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In the framework of the ERC LUSI LAB project lead by Dr. Adriano Mazzini at the CEED - University of Oslo, Norway - I visited the group of Crustal Deformation and Fluid Flow lead by Prof. Matteo Lupi at the University of Geneva, Switzerland from the 6th to the 22nd of November 2017. Lusi is a sediment hosted hydrothermal system located in East Java active since 2006. I used a network composed of 31 seismic stations deployed in this region to monitor the seismic activity occurring around Lusi. The network encompasses the volcanic arc, the back arc basin where Lusi resides and the strike slip fault system connecting the two.

Additionally, I also used seismic data from the Aegean Sea to study the seismic activity promoted by a M6.9 strike slip event occurred in May 2014 on the westernmost branch of the North Anatolian Fault.

The scope of my short-term mission was to exploit the datasets and tackle the following scientific questions (SQ):

1. **Is it possible to locate anomalous sources of noise in East Java.** We used grid-search methods to investigate whether it is possible to localize geological events with regional seismic networks.
2. **Is it possible to identify seismic precursors by monitoring seismic parameters before and after the M6.9 earthquake occurred at the western end of the North Anatolian fault in May 2014?**

The results of these studies are briefly outlined below:

SQ1. We used records from 31 seismic stations deployed around Lusi and its neighboring volcanic arc as well as additional seismic stations from BMKG network in Java (Fig. 1). Fig. 2a shows spectrograms of the vertical-component continuous seismic records at stations SP01, SP05, BLJI and GMJI. From November 2015 to March 2016, seismic noise and spectral analysis of continuous seismic records at Lusi network and BMKG network stations in East Java suggest the presence of a localized source around Tengger Caldera. An eruption began in November 2015 at the Bromo cone of Tengger Caldera and continued for about a year. At the same time Lusi eruption reached a peak in flow rate.

The RMS amplitude and spectral analysis reveals the existence of monochromatic low frequency seismic signals (~0.3-0.7 Hz) that begin from November 2015 and continued for about four months. These signals decline gradually with distance from Tengger Caldera in East Java.

Fig. 1. Map of seismic stations from Lusi network and BMKG network in East Java.

Continuous vertical-component seismic noise records of Lusi seismic network and three stations (KRK, BLJI and GMJI) from BMKG network were used to compute daily cross-correlations (CCs) of ambient noise between all station pairs. It has been shown that 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 at the other location. Fig. 2b shows example of daily cross-correlation functions for station pair SP01-SP05 in frequency band of 0.3-0.7 Hz. The observed monochromatic signals in spectrograms are clear on CCs during the same period. Daily CCs were stacked for the period from November 2015 to March 2016 and the obtained waveforms were used to locate the main source of the noise during these days.

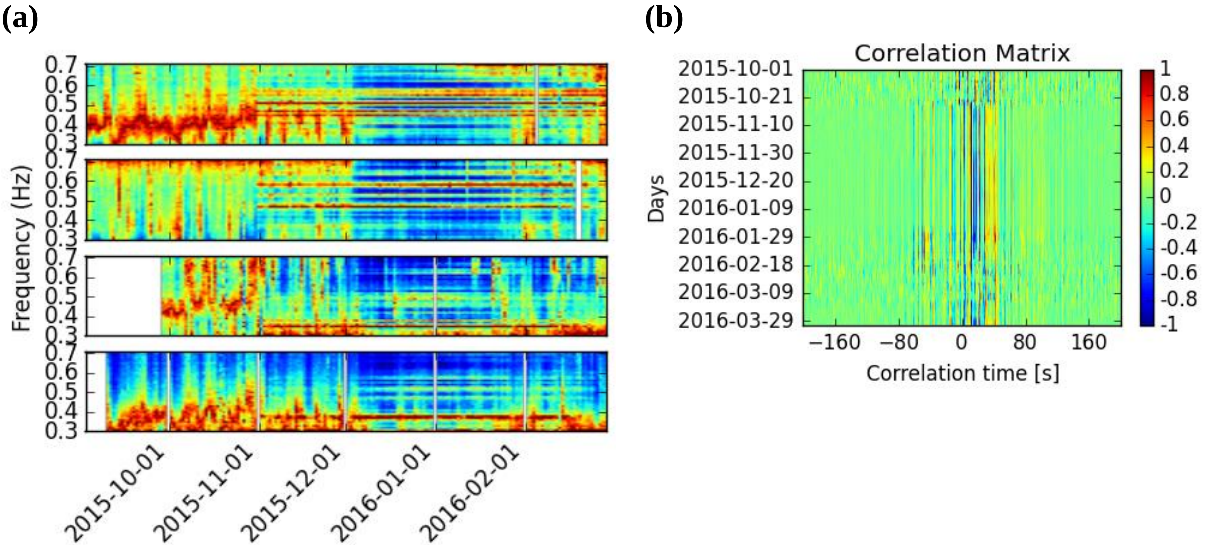

Fig. 2. (a) Spectrogram of the vertical-component continuous seismic record at SP01, SP05, BLJI and GMJI. (b) Daily cross-correlation functions for station pair SP01-SP05 from Lusi Network.

We used two approaches to locate the noise source. In the first approach, we measured the travel times of the maxima of the envelope from the stacked waveforms between all pairs of stations. The travel times and source-station distances were used to define the following misfit function:

$$\sum_{i} \left| \frac{dist(B_i, r_s) - dist(A_i, r_s)}{V} - \Delta T_i \right|$$

where r_s is source position, dist(A_i/B_i, r_s) is the station(A_i/B_i)-source(r_s) distance, ΔT_i is the measured travel time, V is the group velocity and i denotes pairs of stations (A_i and B_i). A grid search has been used to minimize the misfit function in order to find the optimal location of the source (See Mordret et al., 2013 for details of the approach).
In the second approach, a 2D grid of amplitudes has been defined for each pair of stations. For each pair, the travel times of the waves that originate from each grid node (assumed source position) were measured by [dist(B_i, r_s) - dist(A_i, r_s)]/V and their corresponding amplitudes from stacked waveform were attributed to the grid nodes. The advantage of this method is to consider all the amplitudes in the stacked waveform rather than just the maximum amplitude. Element-wise addition of grid amplitudes (defined for each pair of stations) gives the optimal source position.

Results of both approaches are presented in Figs 3a and 3b showing that the noise at frequencies between 0.3 and 0.7Hz could be originated from Tengger Caldera. Spectral analysis of seismic stations around Tengger Caldera shows that low frequency signals were identified a couple of days before the reported eruption at the Bromo cone of Tengger Caldera in November 2015 and last until March 2016.

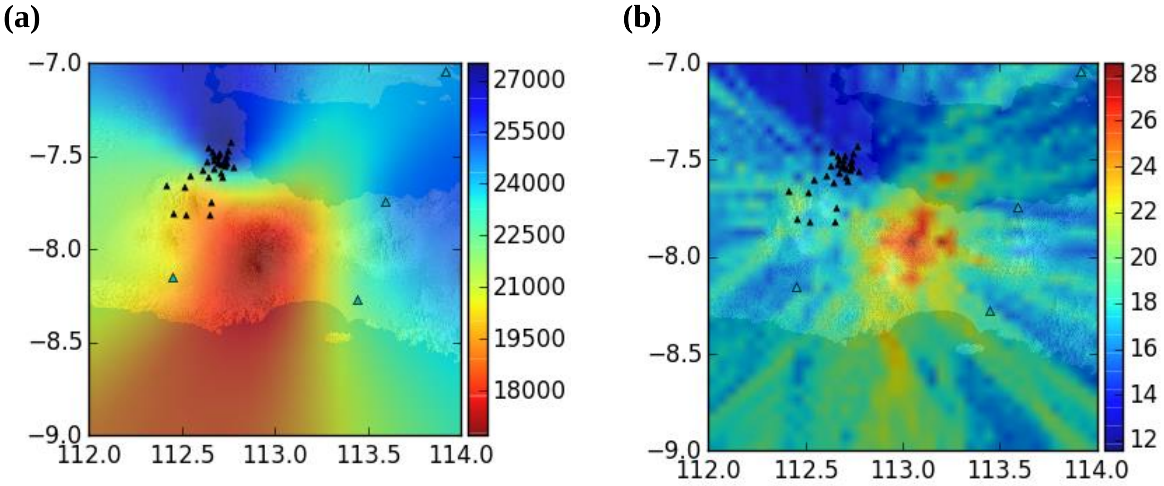

Fig. 3. Results of the locating main noise source for the frequency band 0.3-0.7Hz (a) with maximum amplitude grid search and (b) full waveform amplitude grid search. The colorbar changes from high probability location (red) to low probability (blue). Black triangles show the Lusi network and cyan triangles show the BMKG network stations.

Moreover, from spectrograms of continuous seismic records we observed that high frequency (1-4 Hz) content becomes dominant at stations around Lusi. This brought up an interesting idea of deriving an average 1D velocity model and a high-resolution 3D shear wave velocity model for shallow depths around Lusi. Therefore, during this trip we decided to test the possibility of setting up a near-surface study around Lusi from ambient noise surface wave tomography. We first extracted ambient noise data from continuous recordings of seismic stations around Lusi. CCs on vertical components were calculated at high frequencies between 1 and 4Hz. Fig. 4 shows the daily CCs for pairs of SP05-SP19 and SP09-SP13. Surface waves propagating between the two stations can be clearly seen in this Figure.

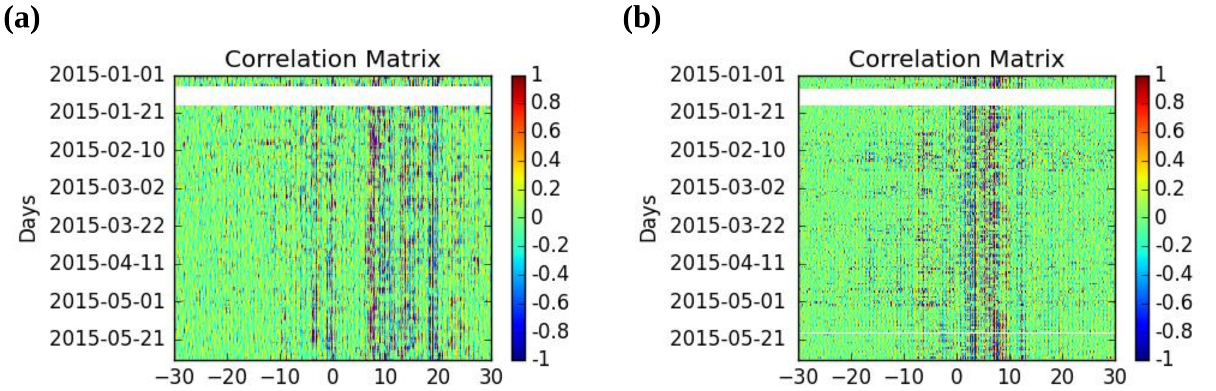

Fig. 4. CCs in the frequency range of 1-4 HZ for (a) SP05-SP19 and (b) SP09-SP13.Color scales indicate the amplitude of the phases.

These preliminary results are positive and promising for future work. This study is currently in progress and for the next step we will invert the surface wave group velocities into 2D velocity maps between 0.25 and 1s. Finally, we will invert 2D velocity maps into 1D flat-layered velocity models to construct a 3D shear-velocity model down to 1 km below Lusi.

SQ2. To monitor possible changes in scattering properties of the medium before the earthquake we applied interferometry methods using continuous seismic noise records at the closest stations to the epicenter. Additionally, spectrograms of seismic records at four ocean bottom seismometers (OBS) in the central part of the Sea of Marmara were analyzed to investigate the dynamic triggering of an active mud volcano located close to the North Anatolian fault.

Fig. 5b shows the daily CCs for ALN-GELI pair from January 2014 to December 2016. Seasonal changes of ambient noise are observed visually (Fig. 5b) and by applying interferometry methods but it reveals stable seismic velocities and coherency without a clear precursor to the earthquake.

Moreover, spectrograms of seismic records at four ocean bottom seismometers (OBS) in the central part of the Sea of Marmara analyzed to investigate the dynamic triggering of an active mud volcano located close to the North Anatolian fault trace.

We find no clear temporal changes associated with the earthquake. The fact that no velocity/coherency variation is observed by employing coda waves, suggests that the source area may be too small for the interstation distance to be detected by investigating the time shifts of multiply scattered coda waves.

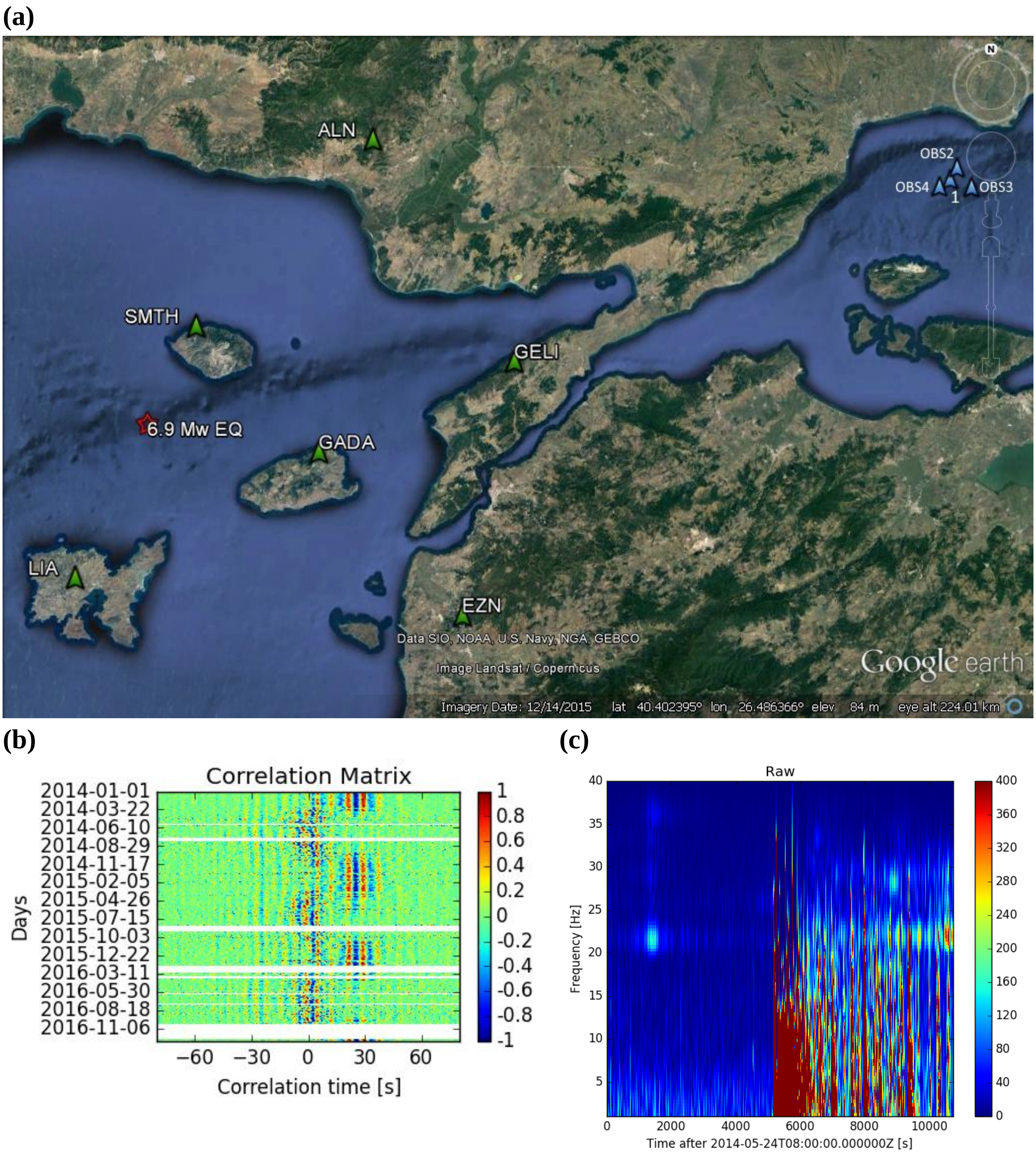

Fig. 5. (a) Map of seismic stations close to the M6.9 earthquake and OBS locations on the sea (Marmara) floor. (b) CCs for ALN-GELI in the frequency range of 0.1-2 HZ and in the period from January 2014 to December 2016. Color scales indicate the amplitude of the phases. (c) Spectrogram of the seismic record at OBS1, ~5000s before and after the earthquake.

References

Mordret, A., Landès, M., Shapiro, N. M., Singh, S. C., Roux, P., & Barkved, O. I. (2013). Near-surface study at the Valhall oil field from ambient noise surface wave tomography. Geophysical Journal International, 193, 1,627–1,643