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The magnetometers and the geomagnetic data from GEOSTAR, a deep seafloor multidisciplinary observatory

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ABSTRACT GEOSTAR, an European-funded project, is based on a submarine multidisciplinary observatory, that gathered geophysical and geochemical data during a period of six months, from September 2000 to March 2001, in its first deep seafloor mission (about 2000 m depth), off the coast of Ustica Island (Sicily, Italy). GEOSTAR was equipped with several scientific instrumentations, among them two magnetometers. Total intensity of the Earth's magnetic field and its vectorial components were recorded by means of a scalar magnetometer (Overhauser type) and a suspended three axial fluxgate magnetometer, the latter being designed and built at the Istituto Nazionale di Geofisica e Vulcanologia laboratories. The adverse conditions of an environment located at 2000 m under the sea surface, obliged the making of a special design for the whole frame, including the use of non-magnetic materials for the structure, and the installation of two opposite expanding arms that contained the magnetometers. The geomagnetic experiment was completed by carrying out two fundamental procedures: the instrumental calibration and the computation of the vectorial magnetometer orientation with respect to the geographical reference, both are described in this paper. We also illustrate some properties of the complete magnetic data set, together with a spectral analysis performed in a particular condition of planetary magnetic activity, as well as applications aimed at extracting information about the crustal electric conductivity from the magnetic data in the area around Ustica Island.

1. Introduction

Even though geomagnetic observatories coveraging of the northern hemisphere is considered adequate by the scientific community, most of the southernmost hemisphere still misses the valuable contribution of a regular monitoring of the Earth's magnetism also because of the more widespread presence of oceanic areas.

The extension of magnetic observations also to seafloors, even if in an unique point of measurement, could have different implications: the improvement of the regional models, the knowledge of geomagnetic field-time variations under the seas, and the role of the seawater in screening time variations with a certain frequency. In order to accomplish all these objectives for the Mediterranean area, GEOSTAR (Geophysical and Oceanographic Station for Abyssal Research), a European-funded project, was designed for release in the Tyrrhenian Sea. The simultaneous magnetic variations recorded at the seafloor and at different locations on land, besides being indispensable for a correct interpretation of data records, are also useful to detect electrical conductive crustal layers or lateral electrical discontinuities in the proximity of the measurement point (Banks, 1974).

Power spectra analysis of natural magnetic variations in open oceans showed that no significant attenuation occurs on signals for periods longer than 30 minutes, while at periods shorter than 5-10 minutes, seafloor magnetic variations undergo considerable attenuation (e.g. Filloux, 1987).

A contribution of one or two orders of magnitude smaller than natural magnetic variations can rise from the conductive seawater motion inside the geomagnetic field for investigations of variations occurring on timescales between 1 day and 1 hour.

For the first time, in the summer of 1998, the benthic station of GEOSTAR was deployed in shallow waters (around 40 m depth) of the Adriatic Sea, for a testing experiment of around 1 month and magnetometers provided a good set of magnetic data (De Santis *et al*., 1999). The GEOSTAR deep sea mission was then performed from September 25, 2000 till March 16, 2001. Details on the GEOSTAR project and its deployment and observational system can be found in some recent literature (e.g. Beranzoli *et al*., 1998, 2000, 2003; Gasparoni *et al*., 1998, 2002; Marvaldi *et al*., 1998, 2002; De Santis *et al*., 1999; Favali *et al*., 2002). In this paper we will devote our attention to the deep sea mission of 2000-2001. We will describe the magnetometers utilized in the mission, the database provided and some preliminary results.

2. The magnetic measurements within GEOSTAR

As already mentioned, two magnetometers operated on the GEOSTAR benthic station for the Tyrrhenian deep sea mission: a scalar Overhauser GSM-19L proton magnetometer by GEM System Inc. (Canada) specifically adapted for the GEOSTAR mission and a three-axis suspended magnetometer, designed and built at the laboratories of Istituto Nazionale di Geofisica e Vulcanologia. Each sensor was housed in a glass benthosphere to be protected from high pressure. Fig. 1 shows the whole GEOSTAR frame equipped with two booming arms to host, at their ends, the two magnetometers. Fig. 2 is a map of the location where the benthic observatory was released. The omnidirectional sensor of the scalar magnetometer provided the total intensity of the geomagnetic field with a nominal resolution of 0.1 nT, an absolute accuracy of 1 nT and a power consumption of 1 W in the sampling rate of 1 value per minute. Soon after the starting of the mission an electronic failure occurred causing a reduction of the sampling rate to only 1 value every twelve minutes. Nevertheless, these limited sampled values were fundamental for the calibration of the instruments and the comparison with a ground-based data set.

The fluxgate three-component magnetometer was designed with a suspended sensor to ensure its verticality. The resolution was 0.1 nT, with an absolute accuracy of 5-10 nT and a power consumption of 2 W in the sampling rate of 6 values per minute. Its analogic outputs were digitalised by a 16 bits A/D converter, achieving a quantisation step size of 1.4 nT in order to cover all possible ranges of the geomagnetic field. The scalar and vectrorial magnetometers are shown in Fig. 3.

In order to validate the whole GEOSTAR data set, we need to determine: i) the disturbance due to the whole structure and the magnetic materials contained by other instrumentations hosted in the benthic observatory; ii) and the orientation offset of the frame with respect to the true geomagnetic north. For the item i) a dedicated instrumental calibration was carried out in the very proximity of the Italian magnetic observatory of L'Aquila (central Italy), some days after the

Fig. 1 - The whole GEOSTAR frame; the mobile docker, the bottom station and one of the two booming arms.

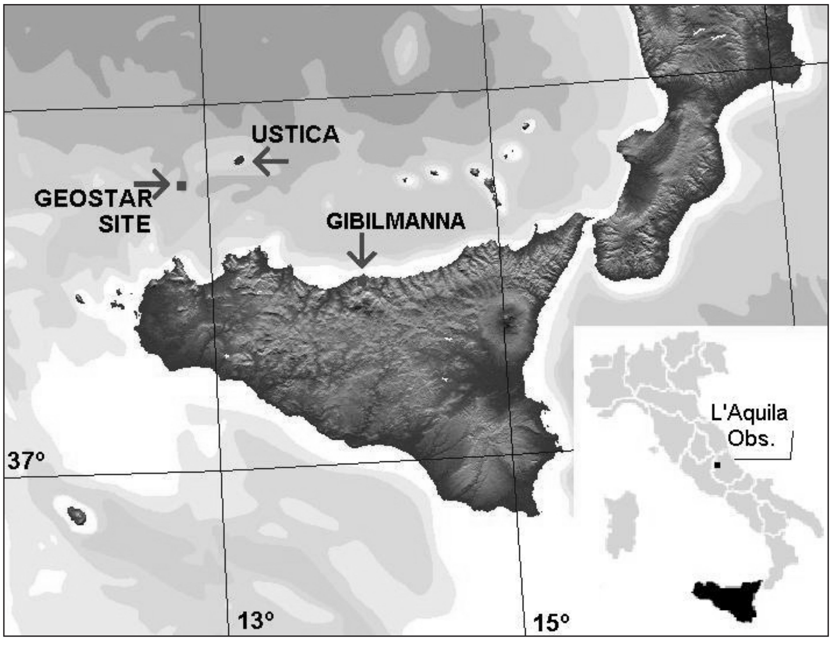

Fig. 2 - Geographical sketch of the GEOSTAR location (38º 32N; 12º 46E) in the Tyrrhenian Sea and the main sites of Ustica Island (38º 42N; 13º 10E), Gibilmanna (37°59N; 14°01E) and the L'Aquila Observatory (42º 23N; 13º 19E).

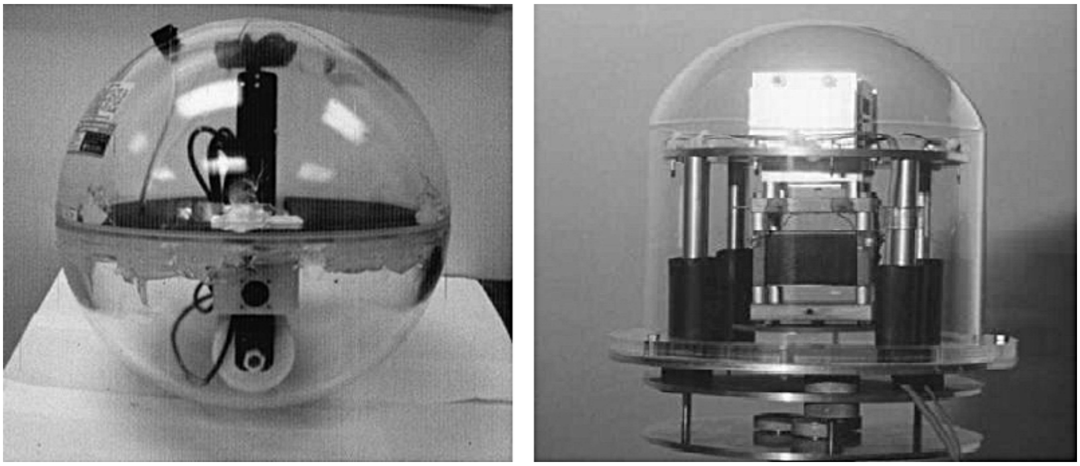

Fig. 3 - On the right: the GEM scalar magnetometer. On the left: the suspended three-axial magnetometer. Both of them were mounted on GEOSTAR.

recovery. The second point was fulfilled by means of a comparison between the contemporary recordings of the magnetic field components from L'Aquila and from the magnetometers mounted at the extremity of the booming arms on the submarine module, providing a quantification of the artificial offset entered by GEOSTAR.

The compensation model used consists of two separate contributions: the permanent and the inductive parts. The inductive contribution is practically negligible while the permanent contribution was calculated as Bx_{perm} = 1075.4 nT, By_{perm} = 448.2 nT, and Bz_{perm} = 1077.6 nT. The scalar magnetometer provided values that needed a correction of -295 nT.

An accurate evaluation of the GEOSTAR frame orientation was made comparing seafloor data

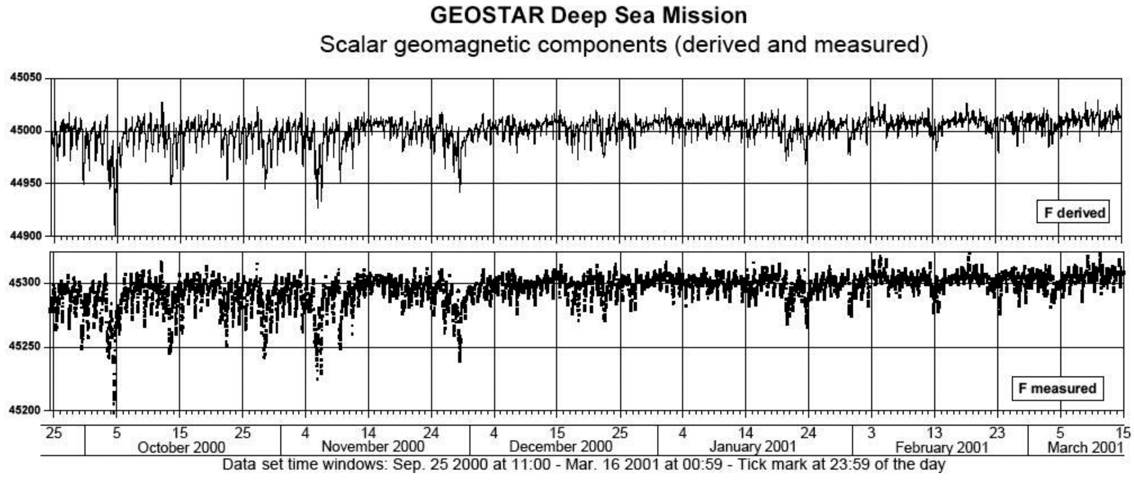

Fig. 4 - Six months of seafloor recordings. Comparison between derived and measured scalar (F) at the sea bottom. Unit of vertical axis is nT.

with data from the two temporary land stations installed at Ustica Island and Gibilmanna and from the L'Aquila Observatory. Least squares regression provided a rotation angle of about +242° counter-clockwise from north (De Santis *et al*., 2005). The knowledge of the precise orientation of the whole GEOSTAR structure was, in turn, of valuable importance to give a geographical reference to the seismic tri-axial recordings and to the other vectorial observations (water currentmeters, chemical packages).

3. Magnetic data set and data analysis

GEOSTAR deep sea mission of 2000-2001 provided 4123 hours of geomagnetic data. The definitive data set was achieved after the application of the rotation and calibration corrections, as described in the previous section, to the vector and scalar magnetometer recordings.

The scalar magnetometer provided a total of 20,615 records. Total intensity (F) of the magnetic field, both measured and derived (as the square root of the sum of the squared re-oriented and calibrated three components) is shown in Fig. 4.

The vector magnetometer provided a total of 1,484,282 records but a number of 6 to 15 spikes are present in each 24-hour segment of recording. The sampling rate of 6 values per minute was averaged to obtain 1-minute values after a spike remover filter (see Fig. 5 for each component plot).

The variation in F, of around 20 nT during the whole reflects the regional "*secular*" variation (around 40 nT/year) occurring in the study area.

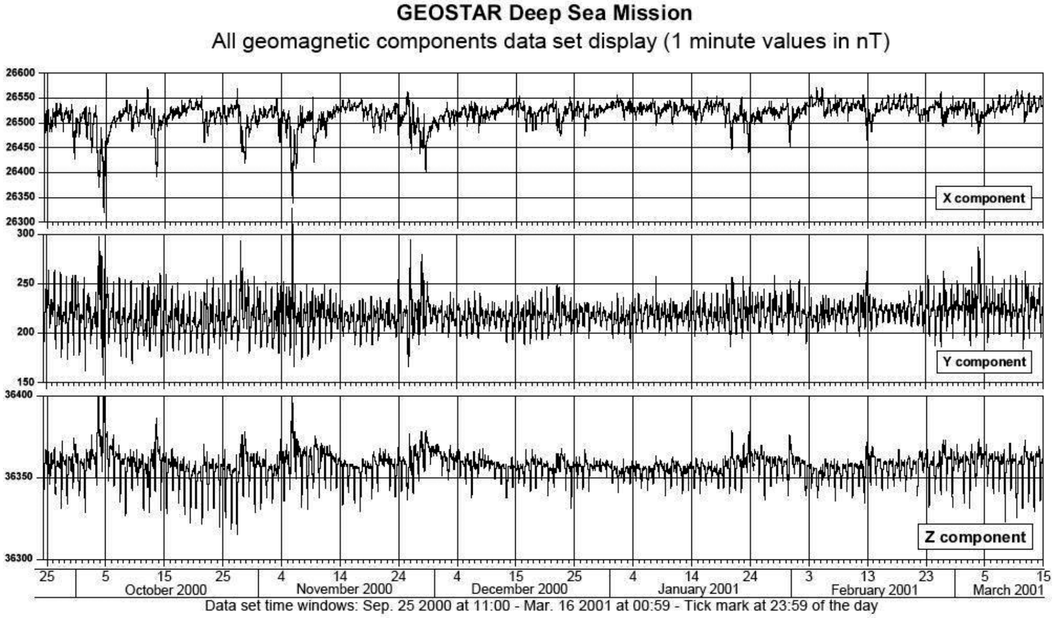

Fig. 5 - Cartesian components (upper panel: X-component; middle panel: Y-component; lower panel: Z-component) of six months of seafloor recordings. Some magnetically active intervals are clear in all curves. Unit of vertical axis is nT.

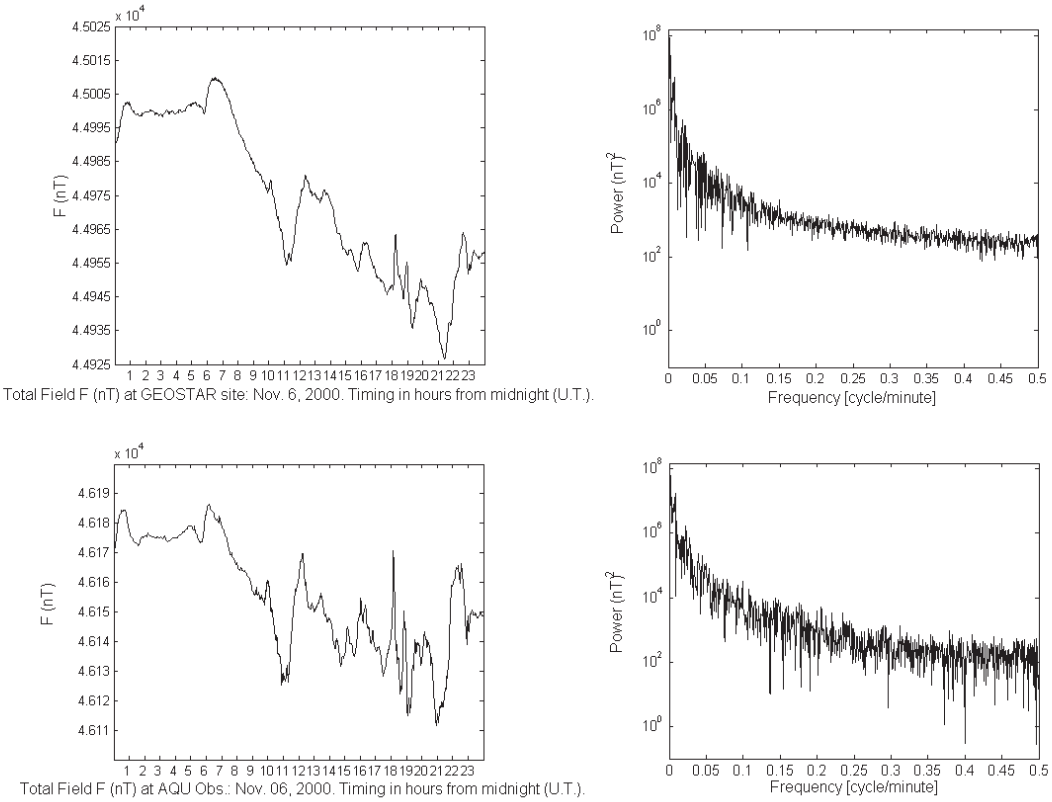

Fig. 6 - Signals from GEOSTAR (top) and L'Aquila (bottom) data sets (left-hand panels) and the corresponding power spectra analysis (right side-hand panels) for the date of November 6, 2000.

Fig. 6 shows an example of power spectrum for the "magnetically" disturbed day of November 6, 2000: this figure shows that a larger content of high frequency energy is more present at L'Aquila than at the GEOSTAR site in the case of high geomagnetic activity. Instead, the low-frequency energy content remains of the same order of magnitude for any activity level. This behaviour can be explained, as already mentioned, by the screen effect of the seawater, especially on short period components. In general, such a difference becomes less evident with the decreasing of the geomagnetic activity. At high frequencies the power spectrum of GEOSTAR data, asymptotically approaches values that are at least two orders of magnitude lower than those related to simultaneous data recorded at L'Aquila. At low frequencies, the power spectrum of L'Aquila and the GEOSTAR data set are comparable. Some more details are given by De Santis *et al.* (2005).

4. EM Induction and electrical conductivity

To gather some information about the electrical conductivity of the area surrounding the GEOSTAR site, we estimated the induction arrows (or the so-called "Parkinson vectors") of the geomagnetic depth sounding (GDS) technique (e.g. Armadillo *et al.*, 2001). The transformation of the variational fields into frequency-dependent response functions allows a qualitative and quantitative interpretation through the use of a transfer function formulation (Schmucker, 1970). A consequence of the linearity of Maxwell's electromagnetic field equations is the relationship between the anomalous and normal field components (Schmucker, 1970; Beamish,1977), which at a given frequency, after a Fast Fourier transformation of the magnetic components, is expressed as:

$$Z_a = A \cdot X_n + B \cdot Y_n + \varepsilon$$

where the subscripts '*a*' and '*n*' refer to the anomalous and normal parts of the respective field components. ε is an error term approximated by a small-amplitude, usually negligible, white noise. The above linear combination is valid under the assumption of a horizontally uniform external source field (which permits to neglect Z_n) so that, the components of the normal horizontal field (X_n and Y_n) can be considered as the input, and the anomalous vertical field (Z_a) is the output determined by the response characteristics (A and B, complex coefficients) of a filter represented by the unknown conductivity structure eventually present under the observational point. The method adopted to estimate transfer functions was the least-square solution, so that the error term ε in the above formula, is minimized. This technique can be successfully applied also in the band-limited seafloor environment.

The complex transfer functions A and B were used to define a pair of induction arrows, each corresponding to the real and quadrature parts. The magnitude of the real and quadrature induction arrows is given by:

$$R = \sqrt{[\mathrm{Real}(A)^2 + \mathrm{Real}(B)^2]}$$

$$I = \sqrt{[\mathrm{Imag}(A)^2 + \mathrm{Imag}(B)^2]}$$

whereas the corresponding azimuths are obtained as follows:

$$\Theta r = \mathrm{arctg}\,[\mathrm{Real}\,(A)/\mathrm{Real}\,(B)]$$

$$\Theta i = \mathrm{arctg}\,[\mathrm{Imag}\,(A)/\mathrm{Imag}\,(B)].$$

It is a usual practice to reverse the azimuths so that, in their graphical presentation with respect to the geographic north, arrows point at a right angle to the current concentrations and, hence, define the strike directions of the conductive structures causing concentrations of the induced currents (Gregori and Lanzerotti, 1980). Their lengths (magnitudes), being a measure of the anomalous vertical field normalized to the strength of the inducing field, characterise the electrical parameters of the involved structures.

We selected only night-time segments (from 21.00 to 6.00 UT) of data with 512 minutes belonging to magnetically disturbed days, for having a "*robust*" and "*clear*" signal from daylight spurious sources able to trigger inductive mechanisms, collecting 10 samples from 10 different days with moderate and high magnetic activity. In the graphic representation, the real parts of

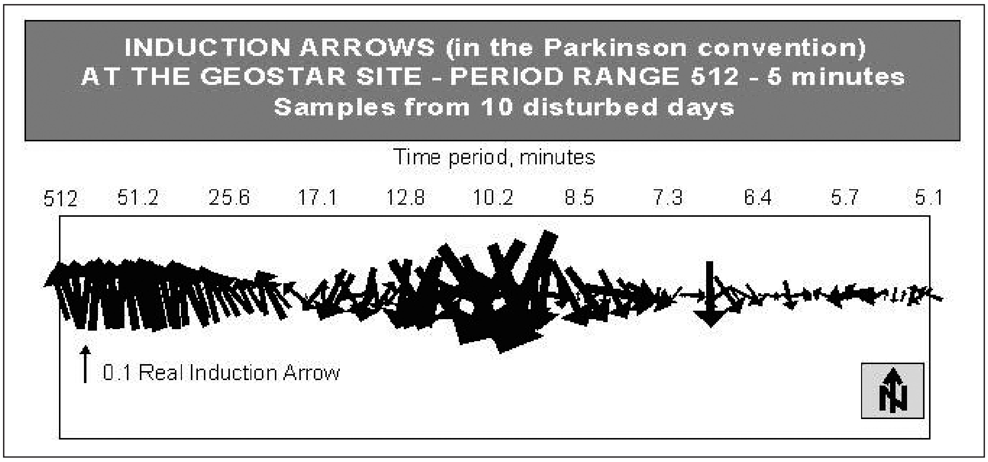

Fig. 7 - Induction arrows at the GEOSTAR site in the period range 5.1 - 512 minute, in the case of a selection of some magnetically disturbed days.

such arrows are directed towards regions with higher conductivity; the longer the periods, the deeper the corresponding sounded layer. In our case, most of such arrows become larger as the period grows: this confirms that at a GEOSTAR depth, the bulk of electromagnetic induction generated by variations in the geomagnetic field mainly contains long-period components. Moreover, for periods greater than 20 minutes, most of such arrows point toward the north, indicating that a higher electrical conductivity contrast is located north with respect to Ustica Island (Fig. 7), probably connected to the asthenospheric upwelling of the Tyrrhenian basin [Armadillo *et al*. (2001) and reference therein].

5. Conclusions

The GEOSTAR project succeeded in providing, for the first time magnetic data from the sea bottom in very harsh environmental conditions at around 2000 m depth. Calibration and orientation procedures were applied to the data set from GEOSTAR magnetometers in order to gather corrected “true” magnetic components. Comparison with ground stations (Gibilmanna and Ustica sites) and the L’Aquila observatory showed a good agreement, confirming the reliability of data, and allowing us to make precise orientation calculations.

Spectral analysis was performed on selected data segments and compared with data from the L’Aquila observatory. Power spectral analysis revealed that the energy content at short periods is generally larger at L’Aquila than at the GEOSTAR site, especially under conditions of high magnetic activity. Differently, the energy involved in longer periods is of the same order of magnitude when estimated at the GEOSTAR site and at L’Aquila independently of the level of geomagnetic activity.

Finally, induction studies showed that a higher electrical conductivity contrast is located north of Ustica Island, probably connected with the asthenospheric upwelling of the Tyrrhenian Basin.

A third project, ORION, funded by the European Commission will deal with the possibility of extending the monitoring capabilities from a single point (as GEOSTAR is) to more sites through a first network of observatories. The network has a main node, the GEOSTAR observatory, which acts as a gateway station, and two satellite nodes in acoustic communication for a 6-8 months experiment, located in the Tyrrhenian abyssal close to the Marsili Seamount at a depth of more than 3300 m.

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