measures. The bottom inset shows the total fast directions at all stations. The mean fast directions are almost orthogonal to the minimum horizontal stress (Shmin) in the area represented by the red double-headed arrow (Cucci et al., 2004). The coloured area corresponds to the variation of delay time (from Pastori Ph.D thesis).

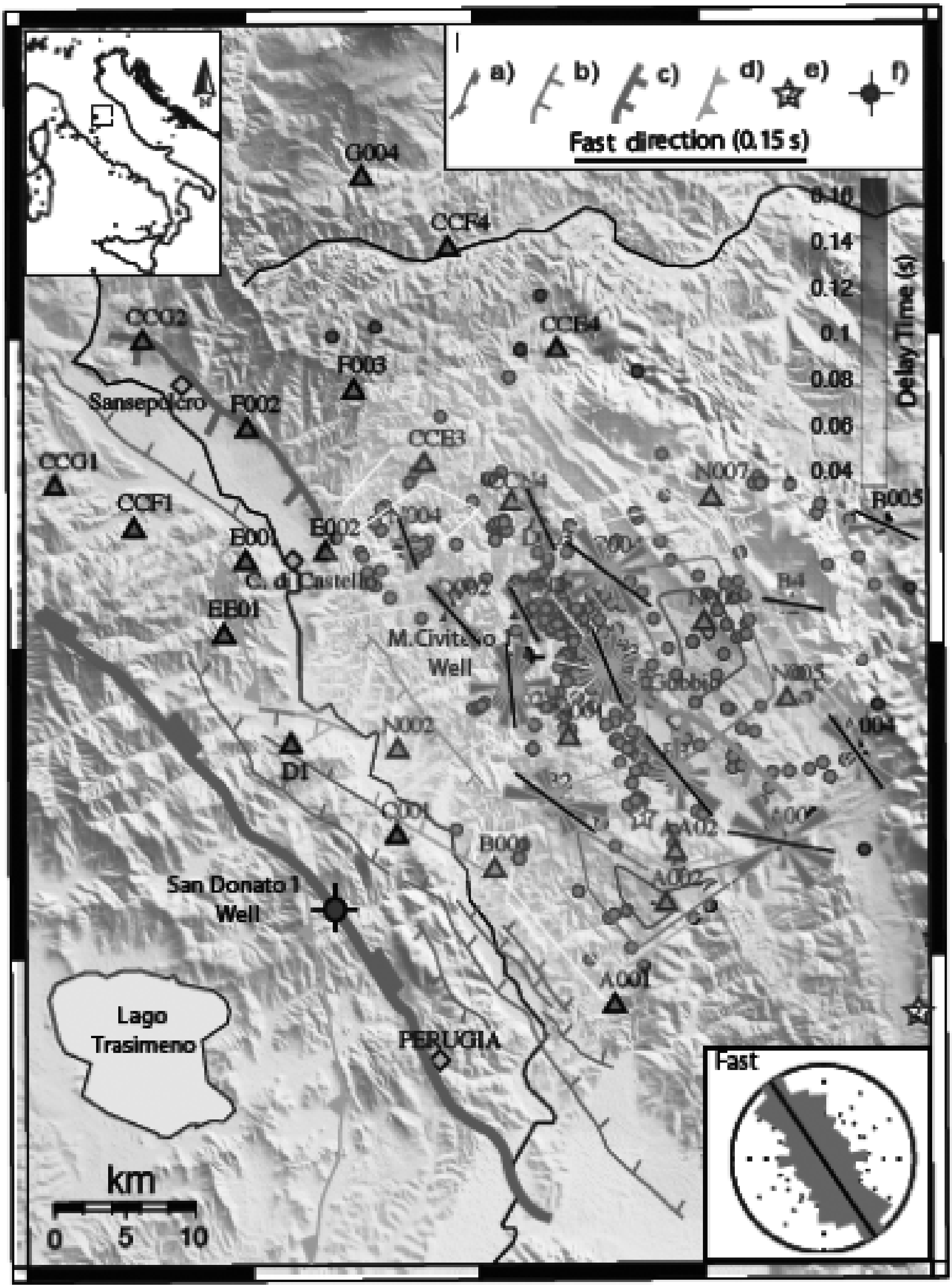

Fig. 4 – Rose diagrams of the fast polarization directions obtained with cross-correlation code; the size of the roses on the map is proportional to the number of measures and the black lines over the rose represent the mean fast direction which length is proportional to the mean, for each station, of delay time. The bottom inset shows the total fast directions at all stations. The mean fast directions are almost parallel to the main geological structures (Mariucci et al., 2008). The coloured area corresponds to the spatial variation of delay time, the grey circle are the selected earthquake locations (from Pastori Ph.D thesis).

moulding the seismicity at the southern termination of the western fault system, where we also found the highest values of delay time, might facilitate future ruptures along pre-existing zones of weakness.

2) Alto Tiberina Fault (ATF) area: I focused my attention in this area because the geometry of ATF is well known and earthquakes with hypocenters down to 30 km were recorded in the area so I might be able to characterize anisotropic behaviour of volume of rock above and below the ATF, by using anisotropic parameters and their variations. I would also compare the characteristics of earthquakes related to the ATF activity from the ones related to antithetic normal faults. These information are relevant for assessing seismic hazard and for accurately constraining possible ground shaking scenarios.

Fig. 4 shows the rose diagrams of the fast polarization directions (as in Fig. 3); the spatial variation of delay time is also reported (coloured background area).

In the total fast plot, lower inset, I observe a dominant direction NW-SE, as well as the major faults in the area and perpendicular to the Shmin of extensional stress field (Boncio & Lavecchia, 2000). Looking the spatial variation of the delay time I see an higher delay times below the stations N006 and A002, but these values are related to few measurements (4-5) connected to deep events, so if the delay times are normalized to length of ray-travel the values are more homogeneous with the others.

In detail the means of fast directions, at the selected 13 stations, are roughly parallel to the main geological structures, even if there are stations with rotated directions (i.e. C002, B4, B5, A003). If I consider only normalized delay times, I observe higher values, 0.01 s/km, located at stations C3 and C004, both situated in the footwall of the Gubbio Fault (GuF) and where most of the seismicity is located. These values suggest a percentage of anisotropy A=3% (A= Vs_{mean} *dtn*100, Wüste-

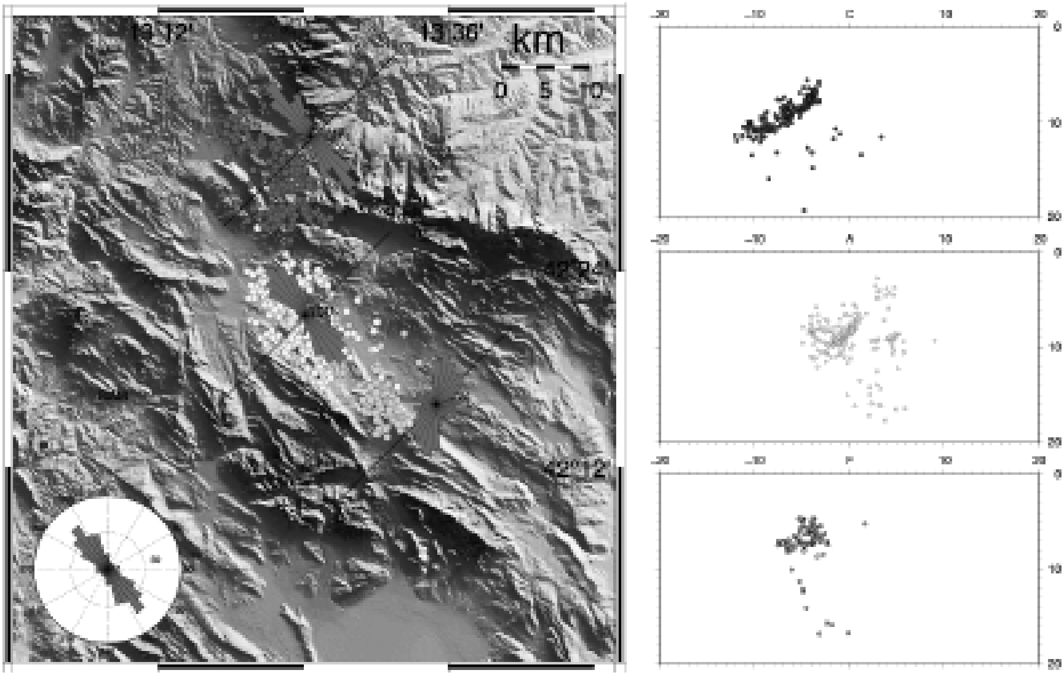

Fig. 5 – In map rose diagrams of the fast polarization directions are plotted, the size of the roses is proportional to the number of measures. The bottom inset shows the total fast directions at all stations. The mean fast directions are almost perpendicular to the active stress field, except to FAGN. The coloured circle corresponds to the selected earthquake locations recorded at each station (red: CAMP; yellow: AQU; green: FAGN; blue: FIAM) and also cross-section for each station are showed (from Pastori Ph.D thesis).

feld et al., 2010, Vs_{mean} is assumed 3.3 km/s, see Piccinini et al., 2003): this anisotropic volume seems to be related to the deep junction between GuF and ATF.

I also studied deep and temporal variations of anisotropic parameters, and I can conclude that 3D variations exist, probably related to overpressured fluids, and temporal changes in delay time e fast direction are to refers to state changes of fluid-filled stress-oriented micro-cracks.

3) On April 2009 the Mw=6.3 L'Aquila earthquake struck central Italy, so I decided to investigate this region of central Apennines. Some authors suggest that observations of shear-wave splitting at seismic stations above a seismic sequence can be used to monitor the build up of stress before earthquakes and the stress release as earthquakes occur (Gao & Crampin, 2004).

For this area I analysed the seismic sequence recorded at 4 stations belonging to RSNC (AQU, CAMP, FAGN and FIAM). Preliminary results Fig. 5) of shear wave splitting show a dominant fast orientation striking NW-SE, in agreement with the active stress field in the area. Furthermore I recognize the same situation at singular stations except FAGN. Delay time values are about 0.01 s/km, but higher values are recorded during the days around the mainshock, with a maximum of about 0.02 s/km. Looking at temporal variations of anisotropic parameters approaching the earthquake, I observe some variations of the seismic wave propagation properties. The elastic characteristics of rocks in the fault region underwent certainly a change in the days before the earthquake and these conditions remained for some days after the main event. From a posteriori observations, which show very scattered measurements, I might suppose that a complex sequence of dilatancy-diffusion processes took place in the rock volume and that fluids play a key role in the fault failure process. Variation of elastic and anisotropic parameters during L'Aquila seismic sequence indicates that a complex sequence of dilatancy and fluid diffusion processes affected the rock volume surrounding the nucleation area (*Lucente et al.*, in press). There are evidences for a major role played by fluids over the seismogenesis, in the only past comparable case in Italy (Chiarabba et al., 2009b; Miller et al., 2004), and over-pressurization in fault structures has been suggested as a primary trigger of normal faulting earthquakes (Sibson, 2000; Chiodini et al., 2004). The three studies suggest that anisotropic fast directions can be used to define the active stress field, finding a general consistence between fast direction and main stress indicators (focal mechanisms and borehole break-outs); and that the magnitude of delay times can be used to define the fracture field intensity, higher values being found in the volume where micro-seismicity occurs. The prevalent carbonatic nature of the seismogenic crust in Italy makes it a favourable candidate for the formation of fluids reservoir at depth: in fact active tectonics produces the fracture field and the presence of deep thrusts and low angle normal faults could act as traps (structural seal) where fluids may accumulate and generate reservoirs (Chiodini et al., 2004).

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