Understanding the inner structure of Larderello (Tuscany, Central Italy) by a multi-scale integration of geophysical data

Claudio Chiarabba[1], Sergio Vinciguerra[2,3], Monia Procesi[1], Davide Piccinini[4], Mario Anselmi[1], Gilberto Saccorotti[4]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma1, Via di Vigna Murata 605, Rome, 00143, Italy

[2]Department of Geology, University of Leicester, Leicester, LE1 7RH, United Kingdom

[3]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, United Kingdom

[4]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma1, Via della Faggiola 32, Pisa, 56126, Italy

E-mail: sv127@le.ac.uk

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ABSTRACT

Larderello is one of the first geothermal systems investigated by geophysical studies and monitored with seismic networks, managed by ENEL operated since 25 years and providing one of the most complete set of seismological observations in geothermal areas. The analysis of microseismicity revealed a clustering of earthquakes along the so-called k-horizon, a sharp seismic reflector interpreted as a fluid-filled layer, and allowed the computation of velocity tomographic models. Very recently, and still operating, a dense 2D seismic network of broadband instruments has been installed by INGV to collect high quality passive seismic data. Aim of this set up is the reconstruction of i) seismicity patterns in space and time, ii) source parameters of micro-earthquakes, iii) 3D velocity and attenuation structure and iv) fractures and fluids in the sub-surface structure. In this framework, the interpretation of geophysical results and well logs, in terms of nature and structure of crustal rocks requires data on the physical properties of rocks which can be obtained experimentally on single samples. In particular, laboratory simulations can allow us to rebuild the thermo-hydro-mechanical mechanisms that occur in geothermal systems, such as, those related to the interplay of supercritical fluids and rock massesIn addition, a better determination of the effects of the confining pressure, temperature and pore fluid pressure on the physical properties of rocks is required for an improved geophysical interpretation of crustal, viz. lithospheric structures, as well as for the understanding of specific failure modes and the identification of brittle-ductile transitions.

1. THE SEISMIC EXPERIMENT

A local seismic network given by 11 broad-band sensors has recently integrated two permanent seismic stations operated in the area as a part of the National Seismic Network (RSN) in order to acquire new information on the microearthquakes occurring in the Larderello Travale Geothermal field (LTGF), routinely monitored by a seismic network from ENEL. Public permanent stations in the area are in operation only since mid 2010, when two instruments (TRIF and FROS; see Fig. 1) were installed as a part of Istituto Nazionale di Geofisica e Vulcanologia's Rete Sismica Nazionale.

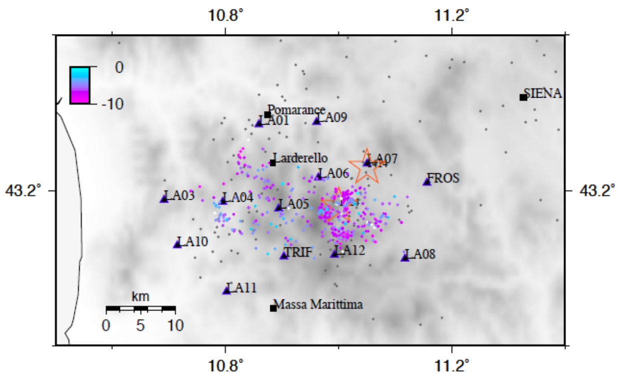

Fig. 1 – Seismicity map of the events recorded during the first four months of the GAPSS experiment (filled, colored circles). The color of the symbols indicates source depth, according to the color scale at the upper left. White dots are hypocenters deeper than 10km. Seismicity located by RSN in the 2005-2012 time window is indicated by gray small dots. Triangles are seismic stations.

By early May, 2012, we complemented the two permanent stations with eleven temporary instruments. The resulting network has an aperture of about 50 km and average station spacing around 10km (Fig.1); the acquisition is foreseen to extend throughout a 15-months time interval. The two permanent stations are equipped with broad-band seismometer. Mobile stations are equipped with compact broad-band, three-component seismometers. Both recorders and seismometers are provided by the RE.MO. (Mobile Seismic Network) facility at INGV-CNT.

In Figure 1 we show the instrumental seismicity recorded and located during the first three months of the GAPSS experiment (see Piccinini et. al, this volume). Seismicity is shallow (Z < 10 km) and widespread throughout the geothermal area. Hypocenters are shallower in the southernmost part of the geothermal field, while moving toward north and east, seismicity gets deeper. Moment magnitude (Mw) ranges between 0.5 and 2.3 (Piccinini et al., this volume). The daily rate (Fig. 2) of located earthquakes is rather constant, and it accounts for an average of 5 event/day. Nonetheless, there are episodic, short-living burst of enhanced seismicity, with peaks of up to 50 events/day.

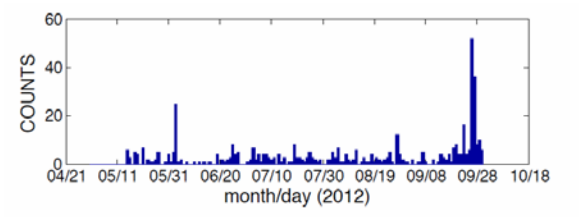

Fig. 2 - Daily number of located earthquakes for the May - September 2012 time interval.

The Vs model derived using a Wadati modified diagram from 2D P-wave velocity model, shows great variability in the residuals suggesting un-modeled, strong lateral heterogeneity of the S wave velocity structure. The Vp/Vs estimated from the whole dataset is 1.73. The acquired data will be the main ingredients for future studies on deep structure and relation between fluids and seismicity. The homogeneous and wide distribution of micro-earthquakes during this experiment is a good pre-requisite to achieve kilometric resolution of buried bodies beneath the geothermal area. Body wave arrival times and waveforms will be used to produce high resolution velocity and attenuation models of the sub-surface that will help tracing the geometry of the underground and location of hot fluids, plutons, intrusive meshes. The relation between micro-earthquakes and deep fluids will be possible for the intrinsic high resolution of the acquired data. The final goal will be the joint use of seismological and petrophysical data to constraint the structure, dynamics and evolution of the Larderello geothermal field.

2. PHYSICAL PROPERTIES AND LABORATORY SIMULATIONS

The interpretation of geophysical results in terms of nature and structure of the lithosphere requires experimental determination of the physical properties of rocks. On the geological scale there is no direct correlation between the lithology and structure and, for instance, seismic velocity. Therefore the interpretation of seismic structures is not unique. Additionally, a better determination of the effects of confining pressure, temperature and pore fluid pressure on the physical properties of rocks is required for an improved geophysical interpretation of crustal, viz. lithospheric structures. Our aim is to achieve a fundamental and precise insight into the structure of the geothermal system and to explain the interplay of supercritical fluids and rock masses. Rock physics laboratory experiments allow determination of how intrinsic properties of rocks (e.g., microstructure, composition, fabric, microcracks, strength, seismic properties and attenuation) vary as a function of extrinsic variables (pressure, temperature, pore fluid pressure, differential stress). In order to simulate conditions at depth in the Earth's crust, it is necessary to conduct rock deformation experiments inside a pressure vessel. A jacketed rock sample is placed inside the pressure vessel, and the vessel is then pressurised (using silicone oil) to simulate the lithostatic stress at depth. A separate pressurisation system is then used to provide water pressure in the internal pore space of the rock sample (known as the pore fluid pressure). The specimen jacket acts to keep the two fluids apart. The sample assembly may then be heated via an internal furnace to simulate the temperature at depth, and finally an axial stress is applied via a loading ram to simulate the tectonic stress. The sample jacket is made of a synthetic rubber compound and contains inserts for the location of piezoelectric transducers that are used for the measurement of elastic wave velocities (both compressional and tangential) and microseismic (acoustic) emission output. A schematic diagram of this arrangement is given in Fig. 3. Two pore fluid ports in

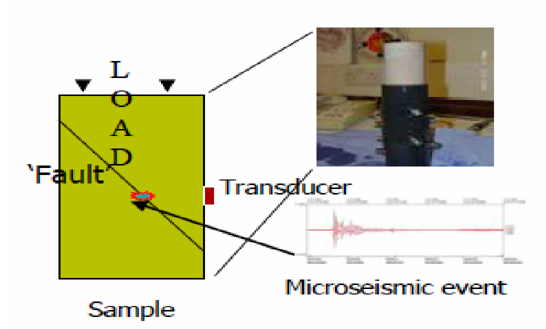

Fig. 3 – Experimental set up for simultaneous measurements of microseismicity, Vp/Vs velocities at in situ effective pressure conditions.

the sample end-caps allow for fluid flow through the sample for the measurement of permeability. The petrophysical properties of the lithologies recovered from boreholes will be investigated throughout direct laboratory measurements of P and S wave velocities, densities and porosities and their pressure and temperature derivatives), to aid the interpretation of geophysical surveys and characterize the geological structure of the inner structure of Larderello geothermal fields. The petrophysical parameters will be measured both under dry conditions and in presence of pore pressure. In addition we will investigate the rheology and mechanical properties of the inner structure (including the brittle-ductile transition), which results in ground deformation and seismicity, through triaxial deformation experiments on rock samples from the recovered cores. This includes experiments of compaction and inflation using vapor as pore fluid, in order to cross the transition from ductile to brittle behaviour (characterized by the evolution of microseismicity. The rock permeability variation with pressure and temperature will be investigated in detail. We are particularly interested in the effect of circulating aggressive fluids that might cement or dissolve phases and vary the permeability. To achieve this aim we will circulate high temperature aggressive fluids and saturated fluids and record the permeability variation with time at simulated in situ conditions.

3. CONCLUSIONS

We propose a joint geophysical study aiming to understand the inner structure of Larderello throughout multiscale integration of geophysical data. Microseismicity recorded at the field scale will be integrated with the outputs of controlled rock deformation laboratory experiments at ‘in situ’ simulated conditions. Theoretical modelling will help validating experimental observations and will be used to extrapolate laboratory observations to the field scale.