Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Submarine Geothermal Systems in Southern Tyrrhenian Sea as Future Energy Resource: the Example of Marsili Seamount

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Keywords: Submarine Geothermal Systems, Geothermal Exploration, Marsili Seamount

ABSTRACT

Italy has one of the greatest geothermal potential for power production in the world. At the present, the exploitation of geothermal reservoirs for power generation is concentrated in two main areas located in the Tyrrhenian pre-Apennine volcanic district of Southern Tuscany: Larderello-Travale/Radicondoli and Mount Amiata. These two geothermal reservoirs are hosted in Mesozoic carbonatic formations and metamorphic basement, with temperatures of 200–350°C at a depth of 500–3500 m. In the 1970s and 1980s a joint-venture ENEL-AGIP performed an exploration program in Latium, Campania and Sicily regions finding great potential but low exploitability due to high salinity of geothermal fluids. A new target for geothermal exploration and exploitation in Italy is represented by the submarine volcanic district of Southern Tyrrhenian Basin. The latter is a geologically young (Upper Pliocene – Pleistocene) area characterized by tectonic extension with associated magmatism. In this context numerous volcanic centers developed and provide important heat sources; heat flow data of the area show positive anomalies comparable to those of onshore geothermal fields. Fractured basaltic rocks facilitate seawater infiltration and consequent circulation of hot water chemically altered by rock/water interactions, as evidenced by the presence of hydrothermal deposits on Tyrrhenian seamounts, collected during previous oceanographic samplings. A geothermal exploration program of the Marsili seamount, the greatest volcanic edifice in the European area, started in 2006. Preliminary data interpretation suggests the presence of geothermal activity and further research is foreseen to better characterize the whole volcanic-geothermal system. If realistically exploitable geothermal reservoirs are discovered, submarine geothermal systems will be an important – potentially infinite – renewable energy resource in Italy, opening a scenario for a future development of offshore geothermal power generation.

1. INTRODUCTION

In the last three decades a huge amount of data has been acquired on the geological, geophysical and geochemical features of submarine environments. One of the most important aspects of these investigations concerns the volcanic activity along mid-ocean ridges and/or away from them in isolated areas (seamounts). This magmatic activity is currently associated with the release of large amounts of hydrothermal fluids or plumes (Baker et al., 1995; Lupton, 1995; Elderfield and Schultz, 1996). These fluids, because of their enormous quantity and virtually infinite recharge, high temperature and relatively low-salinity, potentially represent one of the most abundant energy resources worldwide. In addition, the recent and significant developments in offshore drilling facilities and techniques allow for easier exploitation of submarine hydrothermal systems. However, before any reliable energetic utilization of offshore geothermal resources can be quantified, a multi-disciplinary exploration has to be done, including geological investigations, technical and economic feasibilities.

In this study, we report the preliminary results carried out during and after the marine cruise "Prometheus" on board of the R/V Universitatis, in July 2006. This cruise has been aimed to decipher the main geological and geophysical characteristics of Marsili seamount, the largest European and Mediterranean volcano, even larger than Etna. Considering its size dimension and its relatively favourable location in the southern portion of Tyrrhenian Sea, Marsili volcano can be regarded as a possible geothermal energy resource. This should significantly improve the amount of onshore Italian geothermal power generation, which furnishes about 5.5 TWh per year and covering only 1.6% of national mean electricity production (Bertani, 2007).

The exploration and exploitation of high-temperature geothermal resources started in Italy at the beginning of the last century in the Larderello area (Southern Tuscany). Successively, exploration programs were extended to several other areas of potential interest, invariably located in the Tyrrhenian pre-Apennine belt of central-southern Italy and in the Aeolian Islands. At present, the only Italian geothermal fields industrially exploited are all located in Southern Tuscany: 1) Larderello-Travale/Radicondoli and 2) Mt. Amiata (Bagnore and Piancastagnaio), with a total installed capacity of 810 MWe (711 MWe running capacity; Buonasorte et al., 1995). They are both set in a continental extensional tectonic environment (lithospheric thickness between 20-30 Km), characterized by deep and shallow volcanic systems and high heat flow values (regional value of 120 mW/m^2, with maxima up to 1 W/m^2; Baldi et al., 1994). In particular, both these geothermal areas are characterized by: magmatic bodies that provide the necessary heat source, deep and shallow reservoirs hosted in the metamorphic, carbonate and anhydritic formations of the Tuscan units and cap rocks represented by tertiary and quaternary marine and continental terrigenous sediments (Batini et al., 2003; Bertini et al., 2005).

In order to improve the Italian geothermal energy amount, in 1970s and 1980s an exploration program (geological, geophysical and geochemical surveys, as well as drilling activities) took place in Latium (about 100 deep wells were drilled in Latera caldera, Vico Lake, Cesano, Bracciano Lake and Alban Hills), Campania (Phlegraean Fields and Ischia Island) and Sicily (Vulcano and Pantelleria Islands) (Buonasorte et al., 1995). However, several physical, chemical and logistical unfavourable characteristics strongly limited the use of these potential geothermal fields. The geothermal exploitation was hindered by the low-permeability of the reservoirs, the high salinity and acidity of the hot fluids, the sluggish and low amount of groundwater recharge, the high potential explosivity of these magmas (rhyolites, trachytes and phonolites) implying a high volcanic hazard as well as the strong urbanization and/or touristic use of the aforementioned areas.

With comparison to Italian onshore geothermal fields, submarine basaltic Southern Tyrrhenian volcanoes, and in particular Marsili, have the following advantages:

1) A heat source generally represented by hot magmatic bodies at shallow depths (less than 10 km) in strong distensive geodynamic setting, as testified by high heat flow (Della Vedova et al., 2001).

2) A high primary permeability of volcanic rocks due to cooling of magmas, successively increased by the intense and recent tectonic activity (Neri et al., 1996; Turco and Zuppetta, 1998; Pondrelli et al., 2004).

3) A virtually infinite fluid recharge availability supplied by pressurized seawater.

4) A relatively lower amount of dissolved salts with a mild acidity.

5) A low explosivity due to the presence of lesser evolved magmas with a lower amount of dissolved water.

Finally, it is noteworthy to consider that from a technical and logistic point of view, on-site geothermal exploitation and production of electric energy on Marsili is already available, in view of the minimum depth of seawater of about 500-600 m over the volcano summit and its distance from the Italian coasts of about 100 km.

2. GEOTHERMAL FEATURES OF SOUTHERN TYRRHENIAN SEA AND MARSILI VOLCANO

Southern Tyrrhenian Sea is a back-arc basin developed from Miocene to Present in the frame of the coeval formation of Apennine-Maghrebid Chain, structured above the north-western subducting Ionian oceanic slab (Doglioni et al., 2004; Rosenbaum et al., 2004). Its evolution has been characterized by great tectonic extension inducing volcanic activity and recent diffusing seismic activity, all migrated in space and time from North-West to South-East (Savelli, 1988; Beccaluva et al., 1994; Selvaggi and Chiarabba, 1995; Neri et al., 1996; Favali et al., 2004). The geodynamic evolution of Sothern Tyrrhenian basin is morphologically evidenced by two main abyssal plains, the oceanic crust floored sub-basins of Vavilov (4.3–2.6 Ma) and Marsili (2 Ma), respectively; inside them the two greatest Tyrrhenian seamounts developed (Barberi et al., 1978; Kastens et al., 1990). In the surrounding areas of Marsili basin numerous other seamounts are located, representing the Western and North-Eastern submerged prosecution of the Aeolian Arc: Sisifo, Enarete, Eolo, Lametini, Alcione, Glabro and Palinuro.

The Moho depth is located 15-20 km below the Tyrrhenian abyssal plains and ~10 km beneath Vavilov and Marsili seamounts (Steinmetz et al., 1983; Locardi and Nicolich, 1988) corroborated with the following geophysical data. High resolution seismic reflection sections suggest a strong extensional setting of the Tyrrhenian basin (Finetti, 2004). An extremely high heat flow with regional values around 120 mW/m^2 and local maxima in correspondence of Vavilov (140 mW/m^2) and Marsili (250 mW/m^2) areas has been recorded (Della Vedova et al., 2001; Mongelli et al., 2004). Furthermore, on the uppermost and central portions of Vavilov and Marsili volcanoes, heat flow achieves 300 and 500 mW/m^2, respectively (Verzhbitskii, 2007). These positive heat flow anomalies coincide with gravity and magnetic ones (Faggioni et al., 1995; Cella et al., 1998). Thus, the geophysical data strongly suggest the presence of magmatic bodies intruding shallow, thinned and stretched crustal levels. In turn, the diffuse and localised high heat flows are related to the upraising of basaltic melts at lower depth below the Tyrrhenian sea-floor. Therefore, volcanic Tyrrhenian seamounts can be considered huge heat sources; and the Marsili seamount is the most intense one.

Rock samples from Tyrrhenian sea-floor are mainly magmatic in origin. The Marsili volcanic rocks have been collected through several dredging and coring projects (Selli et al., 1977; Savelli and Gasparotto, 1994; Trua et al., 2002). The majority of these samples are basalts and to a lesser extent andesites and trachy-andesites; their compositions have a calc–alkaline affinity, with medium to high potassium contents. Several rock samples have been recognised, such as: lavas, pillows and dikes, with moderate to high vesicularity.

Bio- and magneto-stratigraphical data show that expansion of Marsili basin began between 1.87 and 1.67 Ma (Kastens et al., 1990; Faggioni et al., 1995), while lava sampled on the summit of the volcano provides age between 0.1-0.2 Ma (Selli et al., 1977). Positive magnetic anomaly has been correlated to normal polarity geomagnetic Chrone C1 (Brunhes, 0.78-0 Ma; Faggioni et al., 1995). The basin, inversely magnetized, is attributed to post-Olduvai, late Matuyama Chrone (1.67-0.78 Ma). Some Authors (Marani and Trua, 2002; Nicolosi et al., 2006) postulate an ultra-fast and recent oceanic spreading model to explain these magnetic features. This strong tectonic activity can be expected to increase the permeability of magmatic rocks of Marsili.

In a review, Dekov and Savelli (2004) summarised all the observations since the late 1960s on the rocks sampled from Marsili and surrounding volcanic centres. They concluded that these areas are affected by hydrothermal fluid circulations; in their model, cold seawater enters into fractured rocks and then is superheated by magmatic bodies at crustal depths. This scenario appears to represent a part of the diffusive release of fluids by hydrothermal vents in Southern Tyrrhenian Sea, as now directly observed at Vulcano, Stromboli and Panarea Islands and nearby islets and Marsili seamount (Uchupi and Ballard, 1989; Marani et al., 1999; Savelli et al., 1999). Measured geothermal fluid temperatures are 103 and 53°C in submarine waters near Vulcano (Stetter, 1982) and Panarea Islands, respectively (Italiano and Nuccio, 1991).

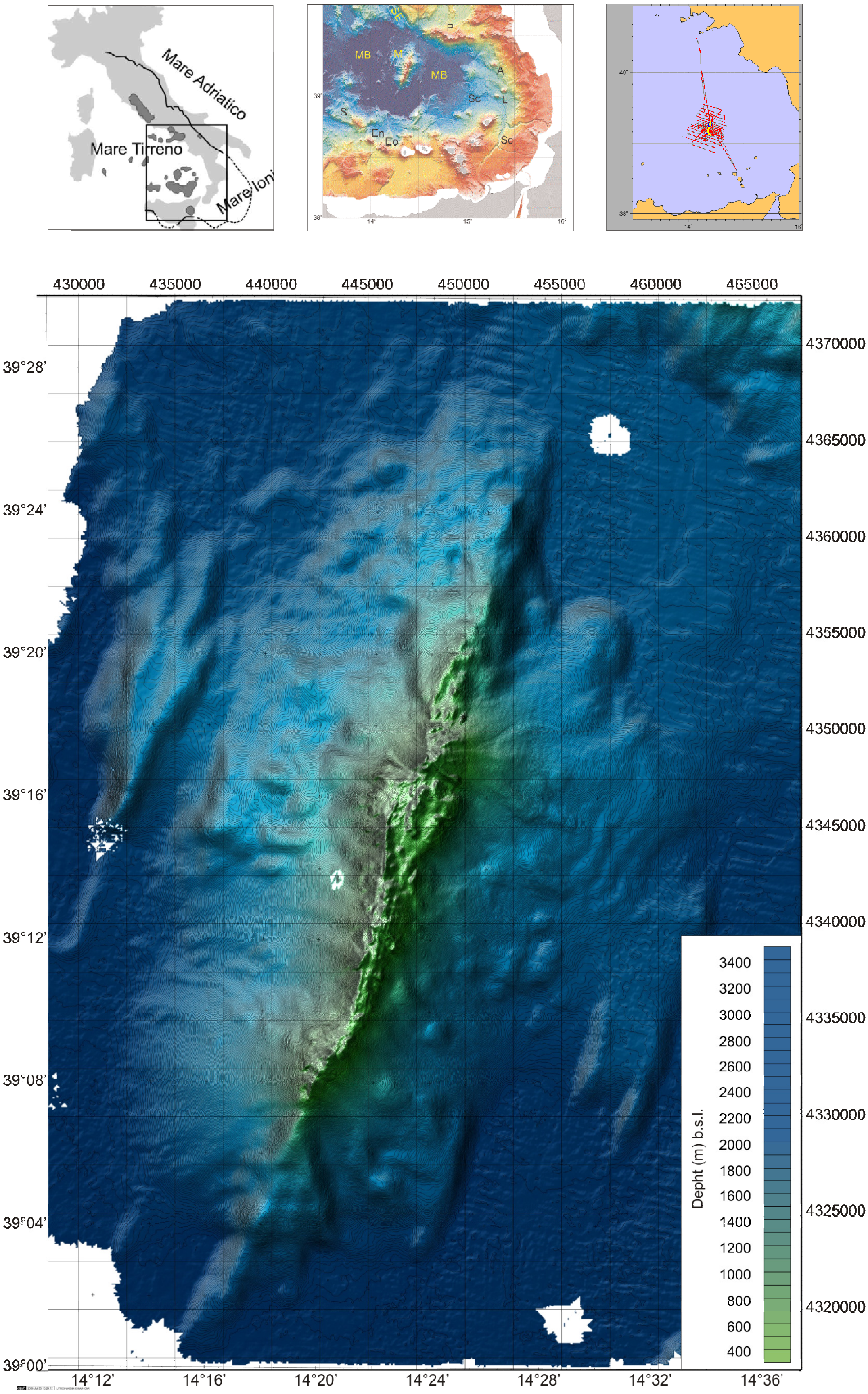

Figure 1: Bathimetric and morphologic map of Marsili volcano (main figure). In the upper insets, Southern Tyrrhenian Sea localization (left), bathimetric map (central; MB: Marsili basin; M: Marsili volcano; P: Palinuro volcanic complex; Sc: Stromboli canyon; L: Lametini seamount; A: Alcione volcano; Eo: Eolo volcano; En: Enarete volcano; S: Sisifo volcanic ridge; modified after Marani and Gamberi, 2004) and "Prometheus" cruise tracks (right) are shown.

Conversely, direct thermal measurement on Marsili seamount is still lacking. However, Marsili seamount appears to be pervaded by hydrothermal fluids, as suggested by the presence of oxy- and hydroxide-deposits; these deposits are predominantly made up of Fe- and especially Mn-rich sediments, crusts and nodules (Marani et al., 1999; Dekov and Savelli, 2004; Dekov et al., 2006). In addition, the presence of sulphide minerals has also been found on Marsili seamount; the sulphides are also Zn- and Pb-rich, but poor in Cu and relatively poor in Fe. A wide spectrum of accessory for sulfosalts and selenides, not typical of mid-ocean ridge massive sulfides, has been found and it is probably a consequence of the wide variety of leached magmatic rocks (Dekov and Savelli, 2004).

A further intriguing point of the volcanic activity of Marsili is the highest $^{3}He/^{4}He$ ratio ever measured in the Tyrrhenian Sea, which was found on the top of the seamount (Lupton et al., 2008). This recent discovery strongly points out that Marsili is still hydrothermally active, in agreement with the previous mineralogical data, and supported by a significant contribution by juvenile fluids.

3. "PROMETHEUS" CRUISE AND RELATIVE METHODOLOGIES

From July 10 to 22 2006, a research group from the Centro Studi e Ricerche Sperimentali per le GEOtecnologie CeRS-GEO (DIGAT department) of the University "G. d'Annunzio" (Chieti, Italy) in collaboration with the Istituto Nazionale di Geofisica e Vulcanologia INGV and the Istituto di Geologia Marina ISMAR-CNR (Bologna) teams, performed the following exploration activities on Marsili seamount:

- swath bathymetry and Chirp Sub Bottom Profiling;
- magnetic survey;
- gravimetric survey;
- seismic monitoring;
- bottom sampling.

An area of approximately 750 km^2 was covered in the surveyed areas during the cruise. Mapping on board was performed by using the PDS-2000 production DTM, interfaced to a sonar positioned on the ship's keel, converted to ASCII, filtered and gridded. The obtained grids were used for navigation, planning, as well as geomorphological and structural analysis.

The ISMAR group used a Marine Magnetics SeaSpy magnetometer. The towfish was kept 120 m off the stern, on the port side. The data was collected by the Marine Magnetics SeaLink software on the multibeam and transit lines. The software integrated positional data by the NMEA GGA and VGT strings was delivered by the ship's DGPS receiver. The INGV team towed two Geometrics Mod-G811 magnetometers in a gradiometric configuration 150+150 m off the stern on the starboard side. The system console received the positional and time data from the ship's DGPS via NMEA GGA sentences. The data was qualitatively checked and processed by the OASIS GEOSOFT software.

A gravimeter was installed by the INGV team very close to the center of gravity of R/V *Universitatis*. A pattern of runlines displaced half way between magnetometric lines were run, thus increasing the resolution of magnetic data.

An OBS/H was deployed by the INGV team on a gentle depression at 800 m depth just SSE of the top of Marsili. The site was chosen by examining available ISMAR's bathymetric data complemented by the cruise's newly acquired data. The OBS/H was released 2006/07/12 and recorded continuous data for 9 days. Sampling frequency of seismic and acoustic data was set at 200 Hz so to detect signals with frequency content up to 100 Hz.

15 grabs and a unique core were recovered during the cruise. They were subsampled, described and photographed on board.

4. PRELIMINARY RESULTS

Morphology. The physiographic features of Marsili seamount are reported in Figure 1, as well as its location and the cruise path. The Marsili seamount rises 3500 m from the abyssal plain to 489 m minimum depth. The volcanic edifice is about 60 km long and about 20 km wide; the other two physiographical smaller structures run parallel to the volcano and are located on its left and right part, with heights in the order of several hundreds metres (Figure 1). Marsili is elongated mainly along a NNE-SSW axis; however, this extensional axis is not perfectly linear but it shows a sigmoid trend, with the southernmost and northernmost axial directions both trending more north-easternly; by contrast, the central axis is closer to the N-S direction (Figure 1). The volcano summit is characterized by a narrow crest, 20 km long and 1 km wide, over the 1000 m isobath, cut by linear structures, mainly disposed parallel to the extensional axis. Steep bathymetric gradients separate the crest portions from the deeper volcano flanks, forming kilometric and lesser sloped scarps extending to the basin. In several places, these lower steep scarps terminate with gently dipping terraces, elevated for several hundreds of meters from the abyssal Marsili basin. The volcano flanks are also cut by several kilometric valleys; the largest of them is located near to the central and top portion of Marsili. It has an amphitheater shape in the uppermost part edged by roughly vertical walls; such geomorphologic feature suggests a flank collapse of this portion of the Marsili flank, with landslide debris accumulated distally on the Marsili basin (McGuire, 1996; Blanco-Montenegro et al., 2008) (Figure 1).

Numerous and spherical cones are present on the crest and on the flanks of volcano with diameters ranging between several hundreds and few kilometres. These cones do not appear to be dissected by successive structures (Figure 1).

Magnetic data. Figure 2 shows the total field magnetic anomaly map, reduced to a magnetic pole, recorded on Marsili seamount. In agreement with literature data (Faggioni et al., 1995; Nicolosi et al., 2006), positive magnetic anomaly maxima are located along the central sectors of the volcanic structure. At northern and southern portions the highest positive anomalies of Marsili are present, with maximum values around 1500 nT; in the central and highest portion of volcano and in the middle of these two former anomalies, the values are around 0 nT, reaching a minimum of -100 nT (Figure 2). Negative anomalies are located at the base of the western flank, with a mean value around -200 nT; the base of the eastern flank again shows negative values, achieving a local minimum of -500 nT in the central and southern portions, whereas the north-eastern part of this sector is characterised by small positive values (Figure 2).

Gravimetric data. According to the map of Faye gravity anomalies of Marsili seamount, positive maximum values, more than 80 mgals, are present on the crest portion of volcano, above the 1000 m isobath, and progressively decrease to about 20 mgals on the volcano base. On the whole, the configuration of gravity field anomalies is strictly related to the topography of the volcano (Figure 3).

Seismological recordings. During the 9 days of seismic monitoring on the crest of Marsili volcano, besides one teleseismic and a few regional and local seismic events, other interesting signals have been recorded, such as very high frequency noise and a surprisingly high number, about 800, non-tectonic seismic events. An intriguing feature of seismic noise is its spectral content; it presents progressively growing energy levels in a broad-band frequency range from 4 to 60 Hz; diffuse spectral peaks are also present between 4 and 30 Hz. The non-tectonic events are characterized by short duration in time (few seconds) and an indiscernible S-phase. On the basis of preliminary observation about their frequency content, they can be distinguished in two main groups: about 720 with frequency content between 4 and 10 Hz; about 80 with very high frequency content, between 40 and 80 Hz.

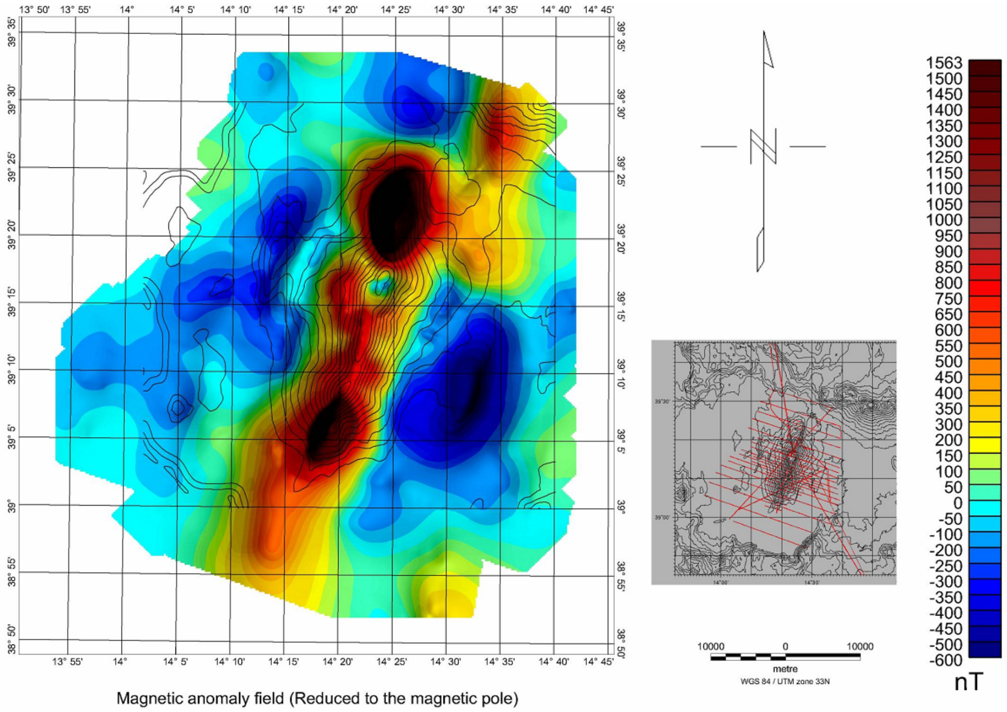

Figure 2: Magnetic anomaly field (reduced to the magnetic pole) of Marsili volcano. In the right inset magnetic survey runlines are shown. Black solid lines are isobaths (200 m equidistance).

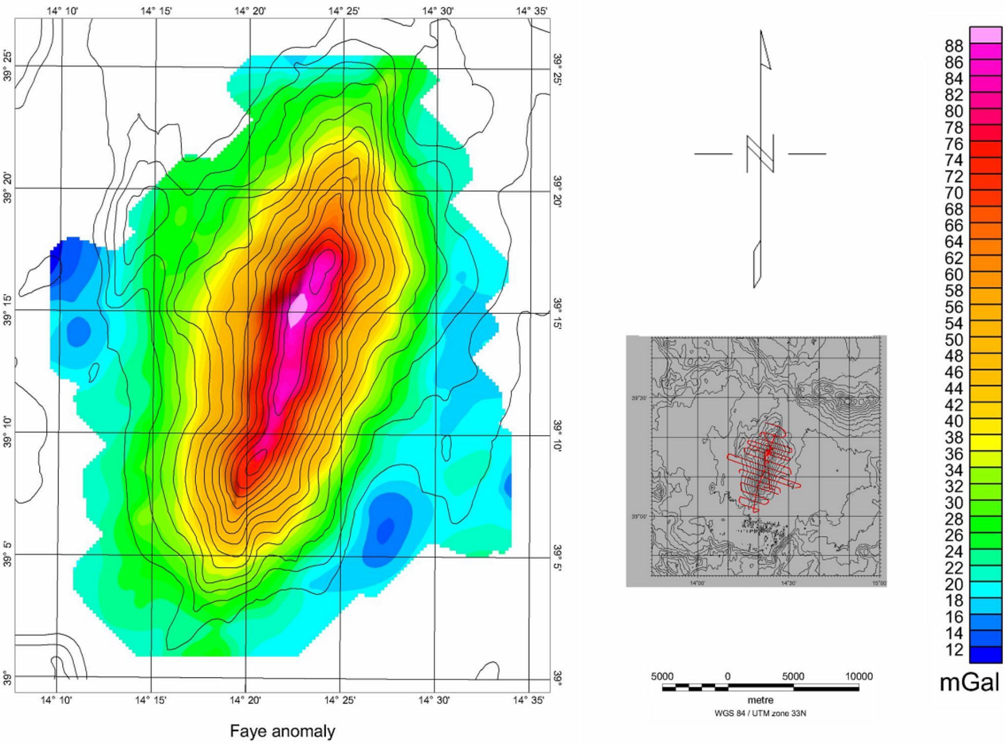

Figure 3: Faye gravity anomaly field of Marsili volcano. In the right panel gravimetric survey runlines are shown. Black solid lines are isobaths (300 m equidistance).

Preliminary petrographical data. The 15 dredged samples with an approximate volume of less than 0.5 m^3 are mainly comprised of loose mud deposits; these samples were collected only in the axial and uppermost areas of Marsili. Such samples are reddish to brown coloured and invariably show alteration features.

First XRPD data reveal an extremely abundant amorphous content, whereas crystalline materials are mainly clay minerals, carbonates, and to a lesser extent micas and quartz. In addition, a unique cylindrical core, with a length of about 1 m and a diameter of 15 cm was sampled near the top of the volcano. Hand-specimen and optical microscopic data reveal a marked presence of tephra deposits with a thickness of several centimetres, interlaid with mud deposits.

5. DISCUSSION

The data collected during "Prometheus" cruise allowed for further constraints when combined with previous geological information about the Marsili seamount. The basaltic to basaltic-andesite rock compositions reported by Trua et al. (2002) are in agreement with the positive magnetic anomalies measured on the northern and southern portions of the Marsili volcanic edifice. Generally, freshly erupted basalts (also rapidly cooled) are strongly magnetic (Hildenbrand et al., 1993; Tivey, 1994) because they have not been exposed at length to demagnetization processes.

However, the most intriguing feature of the magnetic anomaly field of Marsili seamount is the very low anomaly values in the central sector of the crest that testifies to the presence of rocks with very low and/or non-magnetic properties. Hydrothermal activity may be a cause of such magnetic inhomogeneity. The hydrothermal circulation fluids may interact with the source rocks and reduce the magnetization by breaking down the magnetic minerals (Irving, 1970; Johnson et al., 1982); this evidence corroborates with the occurrence of hydrothermal processes, possibly still active or recorded by geothermal deposits on the crest of Marsili volcano (Marani et al., 2002; Dekov and Savelli, 2004).

In addiction, the non-magnetic anomaly can also be correlated to a shallow Curie isotherm; it has been preliminary located at around 4-5 Km below Marsili crest, indicating a temperature of more than 600°C at the volcano base. Such estimation highlights the possible presence of magmatic bodies still active. The high internal temperatures inferred by magnetic data show significant agreement with the extremely high heat flow measurements on Marsili (Della Vedova et al., 2001; Verzhbitskii, 2007). All this complementary data suggests that Marsili is one of the most intense and shallow European heat sites.

The internal structure of the Marsili volcano can be roughly inferred mainly by gravity data. The gravity anomaly field observed (Figure 3) can be fitted only assuming a mean density of the volcanic structure of about 2 g/cm^3, as shown in the model reported in Figure 4. Taking in account the petrographic features of Marsili rocks (Trua et al., 2002) as well as the magnetic data, such values can be attributed to rock porosity/permeability, possibly filled with aqueous and volatile phases. The largest landslide crown observed at just north-west of the top of Marsili (Figure 1) and discussed previously, is located near the most dense (Figure 3 and 4) and locally low-magnetized (Figure 2) portion of the volcano summit. These geomorphologic and geophysical data point out that this flank collapse event has probably exposed the most internal and central portions of volcanic system. In any case the estimated density of this innermost volcanic sector is lower than 2.2 g/cm^3 and also than void-free basalt and basaltic andesite. Therefore, it can be tentatively concluded on the basis of gravimetric data that the Marsili volcano should have a significant porosity, possibly of more than 10% by volume.

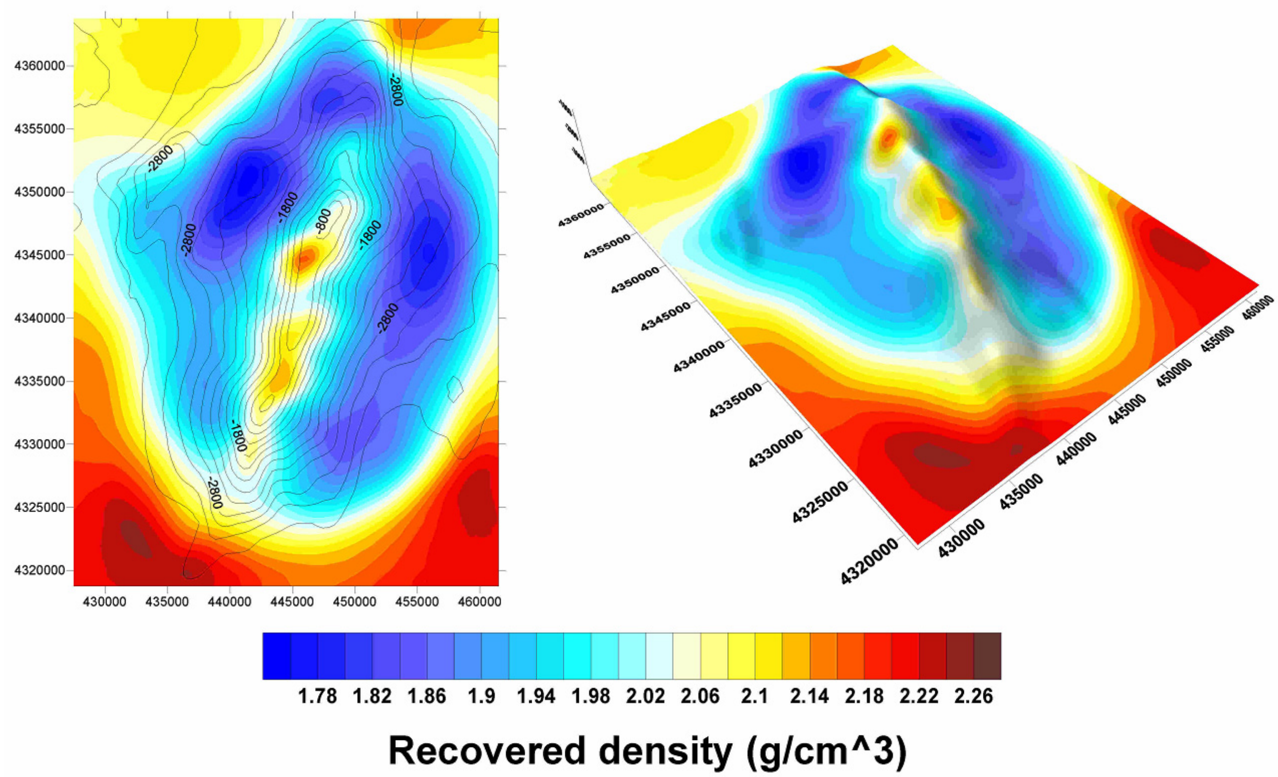

Figure 4: Recovered density model of Marsili volcano. Black solid lines are isobaths (300 m equidistance).

High rock fracturing due to tectonic activity is then supported by seismic observations by means of the OBS/H deployed on the crest of Marsili seamount. Despite the relatively few days of monitoring activity, some clearly tectonic seismic events have been recorded only by OBS/H and not by the onshore networks of seismic stations (D'Alessandro et al., 2009). This element proves the existence of an intense local tectonic activity affecting Southern Tyrrhenian basin (as also observed in Favali et al., 2004) and possibly enhancing the permeability of Marsili rocks. In such a time frame, the very high frequency seismic noise recorded on the Marsili crest significantly supports the hypothesis of still active hydrothermal activity inside the volcano. Historic seismic noise recordings in geothermal areas generally have a spectral content concentrated in the frequency range between 2 and 20 Hz that – in proximity of geysers, hot springs and other surficial phenomena – can be extended until 50 Hz and more. Seismic noise recorded on Marsili volcano looks in frequency content very similar to those signals generated by surficial phenomena such as collapse of the bubbles of the ascending hot hydrothermal fluid, that has been observed in some geothermal fields (Leet, 1991 and references therein).

The observed seismicity characterized by a frequency content between 4 and 10 Hz could presumably be connected to hydrothermal fluid circulation processes, while those with 40-80 Hz frequency content could be generated by surficial degassing phenomena (D'Alessandro et al., 2009 and references therein).

6. CONCLUSION AND FUTURE DEVELOPMENTS

The present and future evaluation of Marsili as a possible geothermal energy resource can be summarised with the following points:

1) Marsili is a shallow and extremely intense heat source.

2) Marsili can be expected to possess an intense geothermal fluid circulation as supported by previous data and this study.

3) The present state of Marsili volcano is still controversial, i.e. active vs quiescent, although several data indicate extremely recent magmatic and related processes (possibly thousands of years before Present).

4) Localization of active venting sites and hydrothermal fluid release with physical and chemical characterization must be performed; this is one of the main purposes of a future cruise on Marsili seamount planned for the next year; the acquired data will be integrated with the already available geophysical data and will be useful to assess the magmatic activity.

5) The ongoing characterisation of solid rocks and loose deposits, already available or to be sampled in the next cruise, from petrographical, geochemical and volcanological point of views will allow the evaluation and further constraint of the geological model of Marsili seamount and any potential hazard it may present.

If strong evidence of potentially exploitableactive geothermal activity are found, the Marsili seamount will become an important and virtually infinite offshore geothermal energy resource, doubling the Italian onshore geothermal power generation. Moreover, this will open a new scenario in the exploration and exploitation of geothermal energy resources, representing the first potential pilot experiment for offshore geothermal power generation in Italy and significantly contributing to the research of new energy resources worldwide.

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