SPATIO-TEMPORAL MONITORING OF SEISMIC WAVE VELOCITIES IN THE UPPER CRUST

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Introduction. Variations in seismic velocity, ratio of P -to S-wave speed (Vp/Vs), and seismic anisotropy were heralded in the 1970s and 1980s as proxies to examine the buildup of stress preceding large earthquakes. The idea is that high pressures could cause rocks to "dilate," changing the elastic properties of the crust by increasing crack numbers and/or dimensions, thus affecting the seismic waves propagation velocities. Rock dilatancy causes the rock to undersaturate, which will strongly reduce Vp. but will have little effect on Vs. resulting in the drop of the Vp/Vs ratio (Sholz *et al.*, 1973). Furthermore, the formation and propagation of cracks within the rock affects its anisotropic characteristic.

Several studies reported changes between properties recorded before and after mainshock occurrences. A recent example is provided by Lucente *et al.* (2010), who reported some clear variations in the seismic wave propagation characteristics approaching a mainshock: the elastic properties of the crustal rocks in the fault region underwent a sharp change about a week before the 6 April 2009, Mw 6.3 l'Aquila earthquake. Back in the seventies, it was hoped that these kinds of studies would allow earthquake prediction to be "just around the corner" (Savage, 2010). Over the subsequent decades, this "corner" is progressively drifted away, nevertheless for seismologists, the understanding of the processes that preside over the earthquakes nucleation and the mechanics of faulting, represents a big step toward the ability to predict earthquakes.

In this regard, the integration of the monitoring of the crustal proprieties variations into middle and long term forecasting tools could help in the definition of priority areas where risk reduction interventions are more urgent, with a consequent improvement in the emergency preparedness.

In the framework of the guidelines defined in the general agreement DPC-INGV for the period 2012-2022, we formed a Research Unit (UR) with the aim to study the seismic property changes occurring around the fault zones to better understand the physics of the earthquake. Our final goal is to eventually provide effective, practical tools to be applied for monitoring purposes and decision making. The UR includes two Working Packages (WP) that will investigate the variation of seismic wave velocities through different approaches. The first WP will analyze the ambient seismic noise cross-correlations to estimate the relative velocity variations occurred in the Po Plain before and after the 2012 seismic sequence, and in the Pollino region (southern Apennines) shaken by multiple seismic sequences during the last years. The second WP will focus on the shear wave seismic anisotropy temporal fluctuation, through the application of a systematic study to all events recorded during the ongoing seismic sequence in the Pollino area.

Methodology. WP1: The cross-correlation of two seismic scattered wave fields (coda or noise) recorded at two stations corresponds to the response of the medium recorded at one of the two stations as if an impulsive source was located at the other station (Campillo, 2006). The exact reconstruction of the Green function (i.e. the impulse response of the medium) is possible only if the energy equipartition principle holds (Sánchez-Sesma and Campillo, 2006). Even though this is not the case, we can retrieve important information from the cross-correlation functions such as the phase arrivals, which can be exploited for monitoring purposes. In fact, through an interferometric analysis of the cross-correlations computed at different times and for several station pairs, we may get insights on the relative velocity variations in the medium during the period of time under study (Hadziioannou *et al.*, 2009). Thanks to this passive image interferometry based on the cross-correlations of the ambient seismic noise, recent studies on seismic sequences (Brenguier *et al.*, 2008; Chen *et al.*, 2010; Zaccarelli *et al.*, 2011) have shown that significant drops in the relative velocity variations accompany the occurrence of the mainshocks. The main interpretation for this

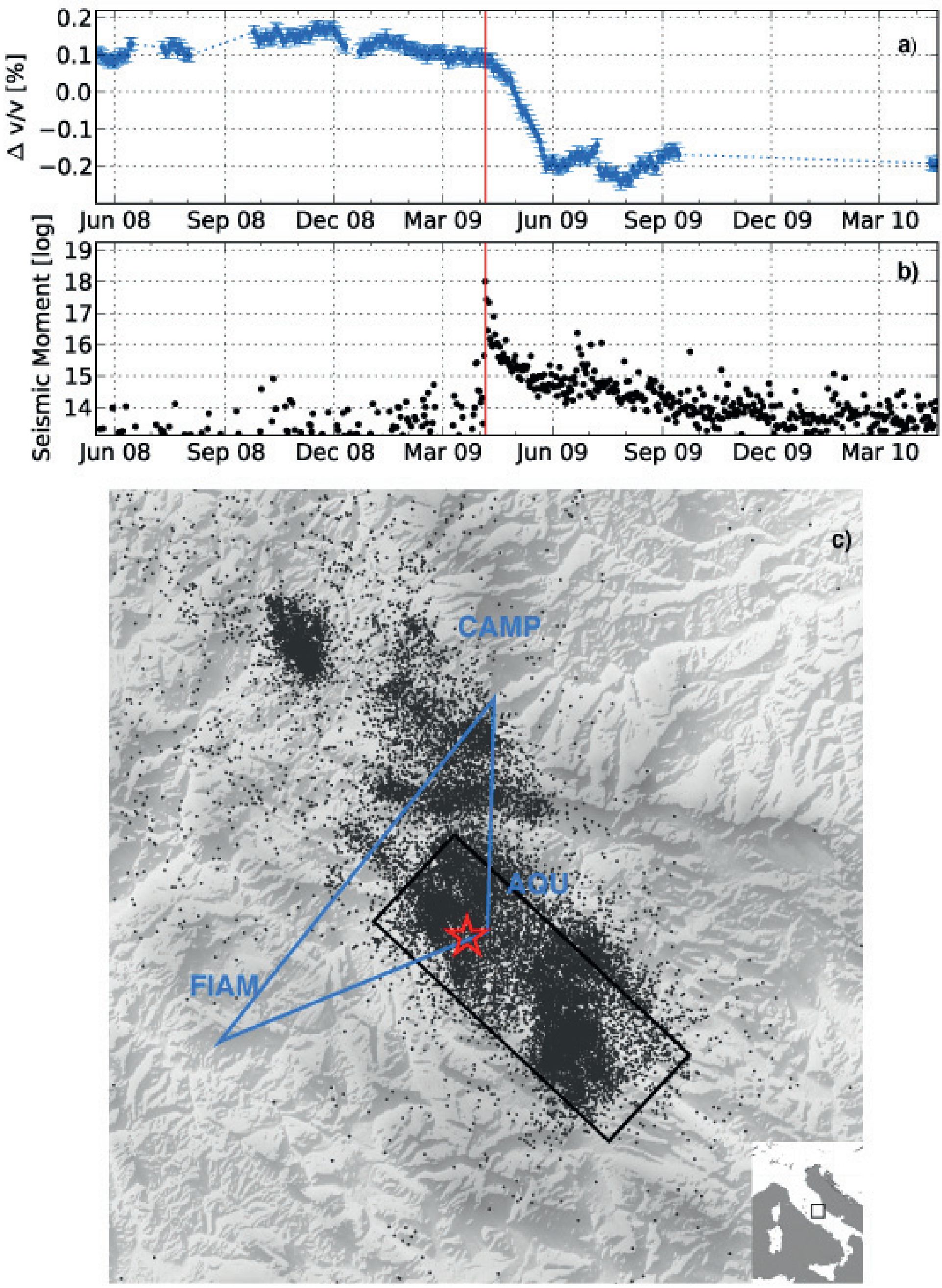

Fig. 1 - a) Relative velocity variations computed from the cross-correlation analysis of the 3 seismic records of AQU, CAMP, and FIAM seismic station. The period of time analyzed spans almost 2 years of continuous recordings from May, 2008 to April 2010; the vertical red line highlights the L'Aquila mainshock occurrence (modified from Zaccarelli *et al.*, 2011). b) Temporal evolution of the sequence, expressed as the logarithm of the daily cumulative seismic moment. c) Map of the earthquake location (Mw 6.3 with the red star, foreshocks and aftershocks with black dots), the fault plane projection (black rectangle, from Cirella *et al.*, 2009) and the 3 seismic stations used for the passive image interferometry.

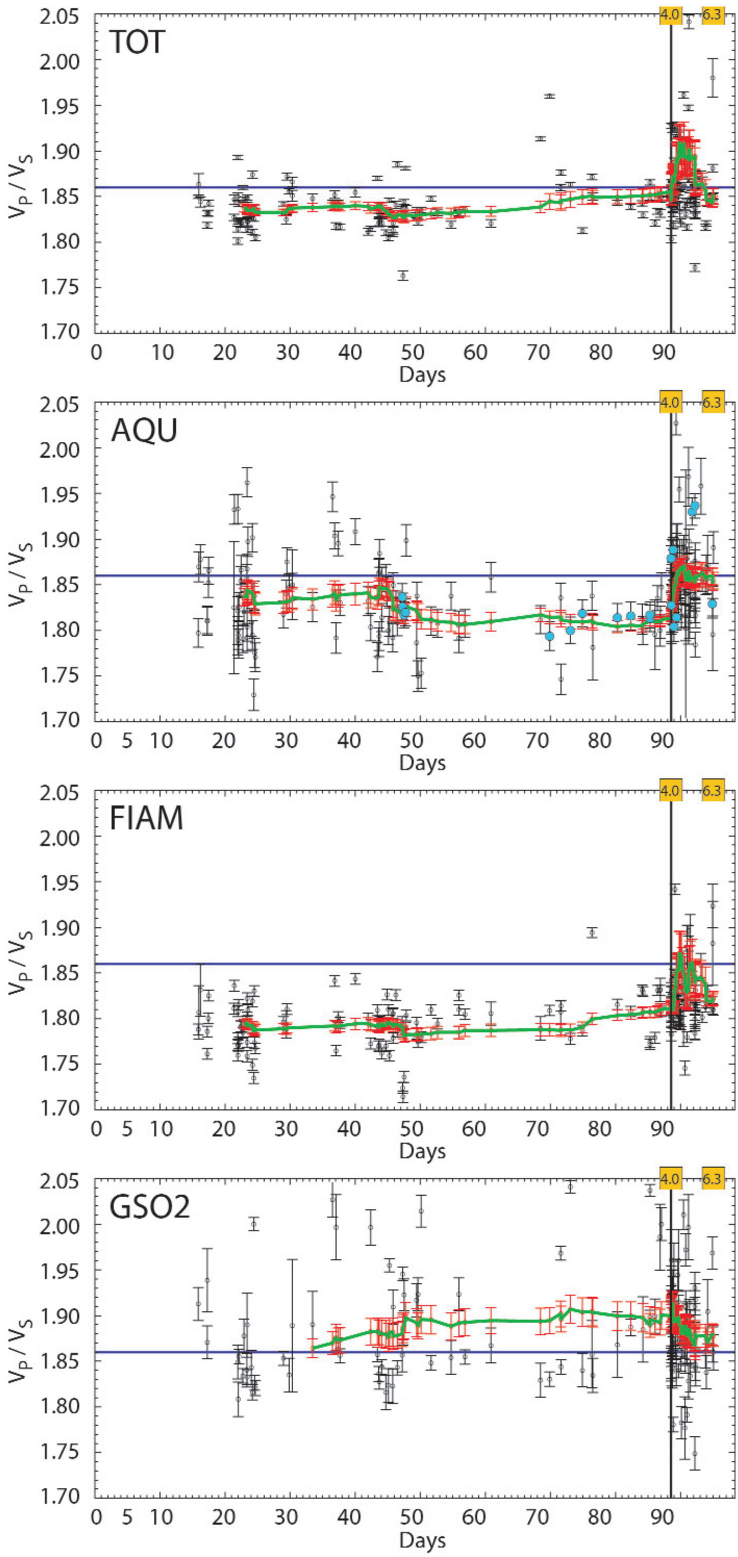

Fig. 2 - Example of temporal variation of the anisotropic parameters for the 2009 L'Aquila seismic sequence: a) delay time and b) fast direction for AQU station. The large dots in a) represent individual measurements, whereas the line is the interpolation of the mean values (small dots) calculated over 5 measurements by using a sliding window. In b) the dashed lines represent the mean of the initial and Dominant Fast Direction (DFD) computed, respectively, before and after the mainshock (indicated by the star). A secondary direction is recognized after the mainshock, given by the 90°-flips from the mean of DFD and also visible in the two rose-diagrams. In the bottom inset, the total fast measurements are also shown; the two shadowed areas represent the standard deviation calculated for the mean values.

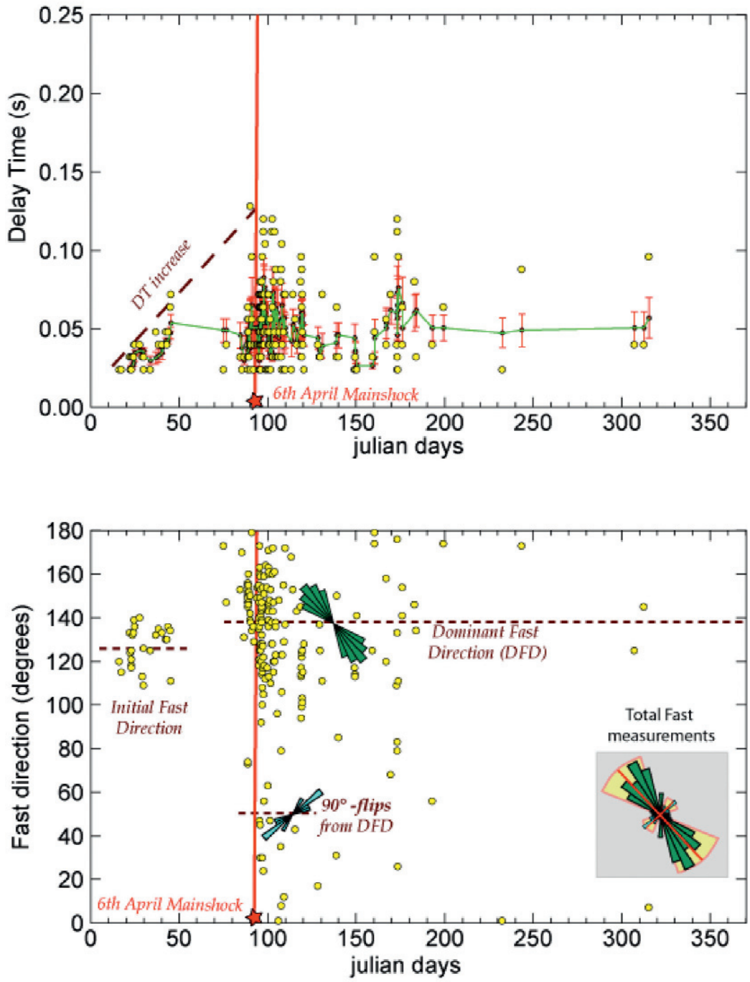

Fig. 3 - Time series of Vp/Vs (ratio between compressional-wave and shear-wave velocity) values estimated for Aquila region for from January 2009 to 6 April 2009. Average Vp/Vs values at whole set of seismic stations (TOT) and Vp/Vs values at stations AQU, FIAM, and GSO2 are shown. On all time series, individual determinations of Vp/Vs are represented by black circles, with black vertical bars indicating errors in measurement. Red circles are mean values calculated on running windows of 20 samples with one sample step; red vertical bars indicate standard deviation of mean; green lines are mean values interpolating functions. Yellow squares on top of each plot represent time of occurrence of ML=4 foreshock and MW=6.3 main shock, respectively. Blue straight line at 1.86 Vp/Vs is mean Vp/Vs ratio determined for study area. On AQU time series, solid blue circles represent Vp/Vs values for closely spaced events.

decrease in seismic velocity is the effect of the co-seismic damaging of the more superficial layers of the Earth crust in the epicentral area, highlighted by the correspondent increase in the seismic moment released during the L'Aquila sequence (Fig. 1). Another advantage of dealing with seismic noise is that it is mainly composed by surface waves (Shapiro and Campillo, 2004), this implies they sample repeatedly the medium (scattered waves travel longer than direct waves) and therefore amplify the effect of a modification in the elastic characteristic of the crust. Thanks to the surface waves properties it is also possible to separate the contributions of the deep from the shallow crustal layers to the relative velocity variations (see Zaccarelli *et al.*, 2011).

WP2: When a shear wave travels through an anisotropic medium it is split into two components, called fast and slow, which have polarization direction orthogonal to each other and different speeds. This phenomenon is known in the literature as "shear wave splitting" (Crampin, 1981). The parameters describing the anisotropic medium are the polarization direction (φ) of the fast wave, which in the crust propagates parallel to the direction of the fractures, and the delay time of the slow wave (dT). In a rock volume the presence of fractures aligned in response to the active stress regime and filled with fluid, can be detected and characterized by analyzing seismic anisotropy. In many cases, the fractures are preferentially aligned in the direction of maximum horizontal stress (Shmax). This type of observation has been the basis on which, in the 1978, Crampin developed the interpretative model Extensive Dilatancy Anisotropy (EDA). Furthermore, by estimating the seismic shear wave anisotropy it is possible to study the spatio-temporal changes in the microfractures opening direction as well as in the state and/or in the 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). To compute shear wave splitting we will use a computer program devised to automatically evaluate shear wave anisotropy parameters starting from three component digital earthquake recordings. The code is based on the cross-correlation of the horizontal seismograms method, and estimates the errors associated to each measurement and was developed in the framework of a previous agreement between DPC and INGV (Piccinini *et al.*, 2012). This represent a valid tool for getting fully-automatic robust estimates of anisotropic parameters for huge amount of data and could be employed in quasi real-time analysis of data preprocessed by monitoring networks.

Discussion. The stress field variations modify the elastic properties of the Earth's crust, including the seismic velocity and anisotropy. We want to apply both passive image interferometry and shear-wave splitting techniques for tracking respectively the temporal evolution of the relative changes in velocity and the modification of the crustal anisotropy during the ongoing earthquake activity in the southern Apennines. Furthermore we intend to study the seismic sequence occurred in the Po Plain since last May through seismic noise analysis methods. The analysis of seismic noise in fact, has the great advantage to be independent of seismic event occurrence, and this is particularly suitable for application in the preparatory phase of sequences that start suddenly, without a clear foreshock sequence. Our main goal is to detect and classify reliable precursory signals in the stages preceding the beginning of the seismic sequence and the mainshock occurrence. Grounds for the planned work are supplied by the recent study on the foreshock sequence of the L'Aquila earthquake (Fig. 2). In that case has been 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 (Fig. 3). Seismological evidences show that the physical processes that lead to instability of a seismogenic fault are promoted by the presence of fluids and their physical state (Lucente *et al.*, 2010). In particular, a primary role is played by fluid migration in time and space and by the presence of fluid overpressure (Antonioli *et al.*, 2005; Malagnini *et al.*, 2012).

The spatio-temporal variations of the shear-wave splitting parameters help to describe 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 may be related to the migration of fluids in the medium in which the fractured seismogenic fault acts initially 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, eventually leading to the nucleation of an earthquake (Nur, 1972; Scholz, 1973). Through the study of anisotropy of S waves it seems therefore possible to measure the presence, migration and state of the fluid in the focal volume, which also provide a valuable route to understand the seismogenic phenomena and their precursors (Crampin and Gao, 2010).

By applying the two techniques on the same region we aim at getting a continuous track of the crustal variations thanks to the seismic noise analysis, and a constrain on their possible interpretations coming from the well modeled anisotropic changes related to the fluid migrations.

Conclusion. We will focus on the detailed analysis of the propagation of seismic waves in the upper crust and how they vary in space and time in the seismogenic volume. Such investigations will define in more detail the characteristics of the fractured medium and the active stress field. Final results from each WP will be merged together and compared to get a more complete view of the crustal changes. Moreover, in the same DPC-INGV S3 project other aspects related to earthquake precursors will be analyzed by other UR in the same regions, and the comparison of their correspondences will be of great interest.

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