ANNALS OF GEOPHYSICS, VOL. 52, N. 1, February 2009

GEOSTAR deep seafloor missions: magnetic data analysis and 1D geoelectric structure underneath the Southern Tyrrhenian Sea

Sergio Vitale ([1]) ([2]) ([4]), **Angelo De Santis** ([1]) ([2]), **Domenico Di Mauro** ([1]), **Lili Cafarella** ([1]), **Paolo Palangio** ([1]), **Laura Beranzoli** ([1]) **and Paolo Favali** ([1]) ([3])

([1]) *Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*

([2]) *Università degli Studi «G. D'Annunzio», Chieti Scalo (CH), Italy*

([3]) *Università degli Studi «La Sapienza», Roma, Italy*

([4]) *Now at Eni s.p.a., San Donato Milanese (MI), Italy*

Abstract

From 2000 to 2005 two geophysical exploration missions were undertaken in the Tyrrhenian deep seafloor at depths between -2000 and -3000 m in the framework of the European-funded GEOSTAR Projects. The considered missions in this work are GEOSTAR-2 and ORION-GEOSTAR-3 with the main scientific objective of investigating the deep-seafloor by means of an automatic multiparameter benthic observatory station working continuously from around 5 to 12 months each time. During the two GEOSTAR deep seafloor missions, scalar and vector magnetometers acquired useful magnetic data both to improve global and regional geomagnetic reference models and to infer specific geoelectric information about the two sites of magnetic measurements by means of a forward modelling.

Key words *GEOSTAR – Tyrrhenian Sea – deep seafloor – electrical conductivity – lithosphere*

1. Introduction

Variations of the magnetic fields produced in the ionosphere and magnetosphere generate electromagnetic (EM) waves that penetrate in the Earth's interior down to the crust and the mantle, inducing electric currents which, in turn, produce their magnetic counterpart at the Earth's surface. Magnetovariational (MV) techniques, which make use of the effects of induction magnetic fields from such sources over an appropriate magnetometric stations distribution, disclose some geoelectric properties that characterise subsurface structures (*e.g.* Banks, 1969; Parkinson, 1983; Gough, 1989; Armadillo *et al.*, 2001).

During recent years it has also been possible to adapt such land based techniques directly to seafloor observations (*e.g.* Filloux, 1987). GEOSTAR (*GEophysical and Oceanographic STation for Abyssal Research*) missions belong to a series of European Projects, led by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), having as main target some long-term deep-sea geophysical investigations. The automatic multidisciplinary station was designed to

Mailing address: Dr. Angelo De Santis, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via di Vigna Murata 605, 00143 Roma, Italy; tel: +39 06 5186 0327; e.mail: desantisag@ingv.it

meet the restrictive requirements of a standard land-based observatory, in spite of the extremely harsh environmental operating conditions. In Europe, the series of GEOSTAR projects is a unique approach and it has been implemented since 1995 in two successive steps (GEOSTAR and GEOSTAR-2), and then integrated in 2002-2005 by the ORION-GEOSTAR-3 (*Ocean Research by Integrated Observation Network*) project with the purpose of developing a prototype for a network of seafloor observatories. Here, we describe the validation of the prototype in the bathyal plain of the Tyrrhenian Sea (Marsili Basin). Further information on all GEOSTAR projects and other seafloor projects can be found in a recent review (Favali and Beranzoli, 2006). This work presents the analysis of magnetic data from the two deep-sea floor missions: GEOSTAR-2 and ORION-GEOSTAR-3, with a short description of the GEOSTAR Observatory and mission plans.

1.1. *The magnetic purposes of GEOSTAR Projects*

During the GEOSTAR missions some of the Earth's tectonic processes (such as seismicity, geomagnetic and gravity fields) and physical, geochemical and biological processes which occur on the seafloor environment with potential impact on geo-hazards and global changes were monitored.

The measurements of the geomagnetic field on the sea bottom are fundamental to complement land recordings in order to have a full analysis of the Earth's magnetic field (EMF).

Measuring the EMF on the deep seafloor has some evident advantages:

1) the temperature stability over time, since any change of temperature can affect the three-component magnetometer performance causing some artificial drifting;

2) the improvement of the knowledge of the EMF itself through a better measurements coverage;

3) slowly varying fields are practically unperturbed while rapidly varying external coverage magnetic fields are screened by the seawater layer.

The magnetic data acquisition on the seafloor is much more difficult than inland. The main problems arise from the increase in pressure with depth (about 0.1 atm/m), corrosion (especially for long periods of running, such as more than a few months), difficulties on vector instruments orientation according to the geographical directions and possible EM disturbances due to dynamo actions of the sea water motion (mean conductivity $\sigma w \approx 3\text{-}6$ S/m) within the EMF.

In spite of the above considerations, in terms of EMF observations, the GEOSTAR projects have given significant contributions to demonstrate: 1) the potential of an almost equal-area distribution of long-term points of observations all over the world to improve the reliability of global (*e.g.* IGRF) and regional magnetic field models; 2) the study of the magnetic field temporal variations from short to long periods (seconds to years), even in marine extreme environment where it is not easy to install a «traditional» observatory; 3) the investigation of the conductivity structures within the Earth by means of MV techniques; 4) the study of the EMF radial variation in correspondence with *Oersted* (1999 - present), *CHAMP* (2000 - present) and future SWARM satellite missions.

1.2. *Structure of GEOSTAR Observatory*

The whole idea behind the GEOSTAR project's concept took inspiration from the experience of NASA during Apollo and Space Shuttle missions, where the «two-body» system was a winning approach. Analogously, the architecture of GEOSTAR Observatory includes a mobile docker vehicle (called MODUS – MObile Docker for Underwater Sciences) and a bottom station. The latter module can run autonomously for long periods (over one year) and it can be employed for abyssal depths (up to 4000 meters). MODUS, properly manouvred onboard a ship, allows the deployment and the recovery of the bottom station directly from the surface (ship facilities), and it is used for the system check and bi-directional communication between ship and bottom station, when it is connected to the station. The bottom station, with a tubular cube shaped structure in aluminum alloy, was de-

signed to host all the acquiring instruments, acquisition and control systems, the communication system and the power supply of the station.

For its multidisciplinary nature, GEOSTAR can be equipped with different instruments in relation with to purpose of the mission. The standard configuration foresees a gravimeter, vector and scalar magnetometers, seismometer, hydrophone, acoustic Doppler current profiler (ADCP), conductivity temperature depth sensor (CTD), transmissometer, currentmeter, and water sampler. The magnetometers installed in two benthic spheres at the ends of two 2-m long booms. These «arms» are positioned at the two opposite corners of the Bottom Station and they are kept in vertical position during the descent phase. When the Bottom Station reaches the seafloor, the booms extends along the horizontal position upon operator command. This separation is essential to minimize the effects of induced current of the Bottom Station in the magnetic records.

The Communication System is designed to allow three different transmission methods. The first is committed to some special capsules (named «messengers») which are periodically released by the station to reach the sea surface (GEOSTAR-2 configuration) and here they establish a satellite communication, to notify their position; the recorded data are stored in these «messengers». Data are also fully stored in on-site hard-disks, recoverable at the end of the mission. The second communication method is a bi-directional acoustic transmission. This latter technique provides a real-time communication of the station with the «mother» ship. In this way an operator can periodically download the acquired data and can also change some parameters of the station according the necessities of the mission. Additionally, a surface buoy serves as radio/satellite bridge communications between the underwater observatory and an inland station (see *e.g.* Favali *et al.*, 2006).

2. GEOSTAR deep seafloor missions

2.1. *Locations*

Both GEOSTAR deep seafloor missions, namely GEOSTAR-2 and ORION-GEOSTAR-3, were undertaken in the Tyrrhenian Sea. Locations are shown in fig. 1 and geographical coordinates in its caption.

GEOSTAR-2 had a duration of about seven months (from September 25, 2000 to April 16, 2001). The station was deployed at 1950 m depth in an abyssal plain SW of the Ustica Island.

ORION-GEOSTAR-3 had a double duration in comparison to the preceding mission. It lasted about fifteen months in total but divided in two legs: the first from December 14, 2003 to April 24, 2004 and the second from June 13, 2004 to May 23, 2005. The station was deployed in an abyssal plain, NW of the Marsili seamount, reaching a depth of 3320 m. This paper uses only the three-component magnetic data acquired during the second part of the mission.

2.2. *Southern Tyrrhenian Sea*

The Tyrrhenian Sea represents a back-arc basin and its evolution, still in progress, has developed since the Upper Cretaceous in a complex geodynamic frame within the collisional system between the European and African Plates (Dewey *et al.*, 1989) and has been increasingly involved in the Alpine-Apennines Orogenesis since the Eocene (Scandone, 1980; Malinverno and Ryan, 1986; Sartori, 1990; Gueguen *et al.*, 1998).

The southern part of the Sea, of our interest, is characterized by a great stretch process that caused the formation of the two main sub-basins: Vavilov (7-3.5 Ma) and Marsili (1.7-1.2 Ma) (Bigi *et al.*, 1989; Cella *et al.*, 1998), with their respective volcanic structures.

In the Southern Tyrrhenian Sea we find two main gravimetric anomalies centered in the two major sub-basins (Rehault *et al.*, 1986), where the lithospheric thickness is about 50 km and the Moho depth reaches about 10 km. In a surrounding regional heat flow of about 120 mW/m^2, there are two heat flow anomalies greater than 200 mW/m^2 (*e.g.* Mongelli and Zito, 1994) placed within the Vavilov and Marsili basins; also magnetic data taken at sea surface show strong anomalies within the whole basin.

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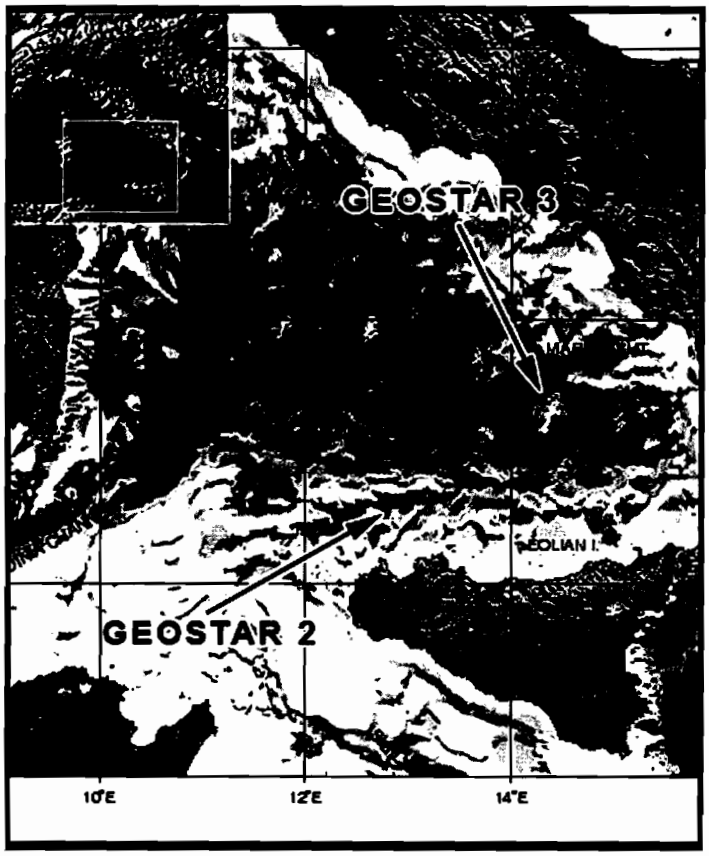

Fig. 1. Locations of the deployments of GEOSTAR bottom station in the Thyrrenian Sea. GEOSTAR 2 geograph. coord.: 38°32'24" N, 12°46'30" E; GEOSTAR 3 geograph coord.: 39°29'12" N, 14°19'52" E.

The Marsili basin is characterized by a stretch process in ESE direction, with a seafloor depth of about 3500 m. The rocks types are basalts and andesites, depth of the Moho of about 11 km, with lithosphere's thickness less than 30 km, heat flow rate more than 200 mW/m^2 and magnetic anomalies typical of expansion basins (Marani and Trua, 2002). An important aspect concerns the volcanic structure of the basin, since Marsili seamount is a morphologic anomaly that rises from the seafloor for about 3000 m. Its shape is lengthened for about 50 km in NNE-SSW in an axial direction and the perpendicular minor axis extends for about 16 km in WNW-ESE direction. This structure shows the main *middle oceanic ridge* (MOR) features, typical for axial or peri-axial zones; magnetic anomalies are positive in the axial zone and negative along the flanks (Marani and Trua, 2002).

3. Magnetometers and preliminary data calibration

In both GEOSTAR deep seafloor missions, a couple of magnetometers were used: a scalar magnetometer and a vector (three-component)

magnetometer. The scalar magnetometer was an Overhauser proton type. For the purpose of the missions, this instrument was an adaptation of the commercial model GSM-19L by GEM System Inc. It was characterized by a resolution of 0.1 nT, accuracy of 1 nT, a power consumption of 1 W and a sampling rate of 1 sample/minute. The vector magnetometer was a suspended three-axis fluxgate magnetometer, developed by INGV. It was characterized by a resolution of 0.1 nT, accuracy of 5-10 nT, a power consumption of 2 W and a sampling rate of 6 samples/minute/component.

During the GEOSTAR-2 mission, vector magnetometer recorded almost 100% of the expected amount of data, but the scalar magnetometer recorded only about 8% because an electronic device failure reduced the sampling rate from 1 sample/minute to only 1 sample every 12 minutes.

In ORION-GEOSTAR-3, the expanding booms were damaged during the deployment operation, preventing storage of X, Y, Z measurements from the vector magnetometer, while the scalar magnetometer worked properly all the time. In the second part of the mission, the vector magnetometer recorded data for 100% of the time while the scalar magnetometer returned data corresponding to the first 42% of this part of the mission.

The recorded data cannot be directly used for analysis, because the acquired magnetic data are affected by magnetic disturbances caused by induced currents from external magnetic

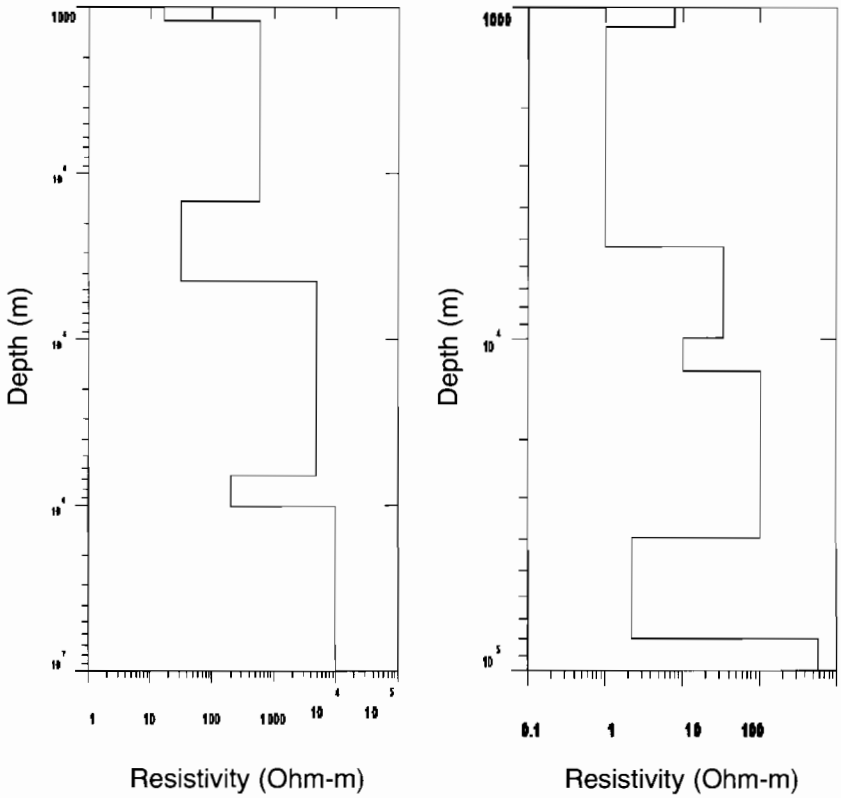

Fig. 2. ~~Apparent~~ Resistivity as given by the forward models for GEOSTAR-2 (left) and ORIONGEOSTAR-3 (right) missions.

field variations (mainly due to the GEOSTAR structure), and by the non-perfect orientation of the GEOSTAR frame. Some calibration and orientation corrections were applied on the recorded magnetic data, with respect to a ground station used as reference (De Santis *et al.* 2006a).

4. Magnetic data analysis and forward models

To consider the ionospheric fields as polarising fields, the usable periods in magnetic data analysis at the sea bottom at depths of 2-3 km are in the band 5h>T>3 min, this because variations with smaller periods are screened while those with greater periods do not satisfy the condition $\kappa^2 < 2\pi\mu\sigma/T$, where k is the spatial wavenumber and μ is the magnetic permeability; in addition for greater periods sea tides and water motions can be significant and produce disturbing local magnetic fields.

A forward model which takes the behaviour of the electrical conductivity in depth (or its reciprocal, the resistivity) into consideration was obtained by using software named «IX1Dv3» by Interpex (www.interpex.com). First of all, we calculated the apparent resistivity values by means of the apparent electrical conductivity profiles for each mission. We then imported these values of resistivity in the software and tried to build a more realistic behaviour of the resistivity profiles. At the end we succeeded in developing two models that took into account the conductivity variations.

As we can see in fig. 2, a lower resistivity appears under the first 5 km of GEOSTAR-3 site, probably due to the more complex tectonic and volcanic processes in the Marsili area. Regarding the lithospheric bottom under the two sites, it can be located from 15 to 45 km for GEOSTAR-2 mission and from 10 to 12.5 km for ORION-GEOSTAR-3 mission, with values of resistivity of 30 Ωm and 10 Ωm respectively, clearly less than the values of surrounding resistivity. Values of lithospheric depth found by means of the forward models confirm those found from previous magnetic data analyses (De Santis *et al.*, 2006b) and from seismic data (Calcagnile and Panza, 1981).

5. Conclusions

The deep seafloor GEOSTAR-2 and ORION-GEOSTAR-3 missions have provided an important magnetic dataset, useful both for the definition of conductivity structures underneath the seafloor and for improving the geomagnetic models. Starting from the three geomagnetic components, we have been able to provide 1D geoelectric models under the two deep seafloors of GEOSTAR-2 and GEOSTAR-3 missions in the Southern Tyrrhenian Sea, in particular the identification of the bottom of the EM lithosphere under the two sites. Moreover, our estimations on the identified depths are in accordance with the literature based on independent data, mostly seismic data.

In future, more analyses will be needed to uncover more details and properties of the Tyrrhenian crust and mantle to confirm the current results and possibly improve them in time, space and frequency domains.

Acknowledgements

The GEOSTAR and ORION projects were funded by the EC under the Marine Science and Technology Programme. We are ver grateful to Christopher Turbitt of British Geological Survey for his suggestions to improve the paper. Discussions with Patrizio Signanini, Bruno Di Sabatino of Chieti University helped some parts of the work. We thank also all the people who were involved directly or indirectly in both projects: without them no possible result or work would have been found or realized.

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