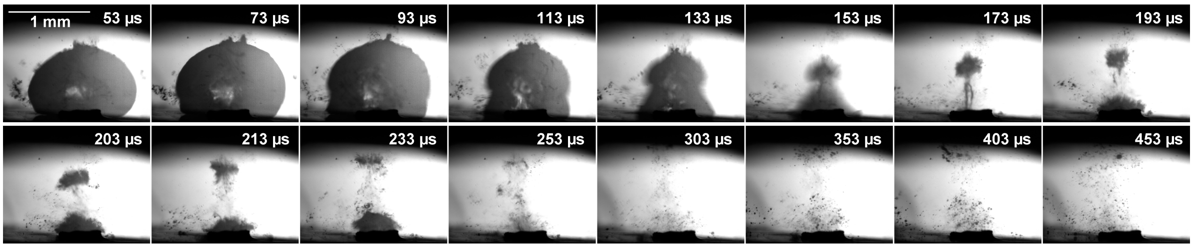

Figure 3: *Dynamic evolution of cavitation bubble when the laser is focused on a target firstly exposed to 1000 laser shots.*

Moreover, the lifetime of the first bubble is also reduced respect to what observed for the undamaged target (the lifetime decreases from 200 down to 170 μs). A material rebound on the crater edge is also visible. On the overall, bubble shape results quite different in the two investigated cases. This behavior could be explained in terms of hydrodynamic effects during the bubble expansion [8]. However, even if preliminary, such evidence is important to provide precise information about single reaction steps occurring during the ablation process.
Now, in order to investigate the influence of the cavitation bubble dynamics on the nanoparticles ablation efficiency we analyzed, by a 3D confocal microscope, the crater profiles obtained for several number of laser shots (10, 50, 100, 250, 500, 1000). In Fig. 4 is shown the crater depth obtained after the target exposure at 250 pulses. Analyzing the crater profile, the ablated mass was quantified. We found that the ablated volume increases linearly as a function of the pulses number (from 15 μg for 10 pulses up to 928 μg for 500 pulses). Hence, within this range of depth, no significant change in the ablation efficiency was observed. However, the observed bubble dynamics changes could influence Ag nanoparticles morphological properties in terms of size and distribution. A systematic study of nanoparticles properties is necessary to better understand all these mechanisms.

Conclusion

In this work, a custom designed setup with a flow ablation chamber was used to examine cavitation bubble dynamics in laser ablation of silver target in water. Cavitation bubbles, generated by a laser pulse, undergo several repeated expansions and shrinkage. Moreover, we have observed that, during the ablation process, the target surface is reached several times by the laser beam and this causes target inhomogeneities. These latter influence cavitation bubble shape and dynamics. Particularly, we found that the cavitation bubble dynamics results different using a high purity-flat and a rough-damaged silver target. Even if cavitation bubble dynamics significantly change, the ablation efficiency remain almost unchanged.

References

[1] V. Amendola and M. Meneghetti, *What controls the composition and the structure of nanomaterials generated by laser ablation in liquid solution?*, Phys. Chem. Chem. Phys., 2013, 15, 3027.

[2] E. Fazio, M. Santoro, G. Lentini, D. Franco, S.P.P. Guglielmino and F. Neri, *Iron oxide nanoparticles prepared by laser ablation: Synthesis, structural properties and antimicrobial activ-*

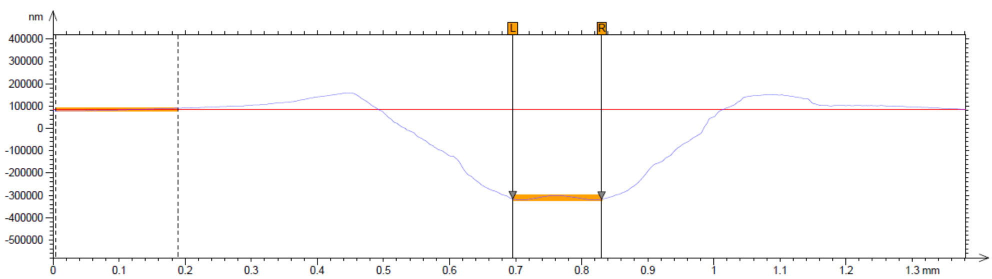

Figure 4: *Depth of the crater realized after 250 laser shots. The measurement was made by confocal optical microscopy on a section of the crater.*

ity, Colloids and Surfaces A: Physicochem. Eng. Aspects 490 (2016) 98-103.

[3] S. Ibrahimkutty, P. Wagener, T. Dos Santos Rolo, D. Karpov, A. Menzel, T. Baumbach, S. Barcikowski and A. Plech, *A hierarchical view on material formation during pulsed-laser synthesis of nanoparticles in liquid*, Scientific Reports, 5 (2015), 16313.

[4] S. Reich, P. Schönfeld, A. Letzel, S. Kohsakowski, M. Olbinado, B. Gökce, S. Barcikowski, and A. Plech, *Fluence Threshold Behaviour on Ablation and Bubble Formation in Pulsed Laser Ablation in Liquids*, ChemPhysChem 2017, 18, 1-8 .

[5] P. Wagener, S. Ibrahimkutty, A. Menzel, A. Plech and S. Barcikowski, *Dynamics of silver nanoparticle formation and agglomeration inside the cavitation bubble after pulsed laser ablation in liquid*, Phys.Chem. Chem. Phys., 2013, 15, 3068.

[6] R. Tanabe, Thao T.P. Nguyen, T. Sugiura, Y. Ito, *Bubble dynamics in metal nanoparticle formation by laser ablation inliquid studied through high-speed laser stroboscopic videography*, Applied Surface Science, 351, (2015), 327-331.

[7] M.S. Plesset, A. Prosperetti, *Bubble dynamics and cavitation*, Annu. Rev. Fluid. Mech. 9, (1977), 145.

[8] D. Autrique, V. Alexiades, P. Perriat, *Hydrodynamics modeling of ns laser ablation*, Electron. J. Differ. quat. 20, (2013) 1.

Moment tensor inversion of the 1978 *Ferruzzano* earthquake (Southern Italy) by analog historical seismograms

S. Scolaro*, B. Orecchio

Department of Mathematics, Computer Sciences, Physics and Earth Sciences, University of Messina, Italy

*Corresponding Author email: silscolaro@unime.it

Abstract

The knowledge of historical earthquakes is crucial for understanding regional tectonics and seismic hazard. The more recent developments concerning moment tensor inversion of modern seismograms and processing of old recordings offer the opportunity to estimate source parameters of historical earthquakes. This study shows the methodology and the results of complex analog seismic data modeling and the analysis of the earthquake occurred in Southern Italy on 11 March 1978. We re-analyzed this event applying a modern-standard time-domain analysis to the original analog data to determine the focal mechanism, the depth and the seismic moment. Our focal mechanism solution shows a normal faulting (strike 185°, dip 69°, rake −86°) in a very good agreement with the study area seismotectonic frame.

Keywords: Historical seismograms, moment tensor inversion, waveform analysis, Southern Italy.

Introduction

Southern Italy represents one of the most interesting sector of the Mediterranean region both for the several descructive earthquakes (e.g. 11 January 1693, I=XI MCS M_w=7.4; 5 February 1783, I=XI MCS M_w=7.1; 28 December 1908, I=XI MCS M_w=7.1, [1]) occured in the last centuries and for the geodynamic framework characterized by the transition between the compressive domain, due to the NW-SE convergence Nubia-Eurasia, and the extensional domain due to the southeastward rollback of the Ionian lithospheric slab. Both the activation mechanisms of the several strong earthquakes and the description of the regional seismotectonic and geodynamic frame are strongly debated in the literature. High energy earthquakes (M> 5) are direct expression of the regional scale processes hence they are a key information for understanding the complex seismotectonic processes, the regional strain release and for characterizing seismic hazard of the study area [2]. Only a small numer of moderate-to-strong earthquakes were recorded in Southern Italy in the last thirty years (recording period of modern standard broad-band seismometers) while, numerous earthquakes with M> 5 were occured in Southern Italy in the early seismic instrumental times 1900-1980 [3]. These events are mainly unexplored because of the limits of data management and analyse techniques. The most recent development about the waveform inversion technique [4–6] and a more accurate knowledge of the recording parameters of old instruments allow to explore these historical events by using data coming from the seismographs operating since the beginning of XX century.

This study shows the methodology of complex analog seismic data analysis and the result obtained for the earthquake occured in Calabria (Southern Italy) on 11 March 1978, prior to the installation of the global digital seismic network. Contrasting and poor resolved solutions of this event have been reported in the literature[7, 8]; it is therefore interesting to analize it by one of the most recent technique of waveform inversion for historical earthquakes [5, 6]. With this study we also test, for the first time on an italian seismic event, the method performance.

The 11 March 1978 earthquake (M_w=5.2), know as *Ferruzzano* earthquake, were recorded by more than hundred seismic stations [9] but the instruments operating at the time were analog mechanical pendulums writing on paper, especially. With the aim to test the methodology for studying the italian historical earthquake, the choise to explore an event occured in the late 1970's has been guided by a major knowledge of the technical features of the seismic stations operating at the time. In the early 1960's the deployment of the World Wide Standard Seismograph Network (WWSSNN) equipped by highly sensitive electrodynamic sensors with galvanometric amplified recordings on paper allowed homogeneous global data coverage. But the real breakthrough came only in the 1990's with the development of high resolution digital broadband recordings with large dynamic range.

Data collection and waveform inversion method

We collected for the *Ferruzzano* earthquake 25 original analog seismograms from 17 seismic stations equipped with three component long- and short-period instruments. Most of the records have been collected from stations located in Europe because they were preserved in the best condition and were most easily accessible. The availability of historical records has been improved thanks to the SISMOS database [10, 11] that collected and scanned original seismograms of italian historical earthquakes. Because the period band of long-period seismograph records is more suited for the earthquake analysis only 11 seismograms could be used. Also not all records have enough high quality for successfull vectorialization, digitized seismograms often have steps and distorsion due to the writing mechanism. The information of the instruments (free period, damping and magnification, the component orientation), that were documented manually, sometimes do not fully correspond to the real values or are not available, so biasing the restitution to true amplitudes of the seismic records. For this reason only 8 seismograms from six stations have been digitized.

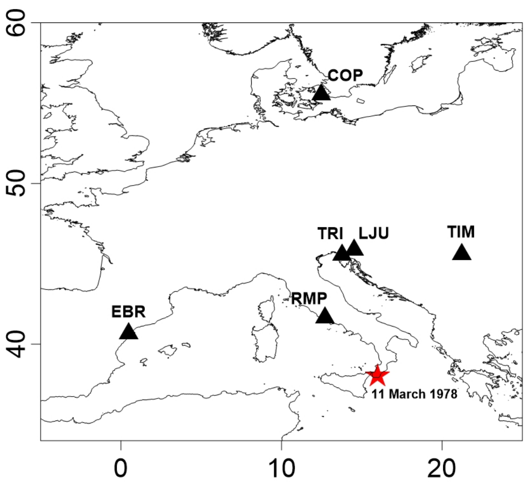

Figure 1: *Recording geometry for digitized historical seismograms of the 11 March 1978 earthquake. The black triangles and the red star indicate the stations and epicenter locations, respectively.*

Figure 1 shows the station geometry for digitized seismograms. For TRI station three components of motion are preserved, while for EBR only single horizontal trace is available and for all the other stations just vertical traces are obtained. It is obvious that considerable azimuthal gaps were left but for an historical earthquake this amount of data is very valuable. Each of these seismograms have been digitized manually using the tool of GIMP (GNU Image Manipulation Program) by redrawing the whole traces and, corrected from curvature, resampled and converted to modern seimological format by TESEO a GIMP plug-in made up by INGV [12]. Figure 2 shows an example of original seismogram of the 11 March 1978 earthquake recorded by the galvanometric Sprengnether seismograph at the LJU station (plot a) and the respectively converted digital trace (plot b).

Modern moment tensor inversion techniques require to rotate the horizontal NS and EW component seismograms into radial (P-SV) and transverse (SH) components. This is difficult for historical records because of imprecise alignment and magnification correction between horizontal components. Also, single components of the instruments may be lost or the instrument consisted of only one component. For this reason one of the peculiarity of the algorith we used for historical data is to work directly on the seismogram components. Feasibility and effectiveness to determine the parameters of an historical earthquake based on limited dataset is supported by the most recent literature (e.g., [4–6, 13]), that proves the capability of this technique to obtain reliable results. Following [5] we apply a modern standars time-domain analysis technique to the *Ferruzzano* earthquake to estimate the source parameters of the event. This technique analyze the least-squares misfit among observed seismograms and their synthetic predictions within a long period passband (20 to 50 s) and, use original waveforms without previous rotation of the horizontal seismograms. In this way errore-prone step in the processing sequence are avoid and single horizontal seismograms can be used. Finally, the individual instrument characteristics were processed to pole and zero type transfer functions [14] and then convolved the instrumental response to the synthetic waveforms.

Results and discussion

The inversion of the 1978 *Ferruzzano* earthquake is based on 8 seismograms from six different stations, the individual traces are weighted to balance the different amplitudes and improve the overall fit of the waveforms (Fig. 3). For the parameter selected, the best solution indicates normal faulting (strike/dip/rake of 185/69/-86 and 354/22/259 for the two nodal planes) and a seismic moment of $M_0=0.128\times10^{24}$ Nm (M_w=4.7). The non-double-couple (CLVD) component of the inverted moment tensor is small (12%) indicating that this earthquake can be adequately modelled as a simple faulting event.The best solution is obtained at a depth of 8 km, more shallow than [7] and [8]. The misfit error as function of depth shows that the solution is stable around the minimum (Fig. 3).

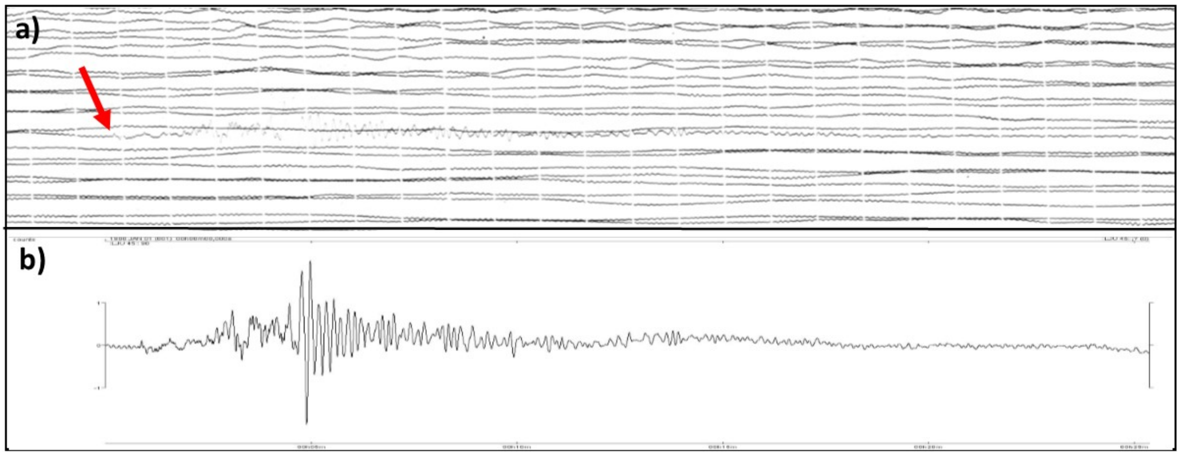

Figure 2: *(a) Original analog waveform of the Ferruzzano earthquake recorded by the galvanometric Spregnether seismograph operating at the LJU station at the time. Although the seismogram presents a non linear trend and gaps at each minute time laps the trace is sufficiently readable. (b) Digital elaboration of the waveform before the filtering process.*

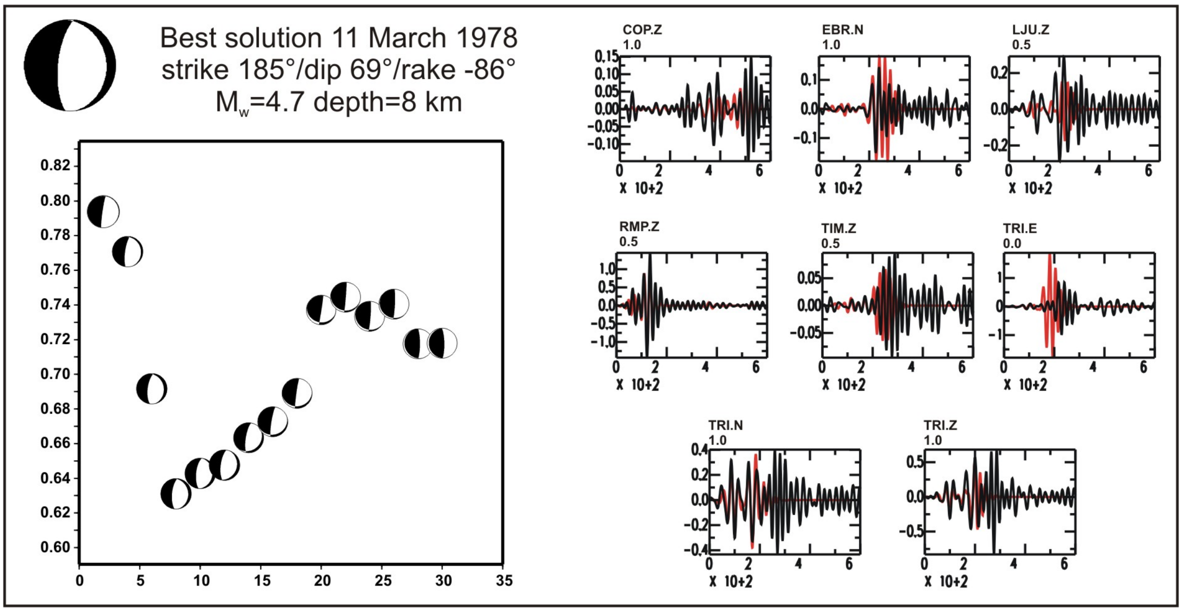

Figure 3: *Best focal mechanism solution for the 11 March 1978 earthquake (Southern Italy), corresponding to normal faulting at 8 km depth. The misfit error as function of depth, reported on the left, shows the stability of the solution around the minimum. On the right the waveform fits for the event are reported, the observed waveforms are indicated by black lines and predicted by red lines. Displacement (y-axis) is in mm and time (x-axis) in s. Above each trace the name of the station and the weighting factor for inversion are reported. All traced start at the P waves arrival.*

Waveform matches (Fig. 3) between the corresponding predictions and the observations are good and reproduced adequately. *P* waves are very well fitted at each station. For the italian station TRI (only for the EW component) we observe effects of limited bandwidth and low resolution, since the recordings understimate amplitudes near the first arrival of long-period surface waves, for this reason we excluded this trace from inversion. The obtained magnitude (M_w=4.7) is smaller than that (M_w=5.2) proposed by [7] and [8], we supposed that possible regional seismic attenuation could affect the propagation wave paths and recorded amplitudes. The presence of asthenospheric mantle material at shallow