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Perspectives of offshore geothermal energy in Italy

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Summary. — Italy is the first European and world's fifth largest producer of geothermal energy for power generation which actually accounts for less than 2% of the total electricity production of the country. In this paper after a brief introduction to the basic elements of high-enthalpy geothermal systems, we discuss the potentialities represented by the submarine volcanoes of the South Tyrrhenian Sea. In particular we focus on Marsili Seamount which, according to the literature data, can be considered as a possible first offshore geothermal field; then we give a summary of the related exploitation pilot project that may lead to the realization of a 200 MWe prototype power plant. Finally we discuss some economic aspects and the development perspectives of the offshore geothermal resource taking into account the Italian energy framework and Europe 2020 renewable energy target.

1. – Introduction

Geothermal energy represents one of the most interesting as well as globally less exploited energy sources. In particular among renewables, it benefits from high potentialities concerning both low-enthalpy applications and power generation. Regarding the second application, Italy has a well-consolidated know-how. Indeed, in 1904, the

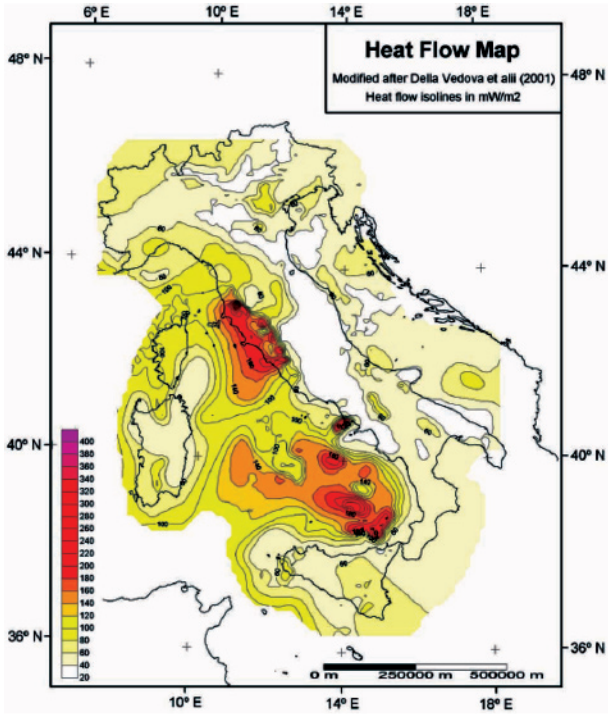

Fig. 1. – Italian territory Heat Flow Map modified after [3]. Note the high heat anomaly in Tuscany and in South Tyrrhenian Sea.

Larderello field represented the first example of geothermal exploitation for electricity production at a global level. Since that important year, geothermal power generation has grown nearly continuously and actually with 5.65 TWh/y it accounts for 1.6% of the total gross electricity production and 6.8% of the electricity production from renewable sources of the country [1]. Until now, all the 843 MW of geothermal installed capacity are located in the provinces of Pisa, Siena and Grosseto in the region of Tuscany only [2]. Nevertheless, geophysical and geodynamical studies performed to achieve a better comprehension of the seismicity and volcanism of the Italian territory, have been extended in order to locate further exploitable high-enthalpy geothermal fields. Besides the well-known heat flow anomalies located in Tuscany and in Phlegraean Fields near Naples, a great anomaly area was revealed within South Tyrrhenian Sea whose maxima are located upon submarine volcanic structures (called *seamounts*) which rise hundreds of meters above the sea floor (fig. 1). In this paper, following literature results, we will present and discuss the possibility of exploiting these volcanic structures as offshore geothermal fields. After a brief overview of onshore geothermal fields and an introduction to the South Tyrrhenian Sea geodynamical evolution, attention will be focussed on the characteristics of Marsili Seamount including those highlighted in a recent highly detailed oceanographic campaign. The reported data will be outlined as indicators of the geothermal potentialities by making a comparison with the properties of onshore fields. Finally, we will give a description of an in progress project devoted to the offshore geothermal exploitation of Marsili Volcano for electricity production and conclusions will be drawn considering the overall issues discussed within the Italian energy framework.

2. – Overview of high-enthalpy geothermal fields

In principle, in every place on the Earth's surface, by drilling down to the suitable depth, it is possible to find the desired temperature for the geothermal application of interest. According to the mean Earth temperature gradient equal to 35 °C/km, on average, the minimum required temperature for high-enthalpy applications for electricity production would be reached at 4 km depth. Under these conditions, for the moment, geothermal exploitation is economically unfeasible. Therefore, high-enthalpy fields require *heat flow anomaly areas* where temperatures of several hundreds of degrees are reached within few thousand meters.

High temperature gradient, thus high heat flow, is not the only basic requirement in conventional technology because in such kind of applications the presence of natural water represents a major constraint needed for effective exploitation. In the following lines we will give a brief description of the main elements constituting *hydrothermal* fields, where conventional exploitation takes place.

Hot body. In most cases, consisting of magma intrusions which provide thermal energy to the system.

Reservoir. Responsible for the collection and the circulation of geothermal fluids which are heated by the hot body, and made up of high hydraulic permeability-transmissivity rocks.

Cap rock. An insulating layer that prevents geothermal fluid leakage outside the system and that ensures temperature and pressure maintenance.

It is important to underline that hydrothermal systems are usually set in old volcanic areas because here the above-described elements are more likely to be present at the same time. This point is fully confirmed by the geothermal fields in Tuscany: old volcanic areas connected to the Apennines chain formation. As a matter of fact, the natural water provision of the reservoir is the hardest condition to be met in general, and it has determined the geothermal inoperability of a great number of heat anomaly areas, non-volcanic ones in particular. Over the last decades, other technologies have been conceived in order to overcome the reservoir water availability: the Hot Dry Rock (HDR) that uses external water injections, and the Enhanced Geothermal Systems (EGS) which are provided with a complete closed circuit of the heat transfer fluid. However, these technologies, in particular the EGS which represents the future generation of geothermal applications, will not be treated further in this article.

3. – South Tyrrhenian Basin and Marsili Seamount geophysics

South Tyrrhenian Sea opening, begun in Miocene epoch nearly 20 Ma ago, is configured in the already complex geodynamical framework of the Italian Peninsula and can be directly related to the African and Eurasian plate convergence. The tectonic activity started from the western margin of Sardinia, migrated eastward giving rise to *rifting* and consequent formation of new oceanic crust domains. This evolution has occurred in two main episodes: the first one with the opening of the Vavilov Basin (7–3.5 Ma) and the second one with the opening of the Marsili Basin (1.7–1.2 Ma) [4]. The extension of South Tyrrhenian Sea, better defined as back-arc basin, has occurred above the westerly subducted oceanic Ionian slab (part of the African plate) which has led also to the formation of the Calabrian Arc. The roll-back motion and high Benioff angle characterising the Ionian slab are of primary importance to understand not only the extensional tectonics of the system but also to comprehend the intense associated volcanism of this area [5]. Because of this intense volcanic activity, the basin domain is studded by a great number of emerged volcanoes (the Aeolian Islands Arc), and submerged volcanoes having both similarities and differences from the geochemical and morphological point of view (fig. 2). This brief description allows us to introduce really important topics to the present discussion. This tectonic model can explain the regional low crustal thickness and the high heat flow of the back-arc basin with the average value of 20 km and 120 mW/m^2, respectively [7]. In particular the minima of the crustal thickness and the maxima of the heat flow of the whole Tyrrhenian Sea coincide with the position of the two main seamounts, Marsili and Vavilov, at the centre of the homonymous sub-basins.

Now, our description will focus on Marsili Seamount whose geological characteristics are partly shared by other seamounts of the South Tyrrhenian Sea, but make it particularly attractive from the geothermal exploitation point of view. The seamount, which is elongated in the NNE-SSW direction, rises from the -3500 m of the basement to the -489 m of the top of the crest; being 60 km in length and 16 km in average width it is one of the biggest volcanoes in Europe. The causes of the formation of the nearly 1500 km^3 structure have been deduced by its morphology and have been identified with the intense magma pulses originated from the subducted Ionian slab melting occurred about 0.7 My ago [9]. The basalt lava rocks composing the edifice belong mainly to the calc-alkaline and to the tholeitic magma series which, due to the quick cooling process after eruption, are characterised by a high degree of fracturing and vesicularity [10]. The submarine volcanic structure gets the maximum of heat anomaly flow of the whole Tyrrhenian Sea with values close to 250 mW/m^2 [3], but recent measurements report values up to 500 mW/m^2 within the crest's summit [11]. To further investigate the seamount's properties a comprehensive measurement campaign took place in 2006 and among the most important data, gravimetric and magnetic anomaly measurements were taken [8]. Results of these measurements reveal strong correlation and lend themselves to interesting analysis and interpretation. In fact, gravimetric anomaly data corrected with standard methods are directly proportional to density variations of buried masses beneath the Earth's surface. In the case of Marsili Seamount, considering a model of the

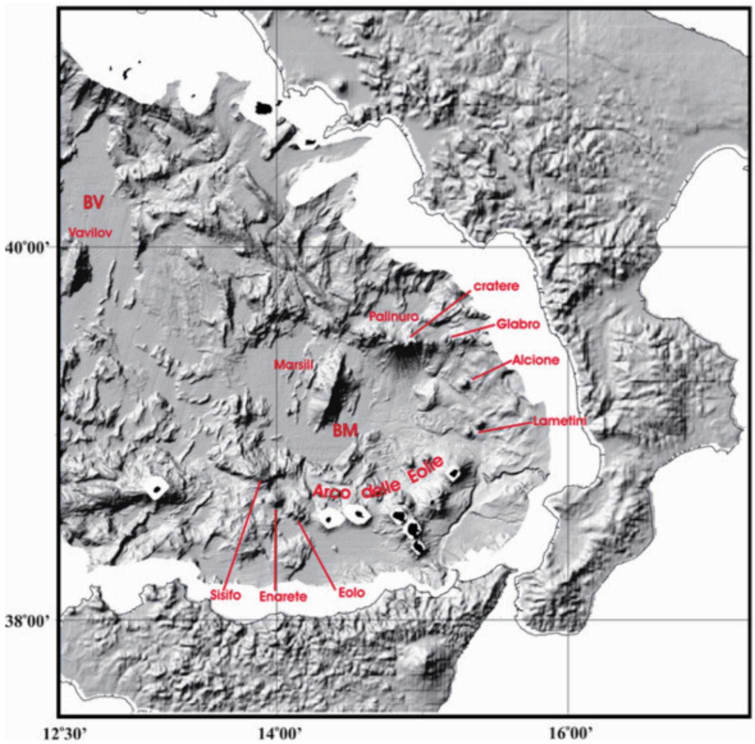

Fig. 2. – Morphology of the South Tyrrhenian Sea floor from [6]. Right in the middle, Marsili Seamount and its basin (BM) are surrounded by several other seamounts following the Aeolian Arch conformation and whose name are reported on the map. On the upper left side, Vavilov Seamount and its basin (BV).

edifice with a constant average density of the basalts equal to $2.67\,\mathrm{g/cm^3}$, the difference between the gravimetric anomaly calculated from the model and that coming from the measurement leads to density values between 1.7 and $2.3\,\mathrm{g/cm^3}$ (fig. 3). In addition, magnetic anomaly minima are associated with the highest gravimetric and heat flow anomalies. These correlated data, together with rock fracturing, have been interpreted as clear indicators of two main issues: the presence of relatively shallow magmatic bodies, and the presence of high-porosity rocks filled with high-temperature fluids. Indeed, the lack of mass can be explained in terms of aqueous and volatile phases filling, that, considering the average water and gases composition, can represent up to 10% of the volume of the edifice [8]. The emission of hydrothermal fluids has been verified directly in water samples collected around the edifice [12] and rocks dredged on the crest show hydrothermal alteration in both chemical composition and structure [13]. Moreover, the spectral analysis of data processed from an OBS/H (Oceanic Bottom Seismometer/Hydrophone) prototype deposited within the volcano's summit has shown characteristic band signals of hydrothermal and degassing activity comparable with the tremor of onshore geothermal

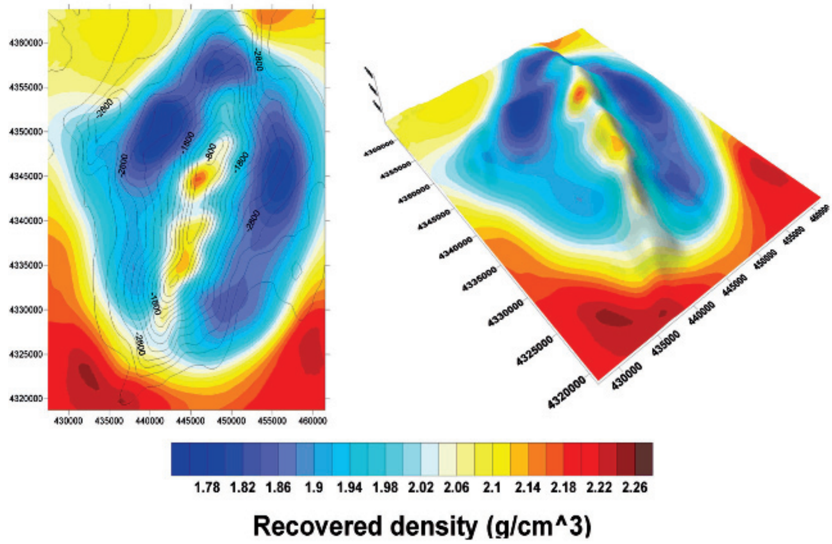

Fig. 3. – Density map from gravimetric measurements of Marsili Seamount with bathymetry (left) and with superimposition to the 3D model of the edifice (right) from [8]. The isobaths (black solid line) are taken with a 300 m depth step.

fields [14]. Ideally, Marsili Volcano could be viewed as a massive boiler structure where huge quantitities of seawater, infiltrated in the deepest part of the basement because of pressure, are heated inside the edifice and ejected from localised vents whose presence has been revealed by a multibeam sonar [17].

The above-described features represent extremely favourable points supporting geothermal exploitation, and so it is of high interest to make a comparison between an onshore field and a hypothetical offshore one. Shallow asthenospheric magmatic bodies inside the volcanic structure would represent the hot body while calc-alkaline hyaloclastites with their high porosity would constitute a great reservoir structure [15]. Conversely, many dregded rocks showing a quite uniform homogeneity of lavas and a limited presence of sediments on the volcanic structure would indicate that the cap rock layer is not present at all. Nevertheless in the offshore contest, differently from the onshore one, a cap rock would be completely unnecessary. This fact can be explained by the great extension of the heat flow area, of the order of hundreds km^2, and at the same time can be linked to a particular phenomenon known as *self-sealing*. This phenomenon is related to the quantity of salts both of marine and magmatic origin dissolved in the water which depends on the temperature and on the pressure of the fluid. The higher the temperature the higher the quantity of salts dissolved in it; so when the hydrothermal water of the reservoir reaches the walls of the volcanic structure because of convection, it is cooled down and the salts it contains precipitate. This precipitation determines the creation of a low-transmissivity "cap rock like" layer and explains the localised presence of hydrothermal emissions revealed on the volcano's surface. Moreover, the seawater surrounding the volcanic structure and the high pressure value due to the bathymetry could provide a practically unlimited quantity of fluid available for recharging the system. This feature represents a strong advantage in comparison with onshore fields where, on many occasion, the water recharge of the reservoir ceases and, in the worst situation, the geothermal wells need to be closed.

4. – Offshore geothermal energy project

The comprehensive oceanographic campaign started in 2006, whose data have been reported here, represents the early step of the first project of offshore geothermal exploitation at a global level: the Marsili Project. The project has been undertaken by the private company Eurobuilding with the cooperation of several public Italian institutions: ISMAR-CNR (Istituto di Scienze Marine - Consiglio Nazionale delle Ricerche), INGV (Istituto Nazionale di Geofisica e Vulcanologia) and CeRS-GEO (Centro di Ricerche e Studi Sperimentali per le Geotecnologie) of the University of Chieti [16]. The project, whose constraints have been defined by the exploratory phase, consists in two further steps: 1) the exploration well drilling, expected to be performed in the next years and granted by a research permit released to the Eurobuilding company by the Italian Ministry of Economic Development in November 2009; 2) the effective power generation.

The drilling site will be located along the volcano crest at the level with the maximum values of the anomalies and, in order to intercept the centre of the reservoir, the depth of the well has been set between 1.5 and 2 km [17]. This phase of the project will give the opportunity to test the estimates processed in the previous phase: the temperature gradient, expected to be around 150 °C/km, the temperature of hydrothermal fluids up to 500 °C, their enthalpy, and their chemical composition which is a major issue of the geothermal environmental impact. Until now, water samples collected around the seamounts have not shown significant quantities of heavy metals or dispersed pollutants.

The last phase aims for the effective power generation and will lead to the realisation of a 200 power plant of 200 MWe. This power size has been chose according to the expected supercritical state of the geothermal fluids whose enthalpy value will set the proper number of wells needed(4 to 6 wells estimated). The offshore wells will be connected, through an appropriate termodynamic cycle, to steam turbines that together with condenser system, power generators and transformers will be hosted on a platform suitably built. Considering the volcanic nature of the rocks and the great depth of the basin, semi-submersible platforms could represent an interesting solution (fig. 4). The power link will be realised with a high-capacity cable connecting the platform to the power grid located on the Italian coast nearly 150 km away. If the prototype power plant performs good results the project plans the construction of three more platforms of the same power size.

Taking as a reference the average capacity factor of onshore geothermal plants, equal to 83.6% (7324 h) [1], the total energy produced by the 200 MWe prototype platform would be up to 1.46 TWh/y. Under the same conditions, the total 800 MWe four-

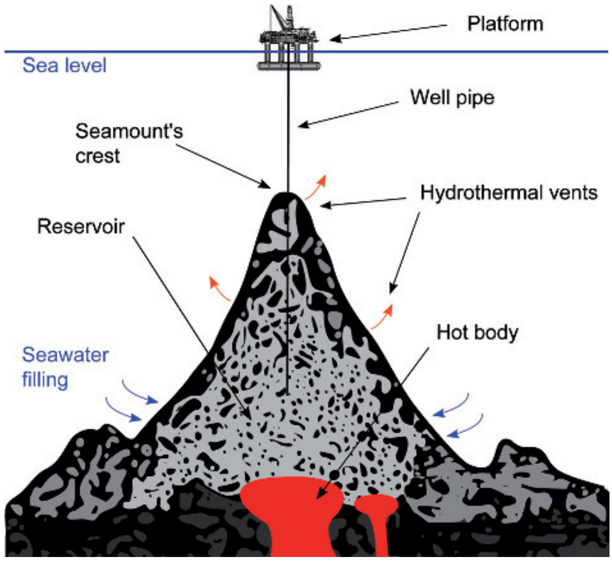

Fig. 4. – Unscaled schematic drawing of an offshore geothermal system. Power cable and platform anchorages have not been reported for simplicity. Great volumes of supercritical state water are expected to be found in the centre of the reservoir.

platform production would reach 5.87 TWh/y, almost doubling the Italian geothermal energy share. Like all geothermal power plants the initial cost represents the most expensive part of the whole investment which is estimated to be around 700 M€ and 2 Bn€ for one platform and for four platforms, respectively [16].

5. – Conclusions

From the above discussed, geothermal energy has high development perspectives but at the same time the conventional system for power generation needs fundamental requirements of heat anomaly and water availability that cannot be fulfilled everywhere. Particularly in Italy, the offshore domain represented by the South Tyrrhenian volcanic district may give an unprecedented opportunity to increase significantly the importance of the geothermal source. In relation to its characteristic, Marsili Seamount has been indicated as the ideal candidate for the first offshore geothermal field. From a practical point of view, all the technologies required for the Marsili Project's infrastructure realisation are already available mainly from the oil industry know-how or at least suitably adaptable from the already existing ones. Despite the high investment cost regarding the platform and power cable (close to 3/4 of the total amount), the high capacity factor can guarantee a faster return of investment in comparison to other renewable sources. At the same time, besides the subsidy policies (Green Certificates), the Levelized Cost Of Energy (LCOE) of geothermal energy is one of the lowest among fossil sources too, in the range 40–140 \$/MWh [18]. It is reasonable to think that the offshore produced electricity would be located basically in the upper part of the same competitive range with further decreases in time following the conventional geothermal trend.

As already mentioned, also other seamounts of this area share, to some degree, Marsili Volcano characteristics: the high heat flow anomaly and the hydrothermal activity are the most important ones. Some rough estimates state that the full exploitation of the South Tyrrhenian volcanic district could satisfy from 7% to 10% of the actual Italian electricity consumption [16]. Taking into account a moderate growth scenario of the electricity consumption, whose projections for the year 2022 range from a minimum of 347 TWh to a maximum of 380 TWh [19], the offshore counterpart could play a fundamental role in the energy framework of the country. Moreover the geothermal energy, already selected as strategic energy source [20], and offshore systems in particular, might represent a key contribution towards the fulfilment of the European 2020 Renewable Energy Directive [21]. Finally, it is important to observe that, from a geophysical point of view, a great part of the high heat flow areas around the world are located offshore: Aegean Sea, Indonesia, several sectors of the Pacific Ocean and Mid-Atlantic Ridge. The realisation of the first offshore prototype power plant on Marsili Seamount could pave the way to a significant increase of the importance of geothermal energy as a competitive and sustainable source at the global level.

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