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Seismic measurements to reveal short-term variations in the elastic properties of the Earth crust

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ABSTRACT Since the late 1960s - early 1970s, seismologists started studying the elastic properties of the Earth crust looking for signals from the Earth interior indicating that a large earthquake is coming. To be useful for prediction a signal needs to: 1) occur before most large earthquakes and 2) occur only before large earthquakes. Up to now, no one has ever found such a signal, but since the beginning of the search, seismologists developed theories that included variations of the elastic property of the Earth crust prior to the occurrence of a large earthquake. The most popular is the theory of the dilatancy: when a rock is subject to stress, the rock grains are shifted generating micro-cracks, thus the rock itself increases its volume. Inside the fractured rock, fluid saturation and pore pressure play an important role in earthquake nucleation, by modulating the effective stress. Thus, measuring the variations of wave speed and of anisotropic parameter in time can be highly informative on how the stress leading to a major fault failure builds up. In 1980s and 1990s such kind of research on earthquake precursors slowed down and the priority was given to seismic hazard and ground motions studies, which are very important since these are the basis for the building codes in many countries. Today, we have dense and sophisticated seismic networks to measure wave-field characteristics: we archive continuous waveform data recorded at three components broad-band seismometers, we almost routinely obtain high-resolution earthquake locations. Therefore, we are ready to start to systematically look at seismic-wave propagation properties to possibly reveal short-term variations in the elastic properties of the Earth crust. One seismological quantity which, since the beginning, is recognized to be diagnostic of the level of fracturation and/or of the pore pressure in the rock, hence of its state of stress, is the ratio between the compressional (P-wave) and the shear (S-wave) seismic velocities: V_p/V_s. Variations of this ratio have been recently observed and measured during the preparatory phase of a major earthquake. In active fault areas and volcanoes, tectonic stress variation influences fracture field orientation and fluid migration processes, whose evolution with time can be monitored through the measurement of the anisotropic parameters. Through the study of S-waves anisotropy it is therefore potentially possible to measure the presence, migration and state of the fluid in the rock traveled by seismic waves, thus providing a valuable route to understand the seismogenic phenomena and their precursors. On the other hand, only in the very recent times with the availability of the continuous seismic records, many authors have shown how it is possible to estimate the relative variations in the wave speed through the analysis of the cross-correlation of the ambient seismic noise. In this paper we first analyze in detail these two seismological methods: shear wave splitting and seismic noise cross-correlation, presenting a short historical review, their theoretical bases, the problems, learning, limitations and perspectives. We, then, compare the main results in terms of temporal trends of the observables retrieved applying both methods to the Pollino area (southern Apennines, Italy) case study.

Key words: earthquake prediction, elastic wave properties, V_p/V_s.

1. Shear Wave Splitting: history and physical basis

Seismologists generally consider the Earth crust isotropic; in this hypothesis the velocity of a seismic wave is independent from its propagation or polarization direction. This assumption greatly simplifies mathematical treatments and is acceptable for most applications. In the real case, the crust is formed by minerals and almost all of them are anisotropic. Since the individual mineral grains composing a rock are usually randomly oriented, the crust will result isotropic at the scale of the wavelengths of typical seismic waves (metres to hundreds of metres). Nonetheless, there are many situations in which significant anisotropy occurs, and attempts to measure, understand and treat anisotropy mathematically are increasingly more common. Anisotropy is usually expressed trough the fastest and slowest velocities measured throughout a material.

In the Earth's crust, preferentially aligned joints or micro-cracks, layered bedding in sedimentary formations, or highly foliated metamorphic rocks may cause seismic anisotropy. Despite these several sources, only crustal anisotropy resulting from vertical aligned parallel cracks can be used to determine the state of stress in the crust, since such cracks (or micro-cracks) are preferentially aligned oriented in the direction of minimum compressive stress (Crampin *et al.*, 1984). In tectonically active areas, such as near faults and volcanoes, anisotropy can be used to look for changes in the preferred orientation of cracks that may indicate a variation of the stress field acting in the area.

Both seismic P- and S-waves may exhibit a (continuous) dependence of velocity upon the direction of propagation.

Anisotropic materials are said to be birefringent, where birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. Crystals with asymmetric crystal structures are often birefringent, as well as rocks under mechanical stress.

Hence, shear waves travelling through anisotropic mediums, naturally "split" into separate arrivals with these two polarizations. In seismology, this phenomenon is called Shear Wave Splitting (hereinafter SWS).

Generally, when a seismic shear wave travels into an anisotropic medium, its energy is split into two components with orthogonal polarization direction that travel at different velocities. The polarization direction of the fastest wave is defined as fast direction, ϕ, and the lag of the slower wave is the delay time, δt; if the S-wave is originally polarized in the fast or slow direction it does not split, or if the medium is isotropic we get a null measurement, in this case we can identify the null direction (which is either the fast or the slow direction of the anisotropic medium).

The main causes of the crustal anisotropies could be summarized in two different sources: i) stress-aligned crack-induced anisotropy (Crampin, 1978, 2004; Babuska and Cara, 1991; Savage, 1999; Bonness and Zoback, 2004) and ii) structural alignments due to rock or mineral fabric (e.g., Brocher and Christensen, 1990).

In the first hypothesis (i), ϕ is typically oriented parallel to the direction of maximum horizontal stress (S_{Hmax}), as suggested by the Extensive-Dilatancy Anisotropy model [EDA: Crampin (1978) and (1999)] and δt is a measure of the intensity and/or thickness of the fracture field. Such micro-cracks are highly compliant and aligned by the stress field into typically parallel vertical orientations. Therefore, by estimating the seismic SWS it is also possible to study the spatio-temporal changes in the direction of open micro-fractures as well as the state and/or amount of fluid present in the fractures in response to changes in the local active stress field. This type of study is well interpreted by the model Anisotropic Poro-Elasticity (APE), suggested by Zatsepin and Crampin (1997). Sometimes the correspondence between fast polarization directions and stress indicators has been observed in different regions of the world. Among the others, in Bhuj, western India (Padhy and Crampin, 2006), in the Coso geothermal field, eastern California (Vlachovic *et al*., 2003), in the Reggio Emilia region, northern Italy (Margheriti *et al*., 2006), in the Umbria-Marche region, central Italy, (Piccinini *et al*., 2006; De Lorenzo and Trabace, 2011), in the Val d'Agri basin, southern Italy (Pastori *et al*., 2009, 2012).

On the other hand, if the anisotropy is caused by structural alignments (ii), ϕ is parallel to the strike of the fracture or the fast axis of the anisotropic minerals and is not related to the active stress field whereas δt measures the fabric strength (Zinke and Zoback, 2000). Peng and Ben-Zion (2004) and Cochran *et al*. (2003) support this interpretation along the North Anatolian Fault and in California.

1.1. Learning, perspectives and limitations

It is a long-established assumption in geophysics that earthquakes are inherently unpredictable (Bak and Tang, 1989; Geller *et al*., 1997). As a result of such assumptions, using SWS to monitor stress-accumulation by changes in micro-crack geometry in order to "stress-forecast" earthquakes, although apparently successful (Crampin *et al*., 2008), is controversial and difficult to get accepted. The technique uses seismic SWS to monitor the stress-induced changes of the micro-crack geometry and estimates the approach of fracture-criticality (and therefore earthquakes) at possibly substantial distances from the impending source zones (Crampin and Peacock, 2005, 2008).

The study of the foreshock sequences, i.e. for the L'Aquila earthquake, has shown that the physical properties of rocks surrounding the nucleation zone of the main shock have undergone major changes during the preparatory phase of the earthquake, in consequence of the evolution of the stress state in the fault area. Seismological evidence shows that the physical processes that lead to instability of a seismogenic fault are promoted by both the presence of fluids and their physical state. In particular, primary role is played by fluid migration in time and space and by the presence of fluid overpressure (i.e., Antonioli *et al*., 2005). The presence of fluids is decisive in promoting a change of some elastic parameters as the ratio V_p/V_s and the anisotropic parameters (Lucente *et al.*, 2010). The spatio-temporal variations of elastic parameters describe very well the complex process of diffusion/migration of fluids in the rock volume (Piccinini *et al.*, 2006; Pastori *et al.*, 2009, 2012). In a classic model of expansion, the variation of these parameters is related to the migration of fluids in a medium in which the seismogenic fault acts first as a seal between two non-communicating volumes, causing the change of the state of the fluid and driving to the overpressure. This process leads to instability of the fault zone, up to the nucleation of a strong earthquake (Nur, 1972; Scholz *et al.*, 1973). Through the study of the stress induced anisotropy it seems, therefore, possible to acquire information on the presence, the migration, and state of the fluids in the focal volume, providing a valuable route to understanding the seismogenic phenomena and their precursors (Crampin and Gao, 2010).

Several difficulties with shear waves splitting interpretation are described in case of earthquakes (Crampin and Lovell, 1991). Because of the relative steepness needed for the incidence wave to make an acute angle with (typically) sub-vertical features, the recording site has to be located within a so-called "Shear Wave Window" (hereinafter SWW). Of course multiple splitting of shear waves makes time delay and polarization azimuth estimation more difficult. Furthermore, it was observed that, because shear-wave delay time and polarization change rapidly between neighboring seismic stations, and because the delay time does not uniformly increase with the length of the ray path, the anisotropy is necessary confined to the near-surface. It is difficult to evaluate the depth-range, because observed shear-wave delay time is the cumulative sum of the delay times along the whole ray path (assuming similar anisotropic orientation, as is often the case). Any observed delay time may be caused either by stronger anisotropy at the end of the ray path, or by uniform but weaker anisotropy along the whole length of the ray path.

Shear wave polarization is heavily scattered and, consequently, variations in delay times are statistically valid only when computed as averages from large data sets (Peacock *et al.*, 1988).

2. Ambient noise cross-correlation: a bunch of history

Probably the first pioneering work on this topic has been presented by Aki (1957), who defined a procedure to exploit the seismic noise (that he calls microtremors) to retrieve, from its auto-correlation function, the dispersion curve of the surface waves and the S-wave velocities for different depths in the subsurface of a seismic station. Claerbout (1968) proposed to use the auto-correlation of the ambient noise record to derive the reflection seismic response and hence get an image of the Earth interior (acoustic daylight imaging). Then, he formulated his conjecture: "by cross-correlating noise traces recorded at two locations on the surface, we can construct the wave field that would be recorded at one of the locations if there was a source in the other". Rickett and Claerbout (1999) presented some practical use of this statement in helioseismology and reservoir monitoring. Major improvements on this topic were conducted in acoustics by Lobkis and Weaver (2001), who demonstrated how the cross-correlation of thermal noise recordings at two ultrasonic transducers (MHz) may provide the Green's function between the two instrument locations. This amazing result, together with the instrumental improvement of the last years (which could ensure a continuous recording at broad-band frequencies) marked the start of a renewal of this subject, which found many different applications in seismology: from the passive seismic imaging (Shapiro *et al*., 2005), to the seismic exploration (Draganov *et al*., 2007), the oceanography (Roux *et al*., 2004), and up to the monitoring of the crustal velocity variations in volcanic areas as well as in fault zones (Brenguier *et al*., 2008a, 2008b; Sens-Schonfelder and Wegler, 2006).

2.1. Physical model

Lobkis and Weaver (2001) proved through a laboratory experiment that the direct Green's function is present in the correlations of the diffuse field within a closed cavity and can be recovered from the cross-correlation of the signal recordings at the two points. This can be retrieved also from the cavity equation by Draeger and Fink (1999). And thanks to Derode *et al*. (2003), these results have been demonstrated to be valid also in an open medium, under the condition that several well distributed sources are operating instead of a single one. This assumption may be considered to stand in a multiple scattering medium, based on the reciprocity, time-reversal, and Helmotz-Kirchoff theorem, so that if the distribution of sources (and scatterers, which act as secondary sources) can form a time-reversal device, the Green's function can be recovered by summing the contributions of all sources. Campillo and Paul (2003) made a first attempt to exploit this property in seismology by cross-correlating seismic codas [i.e., multiple scattering waves from the heterogeneities of the Earth: Aki and Chouet (1975)]. Then, Shapiro and Campillo (2004) transferred the same technique to seismic noise recordings at two locations, finding that their cross-correlation is proportional to the Green's function between these two points. This means that even though it does not correspond to the exact Green's function, it may be used to retrieve the phase arrival times. The authors compared the recovered signal with dispersion measurements made by ballistic waves and they found a perfect agreement for Rayleigh waves. Seismic noise is mostly due to the oceanic microseisms. Compared to acoustic laboratory experiments, the noise sources are not uniformly distributed on the surface (Stehly *et al*., 2006), and they show seasonal variations (Landes *et al*., 2010), but we can randomize them by taking into account long time series of recordings, as well as by scattering from Earth heterogeneities which ensures the energy equipartition (Campillo, 2006; Sanchez-Sesma and Campillo, 2006; Larose *et al*., 2008).

For monitoring the cross-correlation temporal changes, it is not necessary to reconstruct the exact Green's function, the only requirement is a relative stability of the noise sources (Hadziioannou *et al*., 2009). And even if the sources are non-isotropically distributed, their influence would affect more the ballistic than the coda waves, thanks to the role of scattering, which mitigates the errors due to the source distribution (Froment *et al*., 2010).

2.2. Good practice

The monitoring of velocity variations through seismic noise cross-correlation is composed by 3 phases: 1) pre-processing; 2) cross-correlating; 3) measuring relative velocity variations.

1) The noise recordings have to be pre-processed in order to remove all transient phenomena like spikes, earthquakes, and all kinds of signals produced by local and temporary sources. To do so, it is a good practice to normalize both in time and frequency domains (Bensen *et al*., 2007; Brenguier *et al*., 2008b). Among the time domain normalization, we mention the 1-bit which is a quite strong operation; and the clipping or the running absolute

mean, which may be used as described in Sabra *et al.* (2005) and Bensen *et al.* (2007). To normalize in the spectral domain the simplest way is to apply a bandpass filter around the frequencies of interest (Sens-Schonfelder and Wegler, 2006). Another technique is the whitening, which acts on the spectral amplitude by putting zeros out of the band of frequency, while inside all amplitudes are flattened to 1 (Bensen *et al.*, 2007; Brenguier *et al.*, 2008b). Both of them can be used depending on the data, or on the personal choice of the user (Brenguier *et al.*, 2008b).

2) After the pre-processing phase the cross-correlation can start. For monitoring purposes it is necessary to define a reference function (indicative of the background state) to be compared with multiple current functions related to different times. The background state may be easily defined by stacking the cross-correlations over the entire period of time under study. The current functions have to satisfy a good similarity with the reference but still they have to show some peculiarities proper to the shorter period of time they refer to. Therefore, there is a trade off between convergence to the reference and time resolution of the measurements. One way to find a good stacking value is to evaluate how the correlation coefficient between currents and reference varies with the stacking time (Duputel *et al.*, 2009; Zaccarelli *et al.*, 2011).
3) Estimates of the relative velocity variations may act in the spectral or the time domains. In the first case, Brenguier *et al.* (2008a, 2008b) transposed the Multi Window Cross-Spectral (MWCS) analysis by Poupinet *et al.* (1984) from doublets to noise correlations, while Sens-Schonfelder and Wegler (2006) adopted a time domain approach, known now as the stretching technique. Both approaches are valid tools to recover the relative velocity variations and present pros and cons (see: Hadziioannou *et al.*, 2009). MWCS is faster in terms of computation time, more versatile as it can retrieve also possible time shift between station clocks (Stehly *et al.*, 2007), but it depends on many parameters (Clarke *et al.*, 2011). The stretching technique, instead, yields more precise measurements, has less parameters to be set, but it assumes that a homogeneous change of the crustal properties has occurred, and it is a little bit more time consuming. In any case, it is important to apply the chosen technique to windowed correlation functions, in order to cut off the first and last time lags where the signal to noise ratio is less than 1, and also the central part of the correlations (from 0 to ± the surface wave arrival time) where the signal is influenced by changes in the noise sources (Froment *et al.*, 2010).

2.3. Open questions

The main problem in dealing with velocity variations is that their interpretation in terms of crustal changes is not unique. Surface wave velocity may decrease because of an increasing amount of fluid (Sens-Schonfelder and Wegler, 2006), or due to stress relaxation (Brenguier *et al.*, 2008a), or dilation (Brenguier *et al.*, 2008b). In this framework it is important to compare the measured velocity changes with other geophysical or geochemical time series, like GPS measurements (Minato *et al.*, 2012; Ueno *et al.*, 2012), in order to obtain a more constrained interpretation.

Another problem regards the possibility to translate these measurements in terms of stress changes. Chen *et al.* (2010) made a first attempt towards the quantification of the spatial distribution of the velocity variations compared to strain changes during the Wenchuan earthquake.

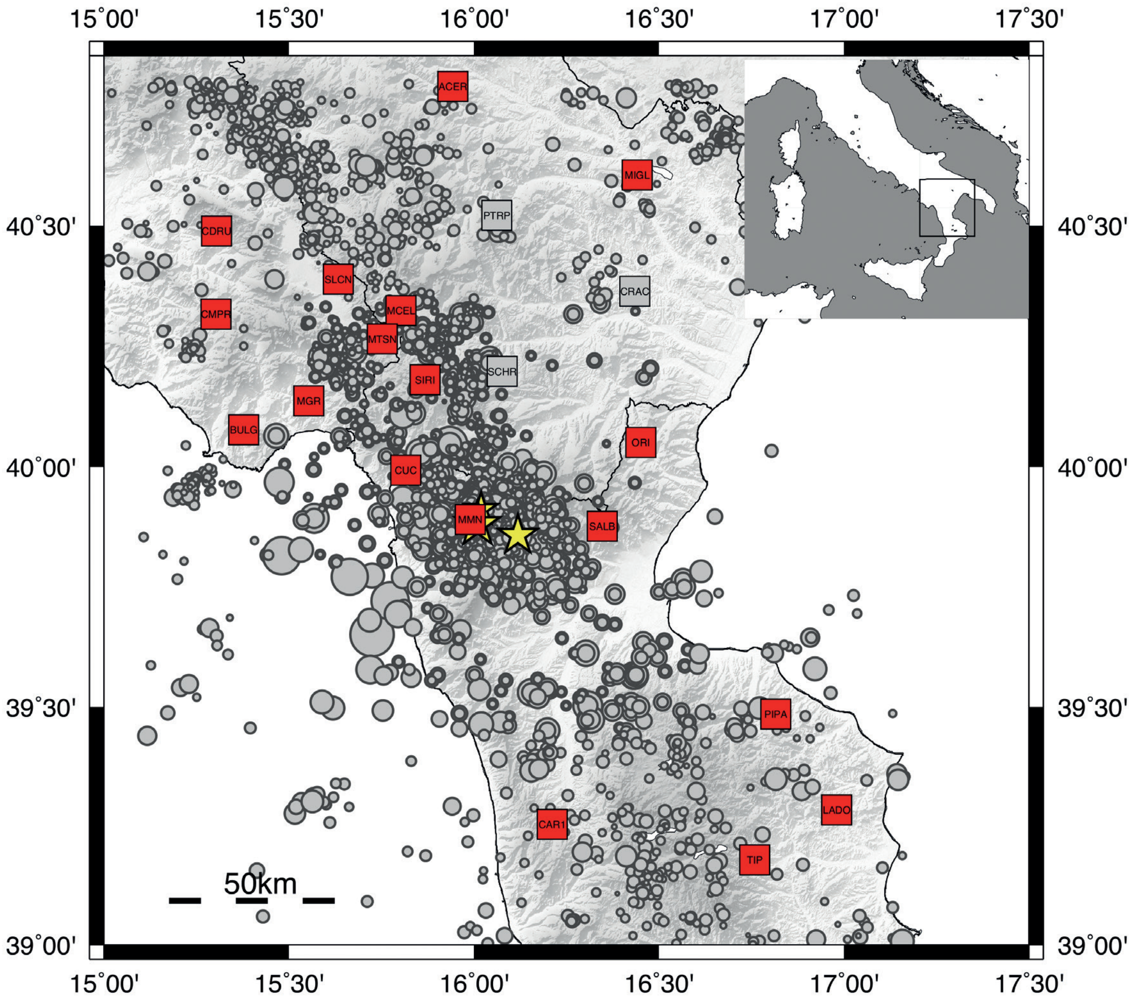

Fig. 1 - Map of the southern Apennines, and of the Pollino seismic activity (gray circles with radius proportional to the magnitude of the event). The stations of the national seismic network are indicated by the squares, in red those taken into account (broad-band), the three gray stations are short-period and were excluded from the analysis. The yellow stars locate the three main events (2 coincide with the position of MMN station): M_L 3.6 of 23/11/2011; M_L 4.3 of 28/5/2012; M_L 5.0 of 25/10/2012.

But it was a rough estimate, not well constrained. The relative velocity variations obtained from passive image interferometry depend on several parameters chosen during the computations (like the frequency range which determines the penetration depth of the surface waves, hence the volume sampled by the cross-correlation analysis), as well as the number of stations, their inter distances, their orientation with respect to the noise sources (Zaccarelli *et al.*, 2011).

A new and intriguing aspect that is emerging from the analysis of the correlation tensor (correlations between all 3 components of a couple of stations) is the crustal anisotropy with a special regard to its main direction, which may be (or not) related to the surface wave polarization (Durand *et al.*, 2012). Unfortunately the behaviour of the surface waves in an anisotropic medium is not well modelled as it is for the S-waves.

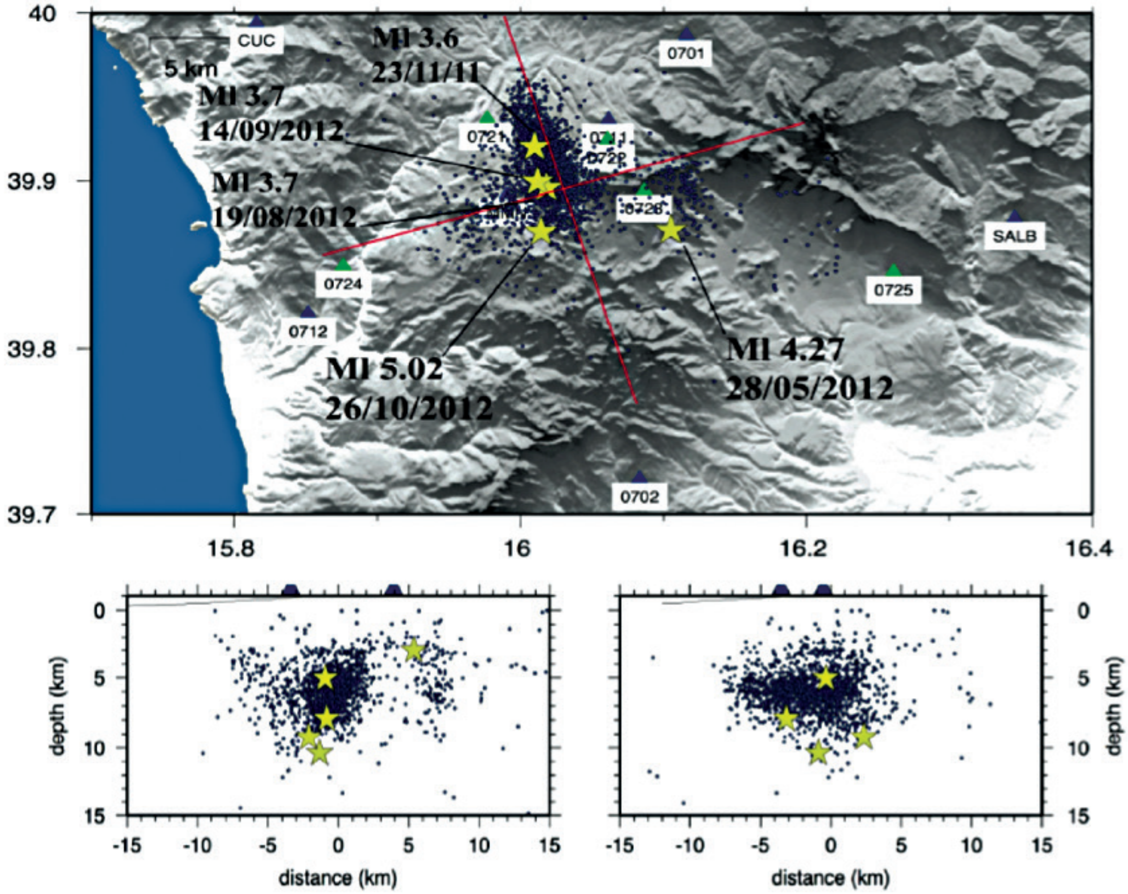

Fig. 2 - Locations and cross-sections of the earthquakes belonging to the seismic sequence of Pollino in the period between January 2010 and March 2013. The yellow stars represent the main events, the blue triangles represent the stations of the National Seismic Network (MMN is partially covered by epicentres of earthquakes). The green triangles represent the temporary seismic stations.

3. Short-medium-term variations of seismic waves velocities: time series of seismic observables from Pollino case study area (southern Apennines, Italy)

In the frame of guidelines defined in the general agreement DPC-INGV for the period 2012-2021, the aim of the DPC-S3 project is to develop procedures for short-term forecasting of destructive earthquakes. In particular, the request is focused on two areas of maximum interest for DPC (central Po Plain in northern Italy and Pollino in southern Italy), where two damaging seismic events with magnitude lower than 6 took place just before the starting of the project.

Our analysis is focused on the Pollino area. This region is affected since 2010 by a seismic sequence with alternating phases of intense and scarce seismic activity, with two events of magnitude greater than four (M_L=4.3 and a M_L=5.0) occurred in recent years (respectively in May and October 2012). For more detail about the spatio-temporal seismicity evolution see Margheriti *et al*. (2013).

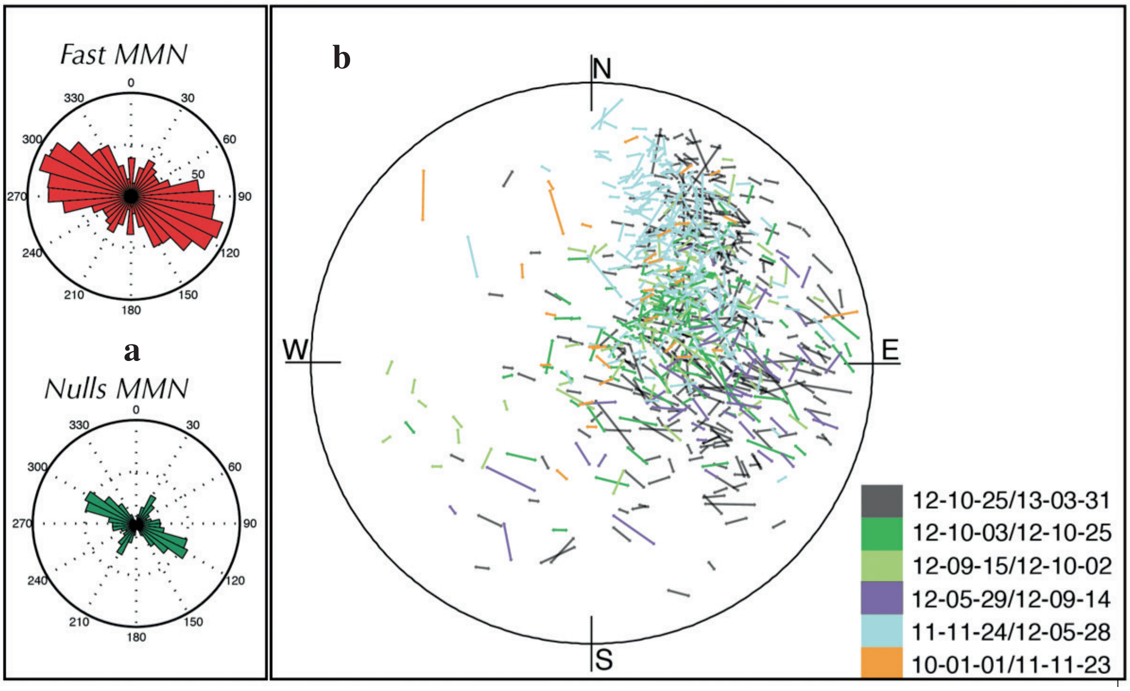

Fig. 3 – MMN station: cumulative fast and null directions (a) and stereographic projection of the anisotropic parameters to the station (b).

3.1. Anisotropy of S-waves propagation

A detailed analysis of seismicity was performed for the study of the propagation of seismic waves in the upper crust retrieving seismic anisotropy parameters from the seismicity occurred in the Pollino area. We have produced the time series of the splitting parameters for the Mormanno seismic station (MMN; see Fig. 1) analyzing their variation in space and time. These investigations, taking also into account the geological and structural knowledge of the area, allowed us to define detailed properties of the fracturing field in the upper crust and of the active stress field in the seismogenic volume.

We analyzed seismic events recorded in the last 3 years at the MMN seismic station and located by the National Seismic Network in the surroundings of the station. We collect a data set of about 5,000 events occurred between January 2010 and March 2013.

To gain a better estimate of the spatial distribution of the anisotropic parameters we also analyzed recordings of the stations of the temporary network installed in the area after the occurrence of the M_L=5.0 earthquake of October 25, 2012. Fig. 2 shows the station MMN and the epicentres of earthquakes for the details of the temporary network, refer to Margheriti *et al.* (2013).

We have selected the SWS parameters of those events with δt>0.02 seconds, cross-correlation coefficient between fast and slow greater than 0.7 and incidence angle of the waves at the station smaller than 45° (geometrical angle). This last condition implies that for the station MMN nearly all the seismic events belonging to the easternmost cluster are excluded. The events for which the analysis provides anisotropic parameters that met these conditions are 859.

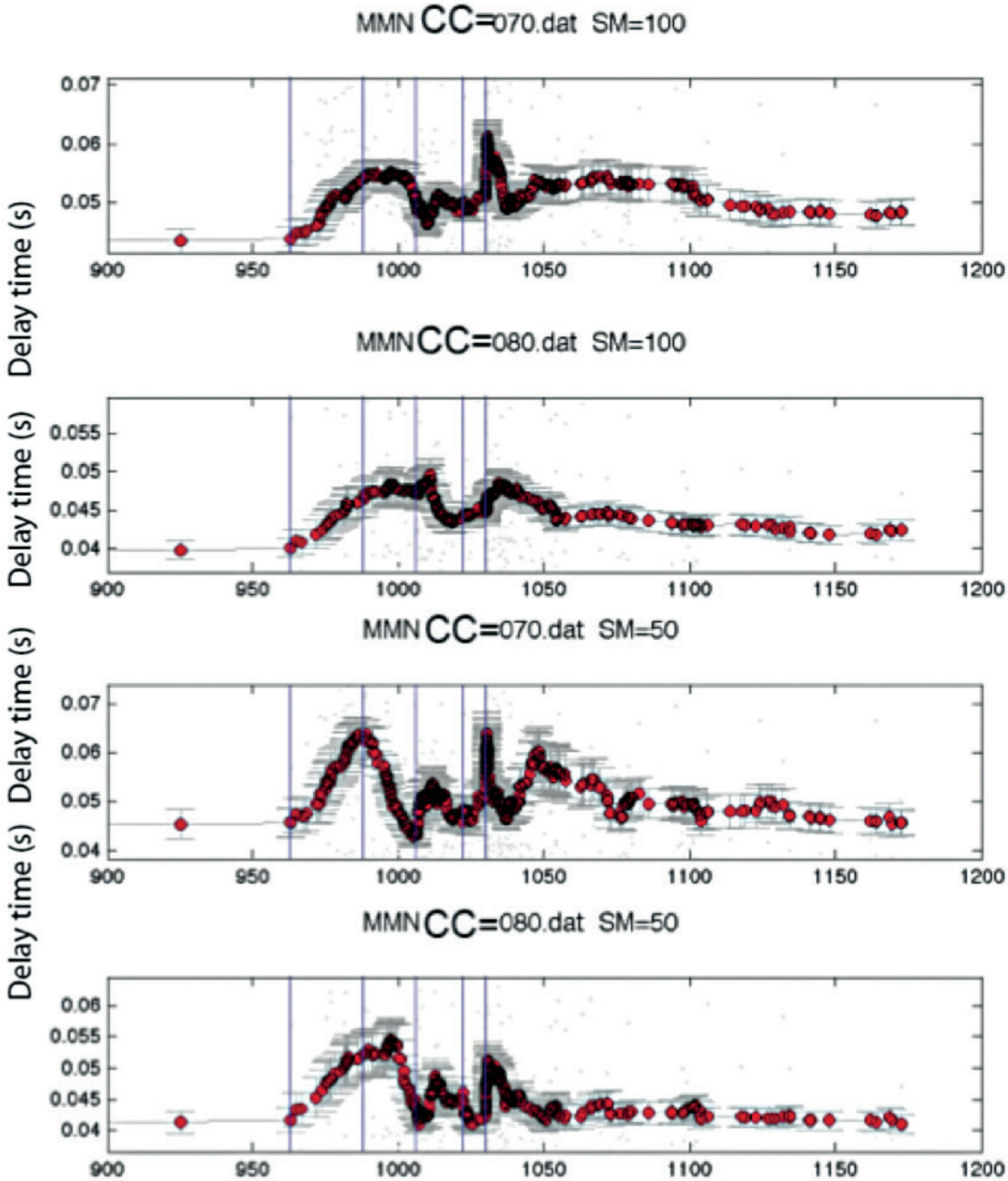

Fig. 4 - Averaged delay time trends trough time. The abscissa indicates the number of the days since January 1, 2010. Gray dots in the background represent the individual measures, the red circles are the moving averages calculated on a SM=50 or SM=100 points (SM represents the number of the averaged measures) by using cross-correlation coefficient greater than 0.7 (cc = 0.7) or 0.8 (CC = 0.8).

In Fig. 3b the anisotropic parameters are shown using a stereographic projection: each segment is oriented along the fast direction and its length is proportional to the delay time. We divided the data set into 5 periods, separated by the occurrence of the 2012 strongest events (May 28, 2012 M_L=4.3; September 14, 2012 M_L=3.7; October 1, 2012 M_L=3.6; October 25, 2012 M_L=5.0). The centre of stereographic projection represents the station MMN while the position of the bar represents the back-azimuth of the event and the distance from the centre is a function of the angle of incidence geometry (the outer circle represent 45°).

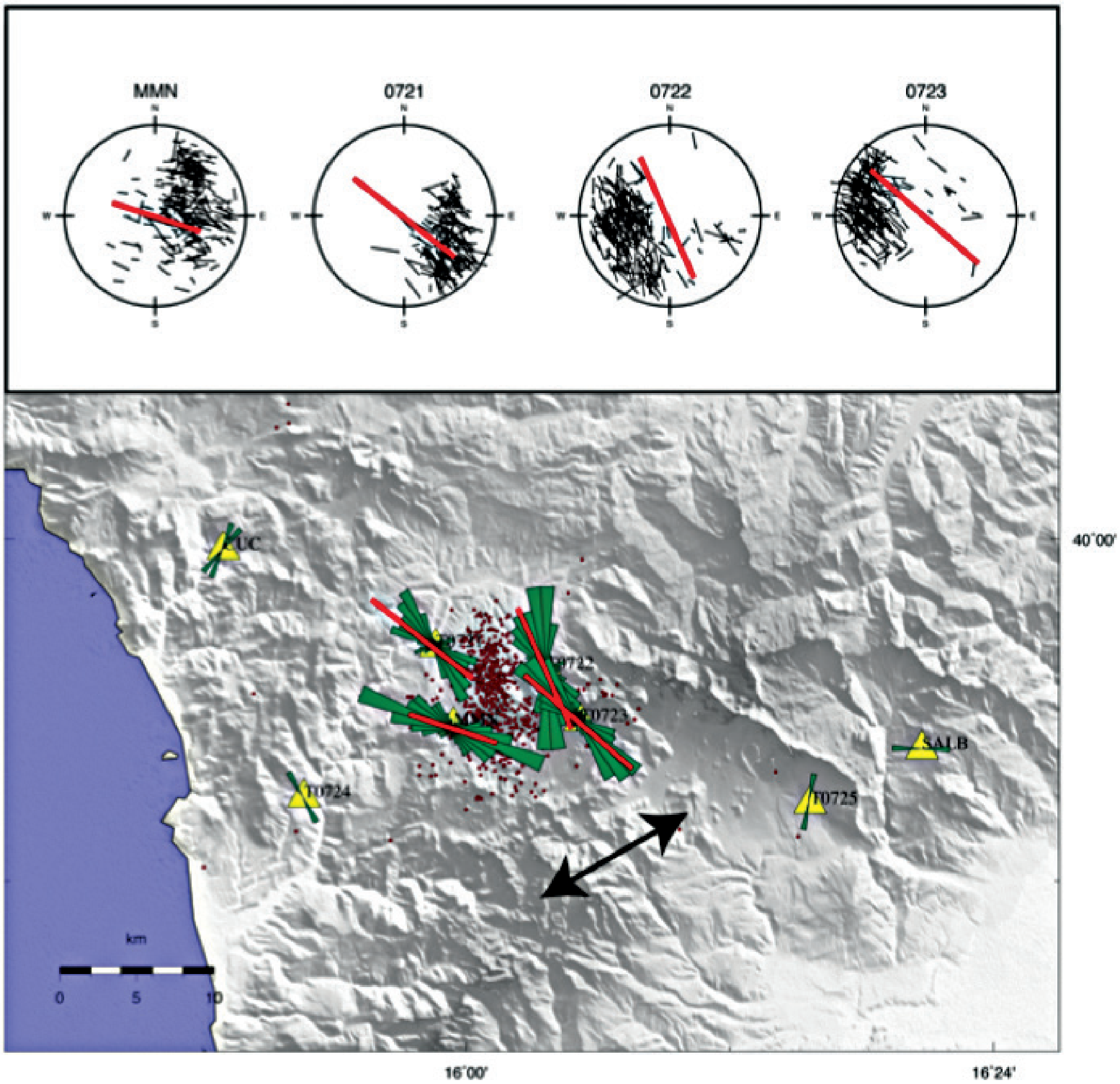

Fig. 5 - Spatial trend of the anisotropic parameters. The upper part of the figure shows stereographic diagrams of the measurements at stations having a significant number of results. At the bottom, in the map of the Pollino area, results are presented as average fast direction and delay times (red bar orientation and length), frequency plots of the fast directions. The black arrow indicates the direction of extension S_{hmin} from GPS data and earthquakes moment tensors.

The temporal trend of the delay time, averaged over time for the period 2012 and early 2013 is shown in Fig. 4. The vertical bars represent time occurrence of 5 events with local magnitude greater than 3.5 (same events of Fig. 3b). The grey dots are the individual measurements; the red circles represent averaged values. The four panels refer to two cross-correlation thresholds (greater than 0.7 or greater than 0.8) and two different lengths of averaged windows (SM represents the number of the averaged measures, SM=50 or SM=100). The averaged trends are obtained using the running average algorithm and an overlap length of SM-1 points.

Although time series obtained show several fluctuations, these are not easily classified as anomalies or seismic precursors although in the past similar fluctuations were attributed to a successfully earthquake forecast example in Iceland (Crampin *et al.*, 1999). On the other hand,

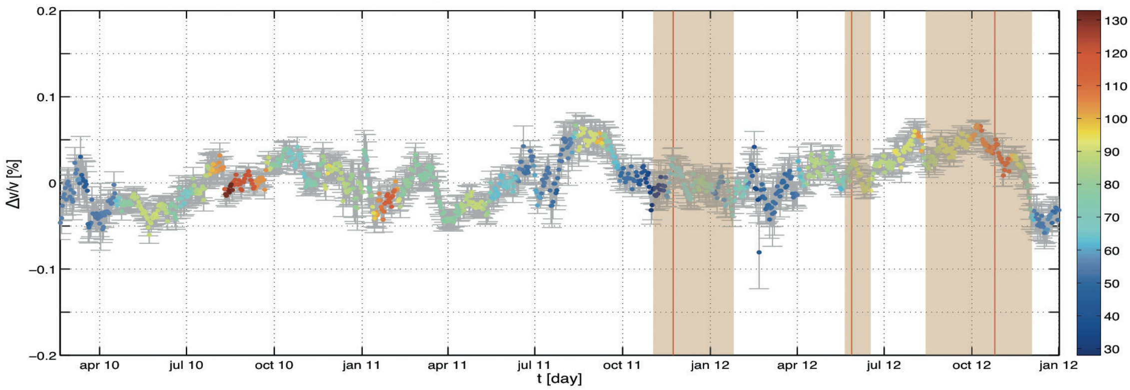

Fig. 6 - Relative seismic velocity variations (percentage) obtained by the analysis of the ambient seismic noise cross-correlations of the 18 stations considered (153 pairs of stations) in the Pollino region (Fig. 1). Each point together with its error bar represent the result obtained for the 50 previous days. The color scale indicates the number of pairs involved in estimating every single measurement: warm colors are for values obtained on a large number of station pairs and correspond to more stable results.

the previous pattern represents one of the longer anisotropic time series ever obtained and therefore it is an important step to identify a proper case-study useful to understand whether this methodology can provide a glimpse in the identification of precursory phenomena of moderate to strong earthquakes.

To understand how the anisotropic parameters vary spatially (Fig. 5) we analysed waveforms recorded at stations installed after the occurrence of the earthquake of October 25, 2012. The red bars in the centre of the stereographic projection represent the average direction of the fast measurements at the stations. The average values of δt range from 0.05 seconds at MMN to 0.08 seconds at T0723 station. Fast directions range from 108°N at MMN to 156°N at T0722.
The green rose diagrams on the map of Fig. 5 are frequency plots representing how fast directions trending NW-SE are prevalent at all stations with a significant number of measures. The black arrow in the figure represents the direction of extension (S_{hmin}) in the area (from GPS data and moment tensor). Average fast directions at the stations are almost perpendicular to the S_{hmin}, as it would be expected for a fracture field oriented in the Apenninic direction and kept open by the active stress field. In this scenario MMN station shows a rotation in the average direction towards WNW-ESE.

3.2. Seismic noise analysis

The goal of this work is to define the temporal evolution of relative velocity variations through the ambient seismic noise cross-correlation analysis, in the southern Apennines (Pollino), affected by the recent seismic sequences. In particular, we would like to relate the relative velocity changes with the seismic temporal evolution, focusing on the early phases, i.e., prior to the start of the sequences, with the ultimate goal to identify any possible precursory signals. The application to the Pollino sequence, instead, represents a breakthrough in the analysis of seismic swarms (low-energy activity which is concentrated in time and space). The intent is to explore the resolution capability of this technique in case of small changes in the stress field, and to compare the results with those obtained for the classic (foreshock-) mainshock-aftershock sequences so far studied.

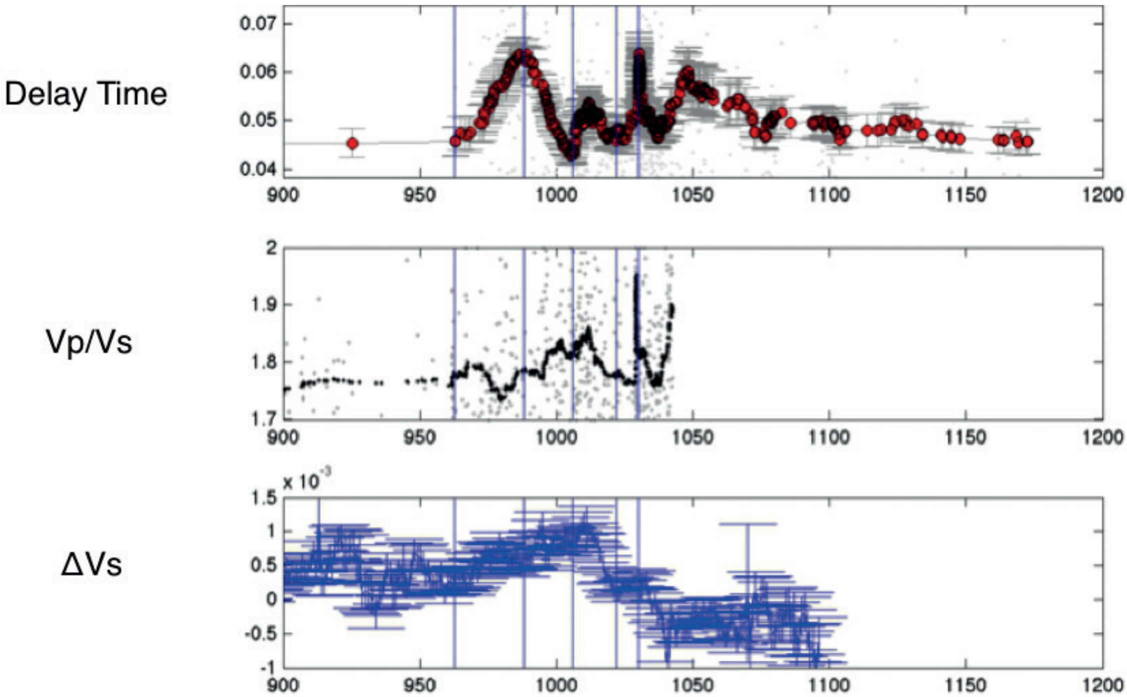

Fig. 7 - Averaged trends, in the period late 2012 to early 2013 (starting point is the Julian day 900 from January 1, 2010), of the parameters studied using the two methodologies in the Pollino area, compared with the trend of the Vp/Vs in the same area.

We took data from the continuous recording of those permanent stations of the National Seismic Network, which were installed close to the area under study. We considered the recordings from 18 stations included in a 100-km radius from Mormanno (the village in the middle of the sequence), along a time period of 3 years from January 2010 to December 2012 (Fig. 1).

We do not provide any interpretation of the results in terms of anomalies, due to the fact that the peaks falling outside of the measurement errors are few and not easily ascribable to seismic activity time changes as by comparison of the temporal trends. These results have to be considered as only preliminary (also given the limited time available), to be validated and tested, but they open the discussion on the usefulness of the technique on these types of applications.

It is noteworthy, in fact, that within this project, we applied for the first time the seismic noise cross-correlation analysis on an area affected by earthquake swarms.

Seismic swarms (low-energy seismicity concentrated in time and space) may not be able to generate variations of the crustal parameters such as to be detectable with this technique which average the results over large volumes of sampled crust: the stations in this area are rather scattered, perhaps it would be more appropriate to analyze this kind of low-energy seismicity through more dense networks of stations. It is intriguing that even an M_L 5 did not generate a significant crustal damaging: in Fig. 6 a velocity decrease begins before the occurrence of the event (indicated by the last red vertical line), and does not seem significantly different from other decreasing trends that can be observed throughout the whole time period. It may be necessary a stronger data manipulation as the use of adaptive filters or other techniques to increase the cross-correlation convergence. The velocity variations may be hidden by possible noise source changes: the geometry of the stations necessarily follows the trend of the geographic region, and the majority of the station pairs are oriented along the NW-SE axis. This feature does not ensure an adequate azimuthal coverage. The problem may be faced and overcome through a focused analysis on the noise source temporal variations.

4. Conclusions

In this paper we review two geophysical methods able to detect short-terms variations of elastic properties in the Earth crust. The former deal with the SWS detection and its spatio-temporal fluctuation; the latter with the relative variations of seismic velocity based on ambient noise cross-correlation analysis. For both of them we debate their physical basis, perspectives and limitations.

These methodologies have been applied to the Pollino area (southern Apennines) where since November 2011 a seismic sequence is ongoing (max magnitude 5.0). We obtained two time series both of which show sharp variations approaching the M5 seismic event. To have an insight on the meaning of the parameter fluctuations over time we compared the time series obtained to V_p/V_s trend evaluated applying modified-Wadati technique over seismic sequence occurred in the time period spanning between the second half of 2012 and the beginning of 2013. These results are summarized in Fig. 7: we analysed the fluctuations of the time series between June 2012 and April 2013 where a major oscillation in both the delay time and the V_p/V_s can be noted. This is positively correlated with a decrease in ΔVs, already started at least 20 days before the event.

In conclusion, these investigations obtained by merging and comparing each methodology provide a more complete view of changes in crustal behaviours, defining in detail the characteristics of the fractured medium and the active stress field in the Pollino area.

We strongly believe that physical changes of material properties governing seismicity evolution over a fault system, such as SWS, seismic noise cross-correlation analysis or V_p/V_s ratios, deserve in-depth systematic investigations. To do this, we need to build up the necessary statistics through the compilation of a reference catalogue where such properties variation in time obtained by independent techniques are systematically analyzed and compared.

Results here presented have to be considered as only preliminary (also given the limited time available), to be validated and tested, but they open the discussion on the usefulness of the merged techniques on these types of applications.

We deem that these findings can help in getting new insights in the identification of precursory phenomena of strong earthquakes but further investigations are needed to better understand their statistical significance and what is the physical phenomenon that produces them.

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