TOMO-ETNA: AN ACTIVE SEISMIC EXPERIMENT AT ETNA VOLCANO

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Mt. Etna's eruptive dynamics is the result of a complex interaction between magma ascent in the plumbing system and the regional (deep crust) tectonic regime, together with local (shallow crust and volcanic edifice) structures partially controlled by flank instability. Magma ascent driving conditions (e.g., structural setting, tectonic forces) are not yet completely understood. The main limits in the understanding the eruptive dynamics of Etna volcano are largely due to the insufficient knowledge of its intermediate-deep crust, mostly based on passive seismic tomography and old active seismic experiments carried out more than twenty years ago (Colombi *et al.*, 1979; Sharp *et al.*, 1980; Hirn *et al.*, 1997). The old techniques for crustal imaging and their resolutions are unsuitable for the potential of current modelling and the comparison with the high quality of information provided by in-situ data sets of the volcano monitoring. Since 2000's, recent tomographic inversions have progressively improved our knowledge of Etna's shallow structure (down to 10 km depth), highlighting a complex pattern of magma reservoirs and conduits with variable dimensions and, consequently, the understanding of the most recent eruptions. However, the geometry of the conduits and the dimensions and shapes of small magmatic bodies still require greater investigation. An accurate imaging of the Etna's plumbing system and the host crust is crucial to delineate a working model of this volcano in order to understand its behaviour and evolution of the ascent magma batches.

At Mt. Etna, seismic tomography studies, based on natural seismicity and performed by using P and S-wave velocities, have shown that dike intrusion before eruptions can be associated with anomalous volumes of Vp/Vs in the shallow volcanic plumbing system (Patanè *et al.*, 2002, 2006). Low Vp/Vs anomalous regions were observed during both the July 2001 and the October 2002 dike intrusions feeding these two eruptions (Patanè *et al.*, 2002). Patanè *et al.* (2006) observed Vp/Vs time dependent anomalies by 4D tomography, between the 2001 and 2002–2003 eruptive period, interpreting it as the trace of fluid intrusion (gas-rich magma) and gas migration from the shallow magma body in the upper cracked volume that develops during the eruptive period. By studying the attenuation of P-waves (Qp), Martinez-Arevalo *et al.* (2005) and De Gori *et al.* (2011), identified the location and extent of magma bodies during the 2001 and 2002–2003 eruptions. More recently Alparone *et al.* (2012), investigating the mechanisms of the 2008-2009 flank eruption, calculated 3D velocity and attenuation tomography, including a 3D relocation of the used seismic events.

The most important result obtained from the joint analysis of Vp, Vp/Vs and P-wave attenuation is an anomalous zone with normal to high Vp and low Vp/Vs, which partially overlaps a low Qp volume located along a NS trending "channel" beneath the summit craters. This can be interpreted as a shallow volume characterized by high temperature where the magma including supercritical fluids is located.

At present, the emplacement of shallow dikes that feeding eruptions along the NNW-trending fracture system (S Rift) and along the NE Rift, seems to occur prevalently at the western border of a wide high Vp velocity body (HVB). The HVB is centered in the Valle del Bove with a NNW-SSE to NS orientation, between -1 and -7 km depth (slight rotated at greater depth). This volume is mainly aseismic and seismicity is located around it, mainly to the west and east.

The HVB that controls the ascent of magma, has been interpreted by several authors as a high-density cumulate body crystallized at depth (Chiarabba *et al*., 2004 and references therein).

Although Mt. Etna is one of the best-studied volcanoes by using seismic tomography (e.g. Chiarabba *et al*., 2004 and references therein; Patanè *et al*., 2003, 2006) there are a number of shortcomings in the information which currently limit the reliably determination of the volcanic processes constraints, especially along the deepest paths of the magma rising. This inadequacy of the available passive tomography is based primarily on the fact that the majority of the earthquakes are shallow and clustered in small volumes, essentially within or close to the volcanic edifice down to 10 km depth. Thus, this earthquake distribution yields high-resolution tomographic images of the shallow crust and the upper portion of the volcano plumbing system.

Therefore, due to the lack of recent active seismic surveys, a new active seismic experiment has been considered necessary to broaden the knowledge of the inner structure of Mt. Etna roots and the surrounding crust, spanning from the volcano basement down to the upper mantle.

The results deriving from this experiment will constitute an important resource to better understand: i) the relationship between volcanism (i.e. Mt. Etna and Aeolian Islands) and plate tectonics, which still presents some shortcomings that the seismic experiment might clarify. In fact, Mt. Etna lies in the complex geodynamic setting of the south Tyrrhenian – Calabrian Arc – Ionian Basin, which originates from the diachronic and fragmented convergence between the Eurasia and Africa plates, one of the most intriguing tectonic areas worldwide, and ii) the magma ascent and eruptive dynamics of this volcano. Furthermore, integration between data acquired during the experiment with the earthquake dataset of the last 10 years, could provide an unique opportunity to calibrate passive seismic tomography obtained with new techniques in the context of the difficult task of interpretation of the volcano inner structure.

With this vision in mind, we planned and carried out the TOMO-ETNA active seismic experiment during the summer of 2014. TOMO-ETNA, which is part of the European project "MEDiterranean SUpersite Volcanoes (MED-SUV)", has been coordinated by Istituto Nazionale di Geofisica e Vulcanologia together with the Granada University (Spain). TOMO-ETNA experiment integrates MED-SUV efforts with the resources of EUROFLEETS 2, another EC research project, and other funding agencies from Italy, Spain, and Germany. Furthermore, TOMO-ETNA has also been supported by the active participation of the Marina Militare Italiana and by the Dipartimento di Protezione Civile della Regione Siciliana.

The focus of this experiment concerns the investigation of Etna's roots and surrounding areas by means of passive and active refraction/reflection seismic methods. Therefore, this experiment included activities both on-land and offshore with the main objective to obtain a new high-resolution tomography in order to improve the 3D image of the crustal structures existing beneath the Etna volcano and the northeast Sicily (Peloritani - Nebrodi chain) up to Aeolian Islands. Its main objective is to achieve a structural model of the Earth crust in northeast Sicily, including an accurate mapping of tectonic structures (faults) and, consequentially, to define the physical processes controlling magma ascent beneath Mt. Etna. Overall, the information deriving from TOMO-ETNA could provide the answer to the many questions that have arisen while exploiting the large amount of data provided by the cutting-edge monitoring systems of Etna volcano and seismogenic aerea of eastern Sicily.

The scheduled activities were divided into two actions: land and sea, and conducted from June 20 to July 25, although some of them will continue until November 2014. During the June - July period, a total of 13,292 air gun shots were produced by oceanographic vessel Sarmiento de Gamboa (CSIC-UTM, Spain; Fig.1) generating seismic signals recorded by seismic stations deployed on-land and on the seafloor as well as the natural seismicity of the region. More of than 60 researchers participated to the experiment coming from different countries, mainly from Italy and Spain but also from Germany, Russia, U.S., Ireland and Mexico.

Additionally, the Galatea vessel from the Istituto Idrografico della Marina Militare and Levanzo vessel always from the Marina Militare have been used to carry out further geophysical

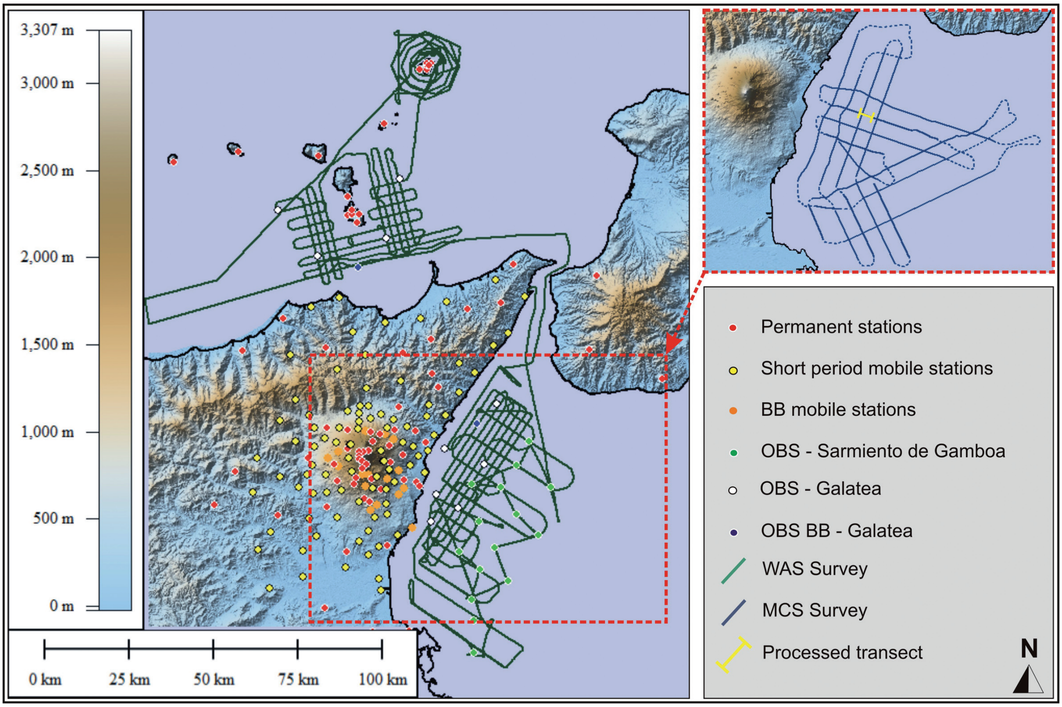

Fig. 1 – Lines of shots: a) Wide Angle Seismic (WAS); b) Multi-Channel Seismic (MCS). In b) the processed transect of Fig. 3 is highlighted.

surveys (such as magnetic measurements) and to support the Sarmiento de Gamboa vessel during the complex survey with a 3 km long multi-channel seismic streamer.

Field operations started one week before the beginning of the experiment, with deployment of 98 seismic stations (80 short period and 18 BB stations provided by the GFZ-Potsdam) on land, supplementing the 70 INGV permanent stations, leading to a total of 168 seismic stations (Fig. 1). Moreover, 27 OBSs (Ocean Bottom Seismometers) were deployed in the Ionian and Tyrrhenian seas (22 in the Ionian Sea and 5 in the Tyrrhenian Sea; Figs. 2,3). 15 OBS/H (OBS with hydrophone) were positioned by the Sarmiento de Gamboa vessel, while 10 OBS-SP (Short Period OBS) and 2 OBS-BB/H (broadband seismometer with hydrophone) by Galatea vessel. The network of OBSs was recovered at the end of the experiment with the exception of the two OBS-BB/H, which will be recovered in November 2014 by the Aegea vessel. These two OBSs will record natural seismicity for a longer period of time.

For the active-source imaging experiment two seismic exploration techniques have been used during the cruise of the Sarmiento de Gamboa vessel, in order to carrier out Wide Angle Seismic (WAS) and Multi-Channel Seismic (MCS) surveys along the programmed lines.

Wide Angle Seismic (WAS): during this phase of the experiment about 9,500 shots were carried out along a total route of approximately 2560 km. The source of the acoustic pulses consisted of an array of two batteries of airguns, each having 8 guns (Sercel, G-GUN II) for a total volume of 5,200 cubic inches generated at about 2000 p.s.i. (1.382×10^7 Pa) pressure. The guns were kept at a depth of about 15 m below the sea level and the shots were carried every 90 seconds. This shot interval was used in order to avoid records contamination by previous-shot induced noise. The configuration of airguns has been opportunely chosen, through previous simulations (performed by UTM-CSIC in Barcelona) to obtain lower frequencies and to allow a greater penetration.

The 3-D velocity structure of Mt Etna and surrounding areas will be performed on the base

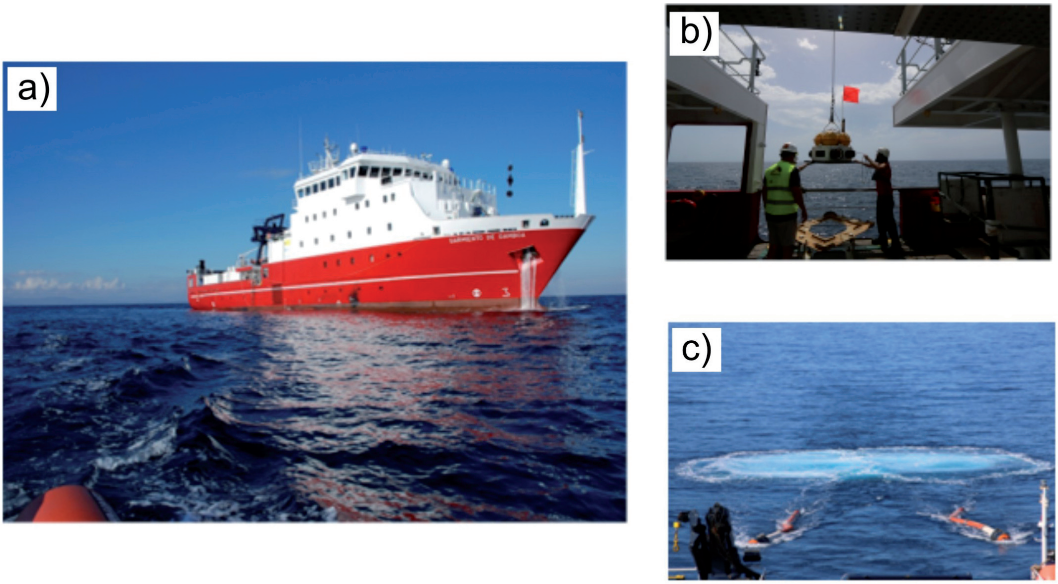

Fig. 2 – a) The vessel Sarmiento de Gamboa; b) activity of discharge of one OBS; c) source of the acoustic pulses generated by the array of two batteries of airguns.

of the above described large data base. It is expected to have more than $2{\cdot}10^6$ first arrivals recorded both offshore and on-land. The algorithm used for the inversion is a modification of the well known ATOM-3D program in which natural seismicity and active signals will be used simultaneously. The first step is to apply an automatic first arrival picking procedure using spectral and temporal characteristics of the signals. The 3-D inversion will be performed in three phases: a) general image of the region under study using large lattices and only with the inversion of the active signals; b) inclusion on passive seismicity to constrain better the deeper portion of the region; c) a high definition seismic tomography of the Etna area using both active and passive seismicity and small cells.

Multi-Channel Seismic (MCS): during this phase of the experiment has been used a hydrophone cable (streamer, SENTINEL Sercel) 3 km long with 240 channels spaced at 12.5 m (each channel contained a group of 8 hydrophone) for record signals produced by airgun shots. The streamer was maintained at a depth of about 10 m from the sea level for an optimal signals acquisition. Also in this case, the source of the acoustic pulses was an array of two batteries of airguns, each having 8 guns (Sercel, G-GUN II) for a total volume of 4,340 cubic inches (cubic inches - us) generated at about 2000 p.s.i. pressure; the guns were kept at a depth of about 7.5 m below the sea level. More than 16,500 shots were generated in this phase. The source frequency bandwidth was designed to ensure a better penetration in the subsoil. During the MCS phase, the airgun array was fired each 37.5 m, i.e., ~ each 20 seconds (considering an average vessel speed of 3.5 knots during the acquisition). This field setup allowed a theoretical maximum fold of 40 traces to each CDP location. Overall, 18 MCS profiles have been acquired for a total length of ~ 620 km.

We show in Fig. 3 about 4 km of profile T-11 (see location in Fig. 1) after a preliminary CDP stack and post-stack depth migration, with the aim of providing the reader with an idea of the overall data quality. CDP data processing included geometry installation, and spiking/predictive deconvolution followed by band-pass filtering. Semblance based velocity analysis methods were used were used to define a 2D background stacking velocity model for CDP ensemble stack. The stacking velocity model was then smoothed and converted in interval velocity to provide an interval velocity model for post-stack Kirchhoff depth migration.

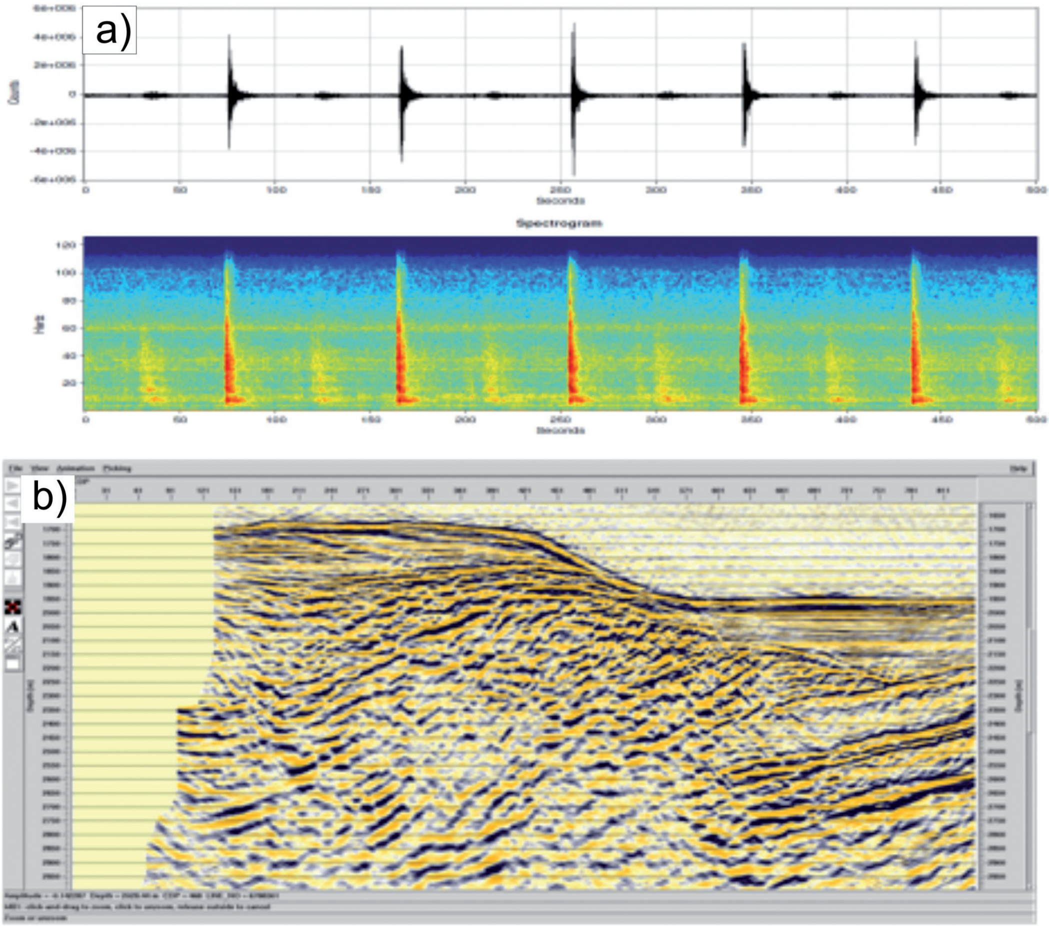

Fig. 3 – a) Example of shots recording at one OBS; b) preliminary Kirchhoff depth migrated CDP stack of profile T11, shotpoints 400-500.

With the aim of better defining the main geological and structural features of the area, the Galatea vessel performed additional scientific activities, such as magnetic surveys and ROV (Remotely Operated Vehicle) dives. New high resolution shipborne magnetic data were acquired offshore Etna volcano covering either major structural features of Timpe area and Riposto ridge. The magnetic data were collected using a Geometrics G880 caesium-pumped marine magnetometers towed 180 m astern of R/V Galatea. 1-Hz raw readings were geographically referenced in real-time using GPS positions provided by the main navigation system (differential correction by using a Fugro Marinestar VBS). The magnetic survey was planned using a line-path oriented along NE-SW direction in order to intersect the major structural–volcanic features offshore Etna. A total of 1340 linear kilometers of magnetic track lines were acquired using a set of 64 NE-SW parallel lines (with a spacing of 250-300 m) and 8 orthogonal tie lines. Raw magnetic data were processed removing spikes and intervening outliers records, further statistical levelling provided a smooth distribution of magnetic pattern of survey area. The Timpe area shows a high amplitude (>700 nT) magnetic anomaly associated with the main structural elements (NW-SE faults system) suggesting a clear interplay between the tectonic setting and the volcanic manifestations. Interesting magnetic features are observed over the Riposto ridge where small high-frequency positive anomalies (200 nT) are correlated to two small E-W structural highs.

The analyses of all acquired data will be done in several steps, with the final objective to integrate results from active seismic techniques (WAS and MCS) with the passive seismic tomography and with the magnetic survey. We hope that our multi parametric geophysical data will allow researchers take a step ahead toward a more accurate and comprehensive image of the Etna plumbing system and of the crustal structures of north-eastern Sicily.

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