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On the origin of micro-earthquakes in geothermal areas (OMEGA): first results from a seismic experiment at Mt. Amiata (Italy)

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ABSTRACT In a joint project called OMEGA, between GFZ-Potsdam and the Istituto Nazionale di Geofisica e Vulcanologia (INGV), an experimental seismic monitoring system was installed in 2015 near the power plants of the geothermal area of Mt. Amiata (central Italy). The main objectives of this three-year experiment are: i) to monitor the seismic activity connected to any type of seismicity inside the geothermal field, ii) to verify if the low local seismicity rate near Mt. Amiata reported by the INGV bulletin is natural, or due to the sparse distribution of the INGV network, and iii) to discriminate natural from possibly induced seismicity. The eight-station network was extended by a seven-element seismic array for the first four weeks. The aim of this paper is to present the first automatic hypocentre locations of the joint network/array analysis.

Key words: geothermal area, induced and natural seismicity, seismic array, automatic detection, Mt. Amiata.

1. Introduction

In Italy, the highest heat-flow values are observed in the geothermal areas of south-western Tuscany and northern Latium. In the areas of Larderello, Mt. Amiata, and Latera the geothermal gradient reaches maxima of 150°/km and may locally exceed those values, as suggested by the recently drilled Venelle well near the locality Lago Boracifero (Bertani *et al.*, 2018). The Tuscan geothermal fields exploited by ENEL-Greenpower are hydrothermal systems (HS), appropriate for high enthalpy energy production. The energy production in HS requires generally no pressurised fluid injection, as the upper crust results extensively fractured and is characterised by high porosity values. At Mt. Amiata, geothermal exploitation started in 1959, by drilling relatively shallow wells (<1000 m depth) for the extraction of vapour/hot water and reinjection of cold water, using the natural fracture system of the rock volume for the circulation of the fluids. Mazzoldi *et al.* (2015) report that after continuous pressure decrease for decades inside the upper geothermal reservoir, the power company deepened in the 1980s the production into a second reservoir, located at a depth of 2500-3500 m.

The seismic activity recorded near Mt. Amiata is generally very low compared to the Apennines, in terms of rate and magnitude. The Istituto Nazionale di Geofisica e Vulcanologia

(INGV) earthquake catalogue (Castello *et al*., 2006; http://cnt.rm.ingv.it) reports for the last 25 years about 140 seismic events with $M \geq 1.5$ (Fig. 1). This may be caused in part by the limited detection capabilities of the sparse local station network and of the regional INGV seismic network: on the other hand, the high heat flow and the consequential ductile behaviour of the uppermost part of the crust may explain this low seismic activity. It is generally an interesting question; how much seismicity is generated by an extinct but still “hot” volcano.

The Parametric Catalogue of Italian Earthquakes (Rovida *et al*., 2016) reports for the Mt. Amiata area 13 moderate seismic events with $4.5 \leq Me \leq 5.3$ between 1287 and 1940, causing damage up to I_{max} = VIII (Fig. 1), proving that damaging earthquakes struck the geothermal areas in southern Tuscany already long before geothermal exploitation started (Braun *et al*., 2016). Recent seismic activity, as the earthquake of 1 April 2000, was of deep concern for the general public. The shallow hypocentral depth of ~4.5 km (Braun *et al*., 2018b) was responsible for damaging more than 50 buildings at Piancastagnaio, and the proximate location of the macroseismic epicentre with respect to the geothermal power plant (Fig. 1) raised the question whether this earthquake was human-induced or of natural origin (Mucciarelli *et al*., 2001). A recalculation of the hypocentre and the focal mechanism could not definitely answer the question about the origin of the 1 April 2000 seismic event, as the hypocentral depth is very similar to the production level (Braun *et al*., 2018b).

In the framework of a collaboration between GeoForschungsZentrum (GFZ) and INGV a seismic monitoring system, combining an 8-station network and a 6-element small aperture seismic array, was installed in the vicinity of the geothermal power plants. The network stations

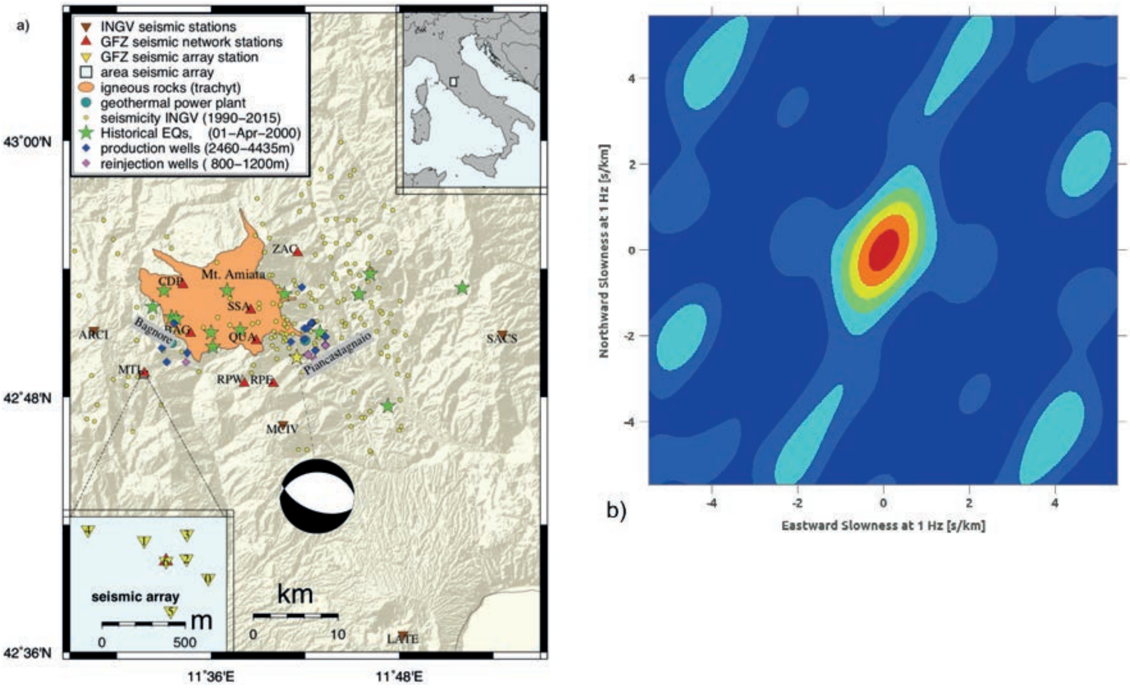

Fig. 1 - a) Configuration of the seismic network/array (INGV-GFZ) operating from 2015 to 2018 in the Mt. Amiata area around the geothermal power plants of Bagnore (III, IV) and Piancastagnaio: historical (green stars) and instrumental seismicity recorded by INGV since 1990 (yellow dots); location of the seismic network (red triangles) and seismic array (green inverted triangles); the beachball indicates the focal mechanism of the M_W 4.5 event of 1 April 2000 (Braun *et al*., 2018b). b) Array response function of the 7-element array around station MTL.

consisted of Earth Data 24-bit digitisers and Mark L-4-3D 1 Hz seismometers, while the array stations were equipped by Cube-digitisers and Le-3D 1 Hz seismometers (Fig. 1a). The main goal of the installation of a combined seismic array/network is to determine the level of seismicity in the area of Mt. Amiata, especially in the vicinity of the geothermal power plants, and to shed some light on the question of how to discriminate anthropogenic from natural seismicity.

2. Geological setting of Mt. Amiata

The Apennines are a fold-and-thrust belt formed by the collision (Oligocene-Early Miocene) of the Adria microplate and the European plate and dissected by a progressive eastward migration of active extension that is superimposed on previous compressional tectonics (e.g. Elter *et al.*, 1975; Lavecchia *et al.*, 1994; Barchi *et al.*, 2007; Carminati and Doglioni, 2012). Since the Early Miocene, the internal zone of the northern Apennines is characterised by a set of low-angle faults, dipping E-NE, with decreasing age eastwards (Collettini and Holdsworth, 2004). Their lateral continuity is interrupted by NE-SW tectonic alignments, which in time acted with different tectonic kinematics, as e.g. relay ramp, transfer zone and normal or strike-slip faults (Signorini, 1935; Bortolotti, 1966; Costantini *et al.*, 1980; Boccaletti *et al.*, 1985; Pascucci *et al.*, 2006; Piccardi *et al.*, 2017; Caciagli *et al.*, 2019). The collisional and post-collisional processes are responsible for the formation of different tectonic units, which, beneath the Mt. Amiata area, can be described as (from top to bottom; Fig. 2, Carmignani *et al.*, 2001; Batini *et al.*, 2003; Brogi and Liotta, 2008; Bonini *et al.*, 2014; and references therein):

- Ligurian and Sub-Ligurian units (Jurassic-Middle Eocene), composed of remnants of oceanic crust and its marine to pelagic sedimentary cover, thrusted onto the Tuscan units in Late Oligocene- Early Miocene;
- Tuscan Nappes (Middle-Late Trias to Oligocene-Early Miocene), derived from the Internal and External Tuscan domains. The sequence ascribed to the Internal domain (Tuscan Unit) is composed, from bottom to up, of Upper Triassic evaporites (Burano Formation), followed by shelf-to-basin sequences, and by a Jurassic carbonate platform, covered by pelagic and terrigenous deposits (Cretaceous to Early Miocene). To the External Tuscan domain is referred the high pressure-low temperature Metamorphic Tuscan complex (Middle-Late Trias to Oligocene-Early Miocene), found only in boreholes and in xenoliths within the Mt. Amiata lavas, indicating a geodynamic evolution from subduction and crustal thickening to exhumation;
- crystalline basement (Paleozoic), mainly composed by phyllites, quartzites and mica schists downwards.

In southern Tuscany, after the emplacement of the thrust units, tectonic sedimentary basins were formed (as e.g. the Radicofani basin, Fig. 2) with NW-SE trending and lengths up to 40 km, filled with fluvio-lacustrine deposits (Upper Miocene to Quaternary), unconformably overlying pre-Neogene units. The post-Tortorian prevailing extension was accompanied by anatectic magmatism, whose age decreases in the eastward and SE-ward direction (Serri *et al.*, 2001; Collettini and Holdsworth, 2004). Other authors (e.g. Sani *et al.*, 2001; Bonini and Sani, 2002; Bonini *et al.*, 2014) propose alternative models, suggesting that the Late Tortonian-Messinian hinterland basins developed under a compressional stress regime followed by alternate periods

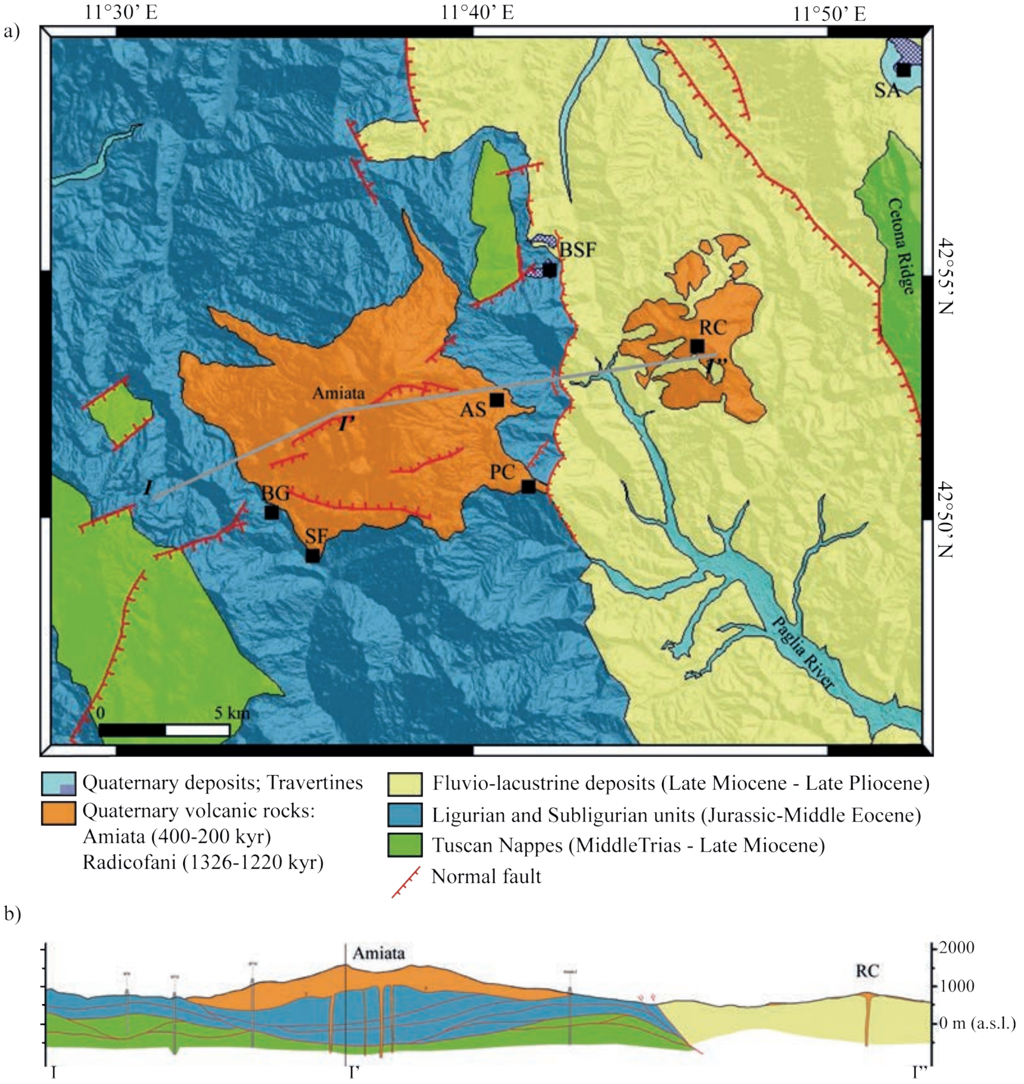

Fig. 2 - a) Geological sketch map of Mt. Amiata and surrounding area: BG-Bagnore; SF-Santa Fiora; PC-Piancastagnaio; AS-Abbadia San Salvatore; BSF-Bagni San Filippo; RC-Radicofani; SA-Sarteano. b) Schematic cross-section along grey line (I - I' - I''), modified from Marroni *et al*. (2015).

of compression and extension. In this scenario the normal faults would represent second-order structures accommodating the thrust activity or recent and active faults.

During the late Pleistocene (400-200 kyr ago) eruptive activity formed the volcanic edifice of Mt. Amiata, which currently reaches an elevation of 1738 m (Gianelli *et al*., 1997). The location of the vents of Mt. Amiata volcano seems to be controlled by a NE-SW oriented Plio-Pleistocene shear zone (along the alignment Bagni San Filippo - Bagnore), affecting the volcanic rocks and its substratum (Fig. 2; Brogi *et al*., 2015; Piccardi *et al*., 2017; Principe *et al*., 2017; and references therein). Some of the faults mapped in the area are considered still active in response to the tectonic regime of the area (Brogi and Fabbrini, 2009; Brogi *et al*., 2015; Piccardi *et al*., 2017) or as result of the spreading of Mt. Amiata volcanic edifice (Ferrari *et al*., 1996; Borgia *et al*., 2014; Mazzoldi *et al*., 2015).

3. Seismic array analysis

The eight-station OMEGA network was operating from end of May 2015 to July 2018. During the first six weeks, six additional three-component stations were installed as small aperture array around the south-westernmost station MTL, near the geothermal power plants of Bagnore III and Bagnore IV (Fig. 1a). Unfortunately, during the experiment, some of the stations have been damaged by vandalism, compromising the data acquisition for 12 days.

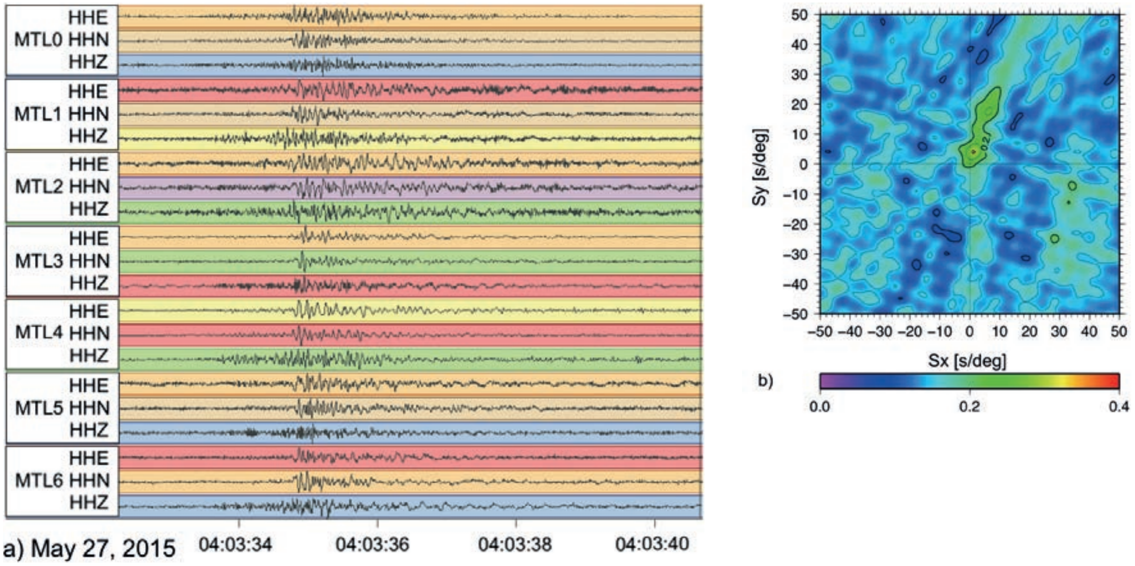

Fig. 3 - a) Seismic traces of a local event of 27 May 2015, 04:03:20 GMT recorded by the MTL array. b) Values for backazimuth of 17.1°, slowness of 4.37 s/deg (»25.44 km/s apparent velocity) and t_S-t_P = 1.184 s indicates a local seismic source.

Systematic analysis of the array data revealed an intense local seismicity, especially in the north-eastern sector. One example is given in Fig. 3 that shows the seismic traces of an M 0.8 event recorded at approximately 8 km depth slightly NNE with respect to the centre of the MTL array. We concentrated our analyses mainly on the northern and eastern sector, within a radius of 5 km from the array centre, where the main industrial activities (e.g. power plants, pipelines, drilling towers, extraction and reinjection wells) connected to geothermal energy production are concentrated. Figs 4a to 4d show the results of the fk-analysis for the backazimuths of a) 25°, b) 55°, c) 65°, d) 145°, assuming an uncertainty ±5°, and the map projection of the main directions (Fig. 4e). Seismic transients reaching the array from SE (Fig. 4d) are probably caused by industrial activities in the quarry located at a distance of 2 km from the MTL array, while seismic signals in the north-eastern sector seem to be generated in the vicinity of specific activities related to geothermal exploitation, as production (Fig. 4a), reinjection (Fig. 4b), or drilling (Fig. 4c).

It is important to underline that i) the recorded magnitudes did not exceed 1.5, ii) only a local seismic array is able to detect such weak signals, iii) the geographical vicinity of hypocentre and anthropic activity alone does not allow to discriminate whether the origin of these events is natural or induced.

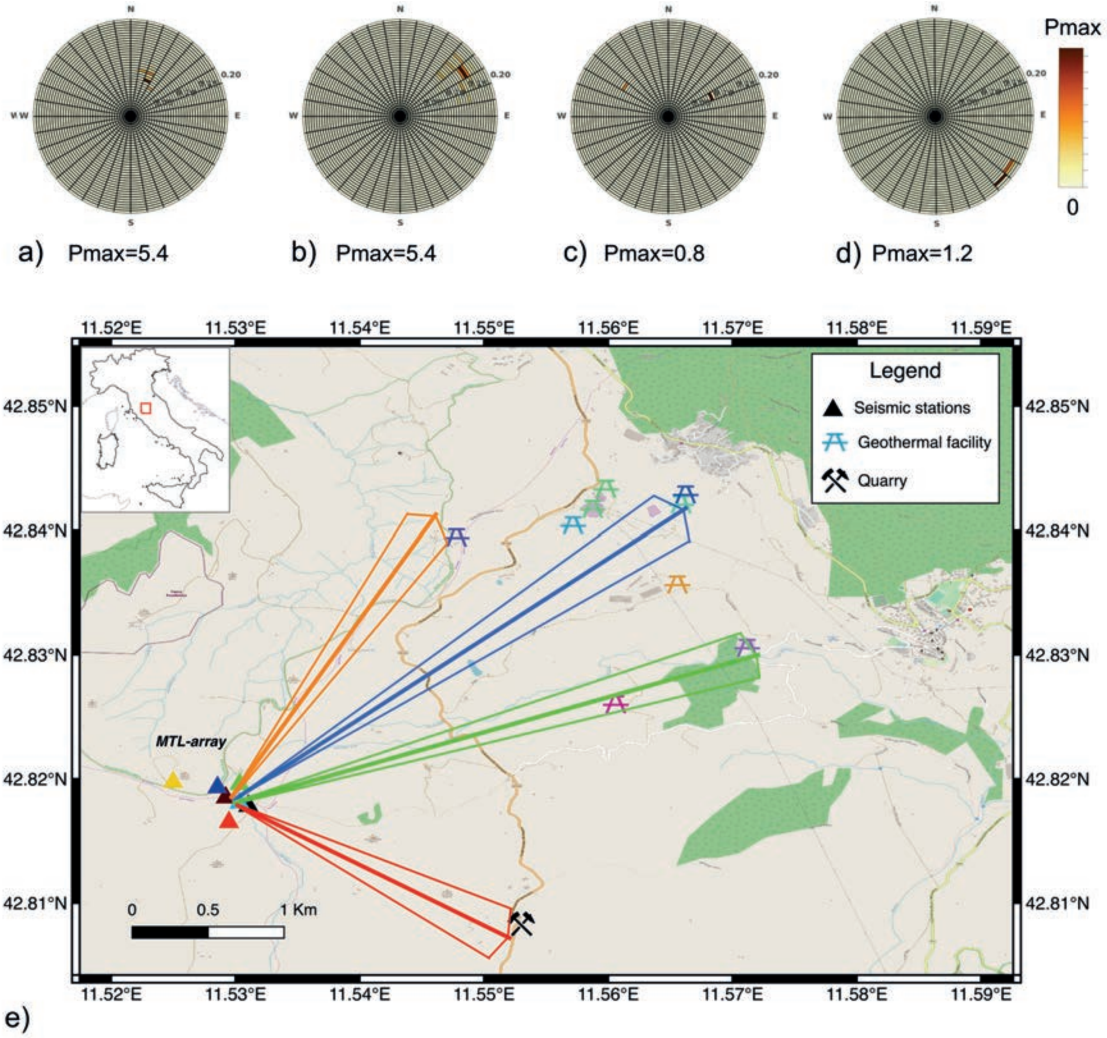

Fig. 4 - Distinction of seismic sources by f-k analysis, Pmax indicated the maximum signal power (panels a to d) and map projection (panel e) of the seismic energy reaching the array from different backazimuths, pointing into directions of anthropic sources, as quarry blasts or geothermal energy production at Bagnore: production wells (yellow), reinjection wells (blue), power plant (red), drilling tower (green).

4. Automatic detection and localisation by using "LASSIE"

In order to rapidly analyse the entire 3-year data set, we applied an automatic detection and localisation code, called LASSIE (Heimann *et al.*, 2017). Lassie exploits a migration-based technique depicting coherent (P and S waves) arrivals at different stations for detecting and locating earthquakes. First of all, a local 1D velocity model is used to calculate once the theoretical travel times for a 3D grid of potential seismic sources within a predefined crustal volume. For our case we chose a 48×48 km^2 lateral extension of the grid, centred at coordinates 42.85° N and 11.60° E, and a depth extent from the surface to 20 km depth. We chose a grid spacing of 2 km. In order to extend the data set as much as possible, we included in our analyses the INGV stations ARCI, LATE, MCIV, SACS already operating around the study area.

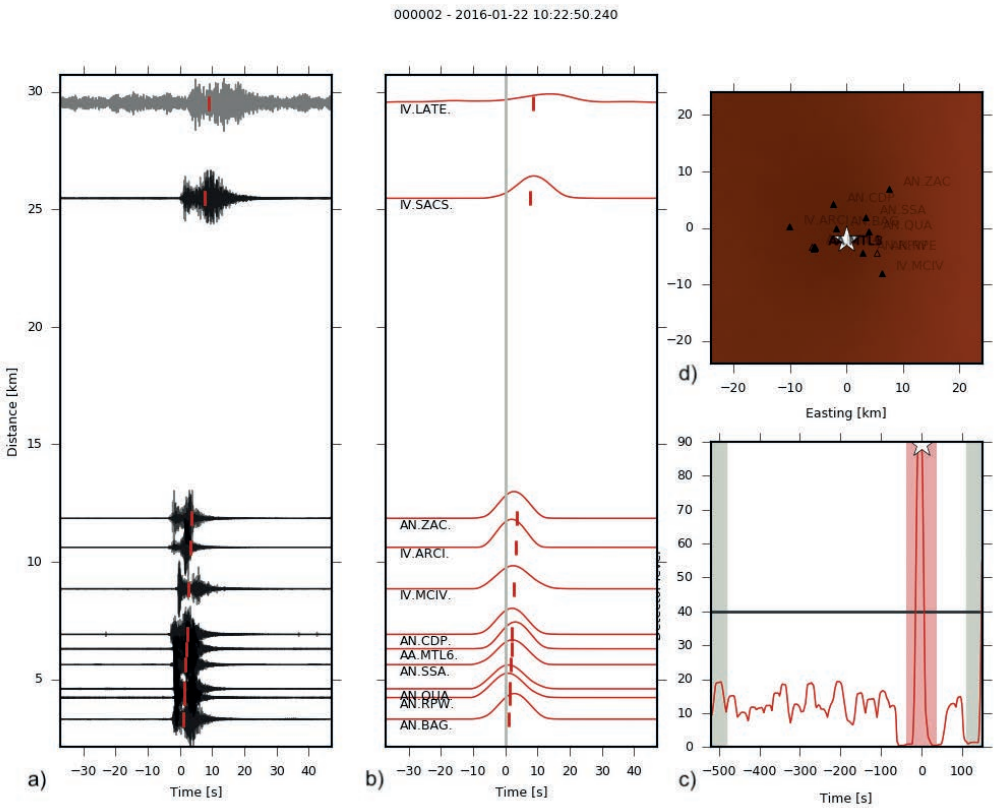

Fig. 5 - Example for LASSIE data detection and localisation (event n° 000002 of 22 January 2016, 10:22:50.24 UTC): a) prefiltered traces used to calculate the envelope; b) application of an STA/LTA trigger to the envelope traces and determination of the P and S onset times by cross-correlation analysis; c) event detection based the overcome of a coherence threshold (using, for each time step, the maximum coherence over the spatial grid); d) grid searching the entire crustal volume and definition of the final hypocentre by the highest coherence value.

Fig. 5 summarises the single steps of Lassie's data processing illustrated by the example of a seismic event detected on 1 June 2015, 10:15 UTC (for details see Heimann *et al.*, 2017):

a) calculate the envelope of the prefiltered traces;
b) apply a STA/LTA trigger to the envelope and determine P, S onsets by cross correlation analysis;
c) event detection (an event is detected any time the maximum coherence over the spatial grid overcomes a threshold value);
d) grid search of the entire crustal volume, defining the final hypocentre by the highest coherence.

Before applying Lassie to the entire data set, several tests were made to define the optimal trigger settings, tuned especially to the local events inside and around the geothermal area of Mt. Amiata. Tuning became particularly important after 24 August 2016, in order to exclude from the detections, the *M* 6.0 Amatrice earthquake and the following long-lasting central Italy seismic sequence, which continued also after the end of our experiment. Table 1 reports the number of events per year and Fig. 6 illustrates in detail the temporal evolution of the earthquake number and the corresponding coherence.

Table 1 - Number of seismic events detected and located by the OMEGA network.

Year	n° of events
June 2015	205
2016	731
2017	144
July 2018	178
Total	1258

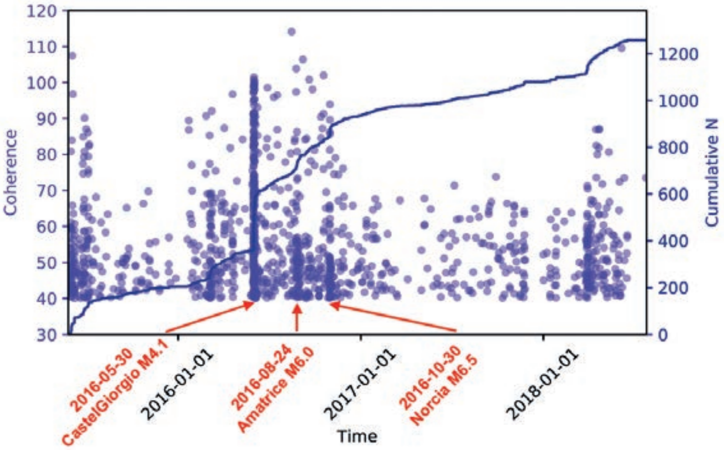

Fig. 6 - Result from scanning the three year data set recorded by the Amiata seismic network, including three additional stations from the INGV network (period from June 2015 - July 2018): temporal evolution of the coherence of the locations.

A further moderate M4.1 earthquake occurred on 30 May 2016 near Torre Alfina/Castel Giorgio, and was followed by a 1-month aftershock sequence (Braun *et al*., 2018a), well distinguishable in Fig. 6. Being these aftershocks located at an epicentral distance less than 30 km from the centre of the OMEGA network, they fall inside our predefined detection volume and were, therefore, not excluded from the analyses.

Fig. 7 shows the epicentral locations obtained by the grid search result of the automatically detected seismic events and summarises the epicentres in a heatmap, divided annually from 2015 to 2018. According to the individual colour bar of each sub-figure, the colour intensity is proportional to the number of events per each 2×2 km^2 grid cell. The spatial distribution is surprisingly homogeneous, except for some border effects, due to the geographical limits of the study area. Locations slightly outside the grid search volume are projected on the border cells, indicating an alleged high number of hits. Examples are the brown-coloured cells on the western side, as well as the events of the May 2016 seismic sequence SE of Mt. Amiata. However, in the central part of the study area seismicity seems to be concentrated near the geothermal power plants (green circles in Fig. 7) of Bagnore (west) and Piancastagnaio (east). As the automatic and rapid detection algorithm is based on a homogeneous 1D-velocity model, LASSIE provides a good image of the distribution of the epicentres, but only a rough estimate of the hypocentral depths, which should therefore not be overinterpreted at the present stage.

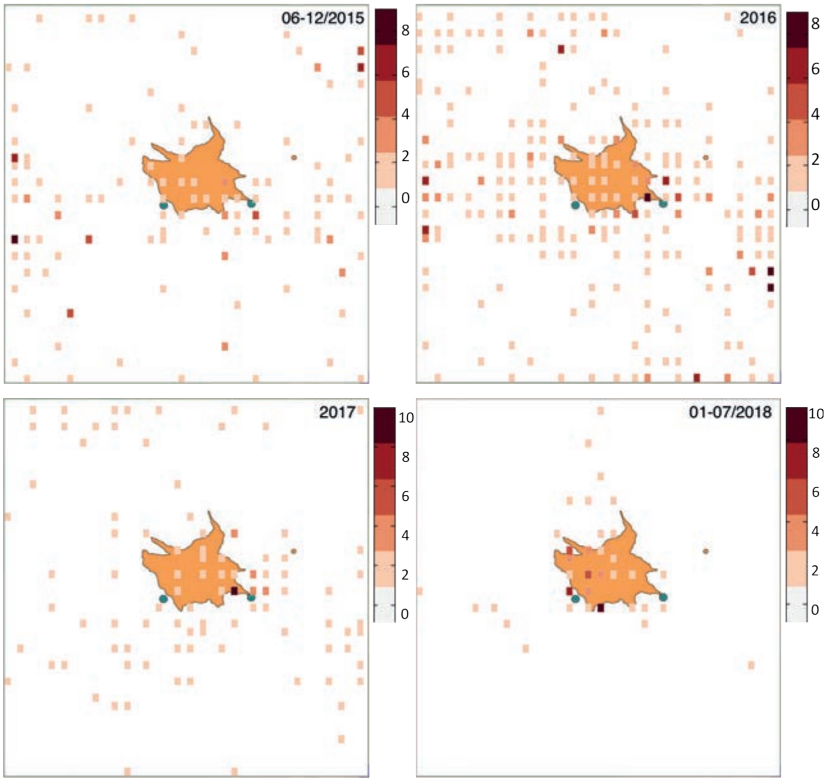

Fig. 7 - Result from scanning the three-year data set recorded by the Amiata seismic network, including three additional stations from the INGV network for the period from May 2015 to July 2018. Green dots represent the localities of Bagnore (west) and Piancastagnaio (east). Heat map: number of localisations per grid cell (2×2 km^2).

5. Discussions and conclusions

Recently, important earthquakes have been reported from areas with geothermal energy production, as e.g. in Switzerland (Kraft and Deichmann, 2014; Edwards *et al*., 2015), in South Korea (Grigoli *et al.,* 2018a) and in Italy (Mucciarelli *et al*., 2001; Mazzoldi *et al.,* 2015; Braun *et al.,* 2018a, 2018b). As geothermal exploitation is often practiced in areas with significant seismotectonics activity, the question raises whether earthquakes in geothermal areas have exclusively natural origins, or if some of them are also triggered or induced by the extraction or reinjection of fluids. A combination of a dedicated seismic monitoring approach and the adoption of full waveform-based methods, as done in this work, were successfully used to shed light on recently debated geothermal induced seismicity cases (Grigoli *et al*., 2018a). In particular, full waveform methods help to detect weak events, with noisy signals, to improve the location accuracy and to potentially resolve source parameters and rupture characteristics (Cesca and Grigoli, 2015; Grigoli *et al*., 2018a). Our results confirm that the full waveform approach provides robust seismicity information and supports the investigation of potentially induced seismicity cases.

Concerning the Tuscan geothermal area of Mt. Amiata, natural moderate earthquakes ($M <$ 5.3) have been reported long before geothermal exploitation started (Braun *et al*., 2016; Rovida *et al*., 2016). For the period 1990-2015, the INGV catalogue specifies only 300 seismic events (1.5 <

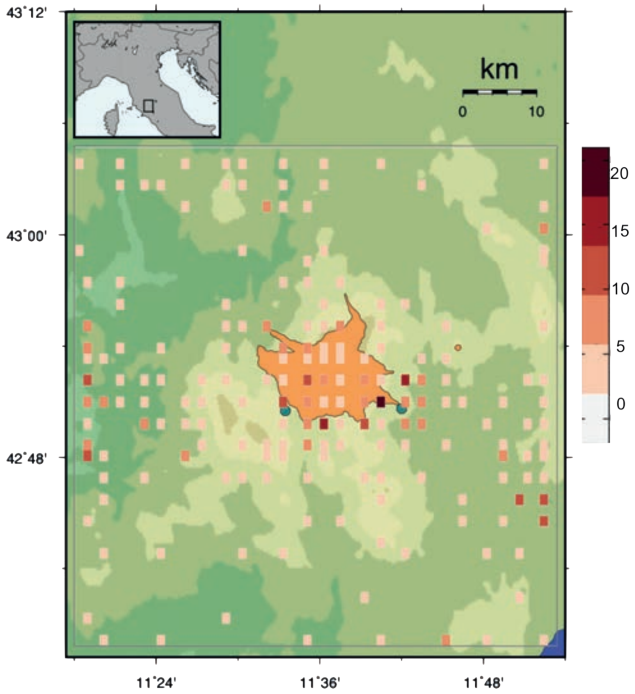

Fig. 8 - Cumulative heat map (from Fig. 7) for the entire three-year recording period of the seismic array/network installation. Green dots represent the localities of Bagnore (west) and Piancastagnaio (east). Heat map: number of localisations per grid cell (2×2 km^2).

$M < 2.5$) for the area of Mt. Amiata, an average value of 12 events/year. On the other hand, most earthquakes around the geothermal power plants (as e.g. the hypocentre of the M_W 4.5 event of 1 April 2000) are located in an upper crustal depth (~4 km), similar to the geothermal production level.

However, to investigate on this topic is the main objective of OMEGA - Origin of Micro-Earthquakes in Geothermal Areas. In the framework of this joint project, between INGV, GFZ-Potsdam, and University of Potsdam, a seismic network/array was installed in the geothermal area of Mt. Amiata (central Italy). In a 48×48 km^2 area around Mt. Amiata, the automatic detection and localisation revealed 1258 seismic events for the period from May 2015 to July 2018 (average value of 1 event per day).

The significant increase of seismicity in the study area during 2016 is partly due to the M 4.1 sequence near Torre Alfina/Castel Giorgio (May 2016), but may also be triggered by the strong earthquakes in the central Apennines in August and October. Fig. 7 illustrates the cumulative epicentral heat map for the entire three years of the OMEGA project as obtained by LASSIE (Heimann *et al.*, 2017).

Automatic detection and location reveal that the major number of seismic events is concentrated near the southern border of Mt. Amiata, in the vicinity of the geothermal power plants of Piancastagnaio (SE) and Bagnore (SW). Actually, the depth resolution of the hypocentres is not high enough to allow a geological interpretation or to discriminate human-induced events. The next step will be to use the result of the present study and to relocate the detected events by using a robust and automated analysis procedures as waveform-based methods (e.g. Cesca and Grigoli, 2015; Grigoli *et al.*, 2018b and references therein), which locate seismic events providing high quality locations in a single step, while the main disadvantage is that they are computationally expensive.

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