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

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Introduction

Since the late the late ’60s-early ’70s era seismologists started developed theories that included variations of the elastic property of the Earth crust and the state of stress and its evolution crust prior to the occurrence of a large earthquake. Among the others the theory of the dilatancy (Scholz et al., 1973): when a rock is subject to stress, the rock grains are shifted generating micro-cracks, thus the rock itself in- creases 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 80s and 90s such kind of research on earthquake precursor 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-fields 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. 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 (Piccinini et al., 2006) and of the relative velocity variations through the ambient seismic noise cross-correlation analysis (Campillo, 2006).

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 understanding the seismogenic phenomena and their precursors (Crampin & Gao, 2010). Variations of anisotropic parameter and of the ratio between the compressional (P-wave) and the shear (S-wave) seismic velocities, the Vp/Vs (Nur, 1972) have been recently observed and measured during the preparatory phase of a major earthquake (Lucente et al. 2010).

The seismic noise cross-correlation analysis has shown remarkable results in studying strong earthquakes (Brenguier et al., 2008). The sudden decrease of relative velocity variations occurring at the same time of the mainshock has been interpreted as due to the modification of the coseismic stress field (Zaccarelli et al., 2011).

This study has been developed by the Research Unit 2 inside the “INGV-DPC S3-Project 2012-2013: Short term earthquake prediction and preparation”. The RU 2 is composed by two Work Packages (WP1 and WP2), aimed to study the variations of seismic waves velocities using different techniques: the cross-correlation of seismic noise (WP1) in the area Po Plain before and after the 2012 Emilia seismic sequence, and as well as the seismic activity of the last few years in the Pollino region (southern Apennines) and the anisotropy of S waves (WP2) to all events recorded during the ongoing seismic sequence in the Pollino area and to compare their temporal trends to other seismic observable as the ratio Vp / Vs.

Datasets

WP1 took data from the continuous recording of those permanent stations of the national seismic network, which were installed close to the areas under study. In the Pollino case 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. For the Emilia region there were only 9 stations in a 100 km radius from Mirandola, and the time window spans the two years from January 2011 to December 2012.

WP2 We analyzed seismic events recorded in the last 3 years by MMN seismic station and located by the National Seismic Network in the surroundings of the station. We collect a dataset of about 5000 events occurred between January 2010 and March 2013.

Results and Discussions

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.

The WP 1 does 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 in FIG. 1). 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 (Pollino); and on a floodplain affected by mild-strong earthquakes in 2012 (Emilia). Both situations are specific and involve several possible interpretations:

Pollino: i) 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. ii) It is intriguing that even a Ml 5 did not generated a significant crustal damaging: in FIG. 1A 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.

Emilia: i) The peculiarity in this case is not due to the seismicity (which is a classic mainshock-aftershock sequence), but to the geographical area: the alluvial Po plain, is characterized by impressive resonance effects due to surface sediments that cause abnormal amplifications under 1 Hz (~ 0.8 Hz and down to 0.2 Hz). This effect interferes and superimposes on the oceanic microseismicity, which usually is taken as seismic noise source in this type of analysis. It is therefore necessary to remove the local amplification from the cross-correlations, for example by using adaptive filters, or by changing the frequency range under consideration. This second option, however, requires a choice of frequencies compatible with the spatial configuration of the seismic stations, as well as a detailed study of the spatial variation of noise sources at different frequencies.

The anisotropic parameters are shown using a stereographic projection (FIG. 2A): each segment is oriented along the fast direction and its length is proportional to the delay time. We divided dataset into 6 periods: 23/11/2011 M=3.6, 28/05/2012 M=4.3, 14/09/2012 M=3.7, 01/10/2012 M=3.6, 25/10/2012 M=5.0. The center 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 center is a function of the angle of incidence geometry (the outer circle represent 45 degrees).
Temporal trend of fast directions and delay time at MMN, averaged over time for the period 2010 – 2010 is shown in FIG. 2B. The vertical bars and colour changes represent 6 events with magnitude greater than 3.5 (24/11/2011; 28/05/2012 M = 4.3; 19/08/2012 M = 3.7; 14/09/2012 M = 3.7; 01/10/2012 M = 3.6; 25/10/2012 M = 5.0). The gray circles are the individual measurements, the green lines represent averaged values over 50 measurements. We considered all parameters with cc greater than 0.7 and delay time greater than 0.02s. The averaged trends are obtained using the running average algorithm and an overlap length of SM-1 points. Frequency plots of fast direction for each period are shown in different colours, the red bar is the average for the period. Although time series obtained have interesting fluctuations, these are not easily classified as anomalies or seismic precursors mainly because the magnitude of the strongest earthquake that has affected the area is only M = 5. However they represent 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 strong earthquakes.
Finally, to have an insight on the meaning of the parameter fluctuations over time we compare the time series of WP1 and WP2 with the trend of Vp/Vs evaluated using the same seismicity in the period range -second half of 2012 - beginning of 2013 (FIG. 3). The seismic event of magnitude 5 is indicated by the last vertical line in the graphs. Analyzing the trends, an important oscillation in both the delay time and the Vp/Vs is visible and it also corresponds to a decrease in Δvs (this decrease had already started before the event). Fluctuations of anisotropic parameters are fairly common in the months before the magnitude 5 earthquake and seems to be correlated with the Vp/Vs trend. The results presented here can help in getting new insights in the identification of precursory phenomena of strong earthquakes; further investigations are needed to better understand their statistical significance and what is the physical phenomenon that produces them.

Acknowledgment
The temporary stations have been installed by the INGV group of the Seismic Mobile Network of Rome and Grottaminarda in collaboration with the University of Calabria and the German Research Centre for Geoscience (GFZ). We thanks Aladino Govoni e Milena Moretti for the P – S arrival times lecture of the dataset of temporary stations and INGV “surfanelpick group” for the event locations.

FIGURE CAPTIONS

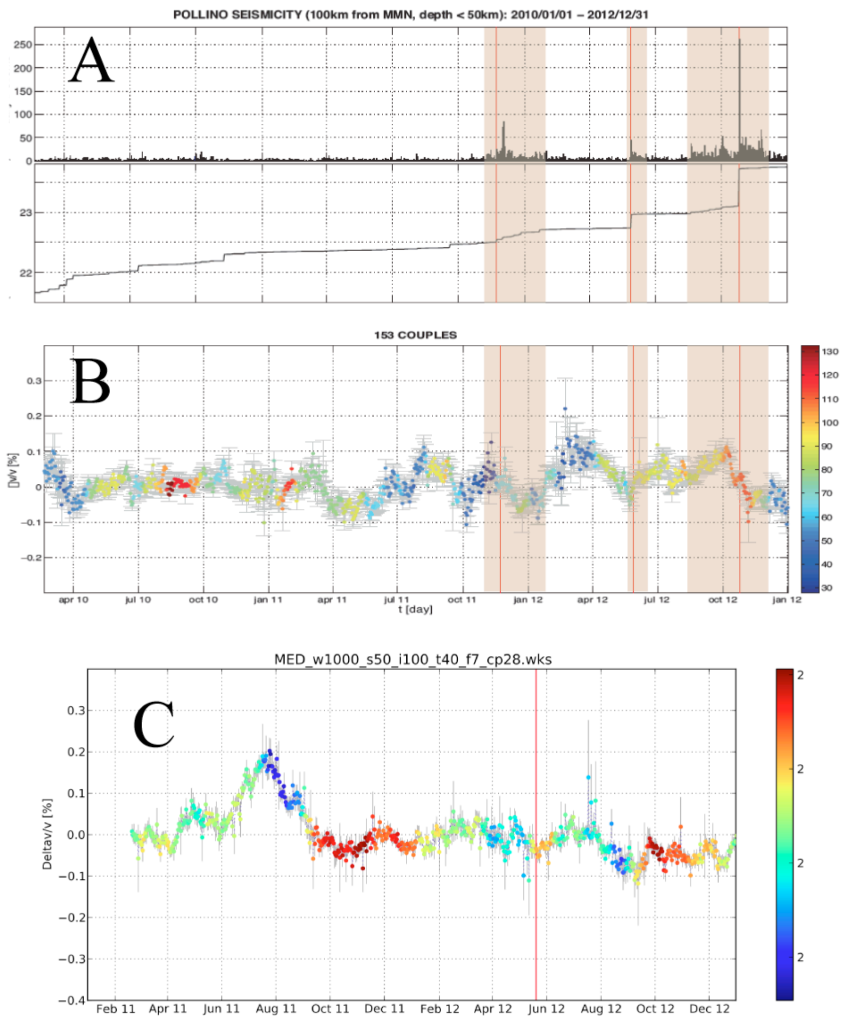

Figure 1 - A) Seismic activity in the Pollino region (events with depths less than 50 km and located in a radius of 100 km from Mormanno in the period 2010-2012). The top panel shows the number of daily events. In the lower panel is the logarithm of the cumulative seismic moment (calculated following Kanamori, 1977). The coloured bars show the three major earthquake swarms and the vertical red lines indicate the time of occurrence of the most energetic event of each cluster. B) 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. Each point together with its error bar represent the result obtained for the 50 previous days. The colour scale indicates the number of pairs involved in estimating every single measurement: warm colours are for values obtained on a large number of station pairs and correspond to more stable results**.** C) Relative velocity variations (percentage) obtained from the analysis of the ambient seismic noise cross-correlations for the 9 stations considered in the Po plain. Each point together with its error bar represent the result obtained for the 50 previous days. The colour scale indicates the number of pairs involved in estimating every single measurement: warm colours are for values obtained on a large number of station pairs and correspond to more stable results. The vertical red line marks the beginning of the Emilia sequence.

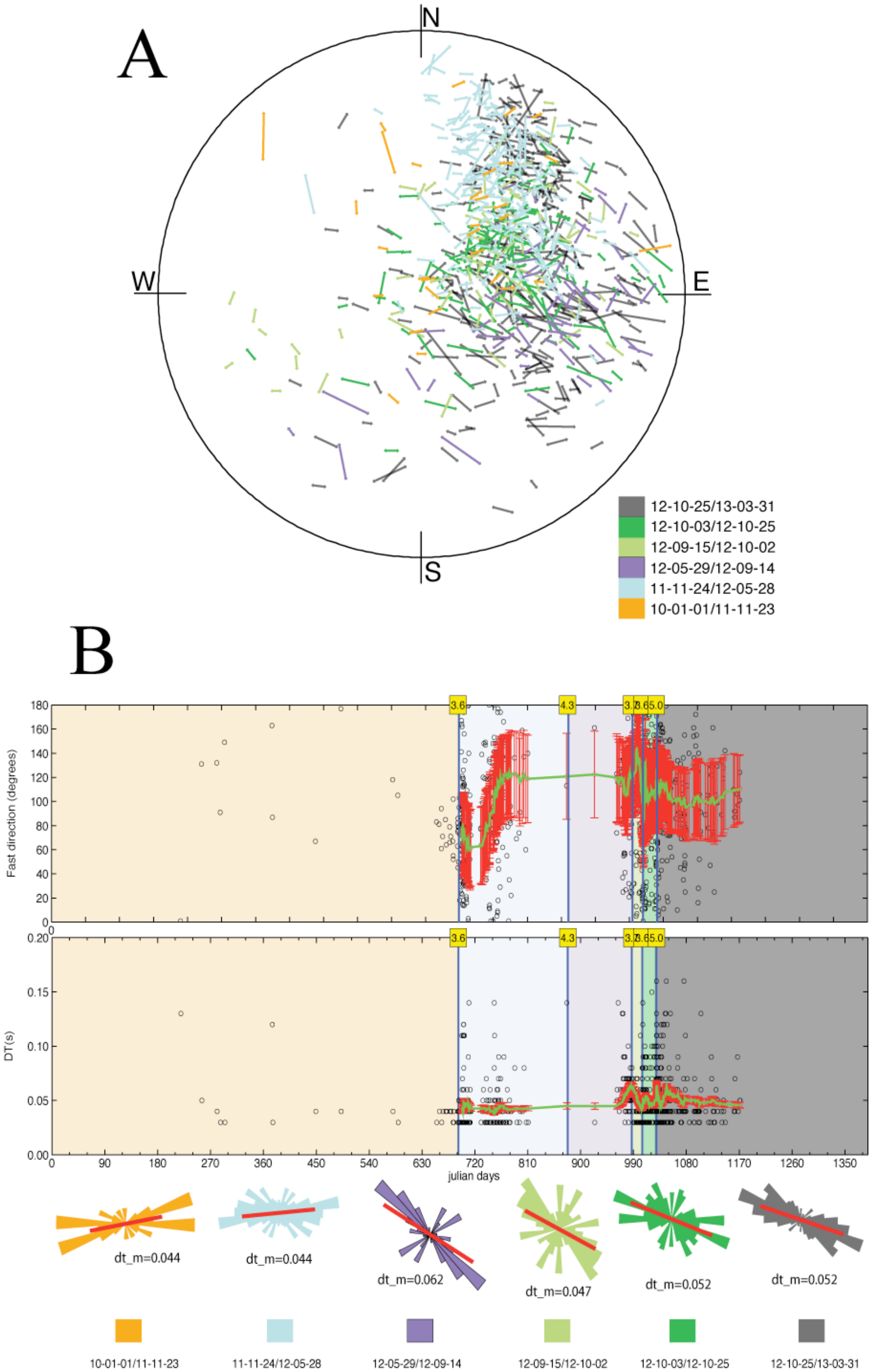

Figure 2 – A) Stereographic projection of the anisotropic parameters to the station MMN: each segment is oriented along the fast direction and its length is proportional to the delay time. B) Temporal trend of fast directions and delay time at MMN, averaged over time for the period 2010 – 2013.

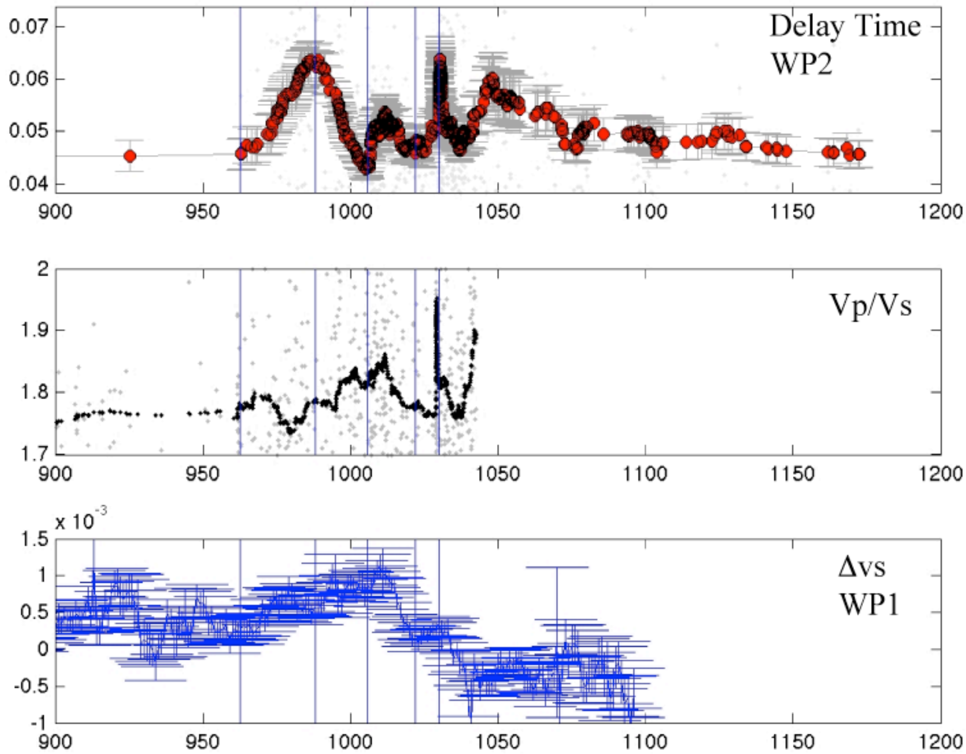

Figure 3 – Averaged trends, in the period late 2012 to early 2013, of the parameters studied by the two WPs of UR2 in the Pollino area, compared with the trend of Vp/Vs in the same area.

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