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RESEARCH ARTICLE

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Automated system for magnetic monitoring of active volcanoes

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Abstract In order to provide a basis for short-term decision-making in the forecasting and monitoring of volcanic activity, we developed an entirely automated system of data acquisition and reduction for magnetic data. The system (Mag-Net) is designed to provide monitoring and analysis of magnetic data on Etna volcano at large distances from the central observatory. The Mag-Net system uses data from an array of continuously recording remote stations spread over the volcanic area and linked by mobile phone to the control center at the local observatory. At this location a computer receives the data and performs data sorting and reduction as well as limited evaluation to detect abnormal behavior or breakdown of remote sensors. Communication software, called MagTalk, is also designed to provide data to distant users. With a view to using continuous magnetic observations in advanced analysis techniques for volcano monitoring, the Mag-Net system also delivers two graphical user interface based applications to provide an interpretation capability. The former, called MADAP, speeds up all the data reduction processes in order to evaluate the reliability of magnetic signals. The latter, called VMM, is a procedure for modeling magnetic fields associated with tectonic and volcanic activity to facilitate the identification and interpretation of the sources of a wide spectrum of magnetic signals.

Keywords Volcano monitoring · Data-handling system · Volcanomagnetic modeling · Mt. Etna

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Introduction

Magnetic monitoring may be a useful method to gather long-term information about ongoing dynamic processes in volcanoes during times of apparent rest. Tectonic events and magma displacements can be detected and recorded with sensitive magnetometers to provide a pattern which can serve to improve understanding of the internal plumbing system of a volcano and improve the capacity to provide reliable eruption forecasts. Geomagnetic observations to monitor volcanic activity have been intensively carried out during the past decade. Significant correlations between volcanic activity and changes in the local geomagnetic field have been observed on several volcanoes (e.g., New Zealand, Johnston and Stacey 1969; USA, Davis et al. 1984; Japan, Tanaka 1993; France, Zlotnicki et al. 1993; Italy, Del Negro et al. 1997b). However, in spite of the significant efforts devoted to establishing and expanding magnetic networks on volcanoes around the world, limited availability of data has impeded understanding of volcano dynamics, on both temporal and spatial scales necessary for the mitigation of volcanic hazards.

Forecasting and monitoring of volcanic activity requires short-term decision-making. To achieve this, it is essential that data collected by the sensors, distributed over a large area, are transmitted in real time to a central observatory for automatic processing, analysis, and display. A brief examination of the systems installed throughout the world for the monitoring of active volcanoes generally reveals a low degree of automation and few have the ability to evaluate data in real time. This has obvious consequences in crisis periods.

Our Laboratory of Geomagnetism (Mag-Lab) has been developing methods, hardware, and know-how for the automated acquisition and management of data simultaneously acquired at a variety of remote magnetic stations. To provide a basis for real-time response during eruptive events, we designed and developed the automated system called Mag-Net. This system represents the state-of-the-art in magnetic monitoring of active volcanoes. The first application of the Mag-Net system is the permanent network for magnetic monitoring of Mt. Etna. The technological achievements related to the planning of the Mag-Net system and its installation on Mt. Etna are illustrated in this paper.

The Mag-Net system

Like most active volcanoes of the world, Mt. Etna was without a permanent magnetic network until the early 1990s. The design and testing of the first system for magnetic monitoring of Mt. Etna was set up between 1994 and 1996 (Del Negro et al. 1995). The system, while primitive, provided continuous data transmission from remote sensors to a central observatory. Thanks to this original experiment, it was possible to evaluate both the reliability of instruments dedicated to working in volcanic areas as well as the application of measurement techniques aimed at reducing the effects of external noise phenomena (Del Negro et al. 1997a).

Thereafter, we developed the Mag-Net system in which data acquisition and reduction is entirely automated. The Mag-Net system also includes automatic analysis of incoming data and data storage in a database. All the incoming data are processed online to provide a real-time picture of the activity of the local geomagnetic field and enable the operator to devote his or her whole attention to the interpretation of the data with maximum efficiency.

The Mag-Net system uses data from an array of continuously recording remote stations spread over the volcanic area and linked by mobile phone to the control center at the local observatory. The Mag-Net system also delivers two graphical user interface based applications to provide an interpretation capability. The former speeds up all the data reduction processes to allow quick identification of fields associated with volcanic events. The latter is a procedure to model magnetic fields associated with tectonic and volcanic activity.

During the planning phase, attention was paid mainly to the following tasks:

1. Remote station architecture.
2. Computer-based control center.
3. Faster data processing.
4. Implementation of modeling techniques.

The first application of the Mag-Net system is the permanent network for magnetic monitoring of Mt. Etna (Fig. 1). At present the network is made up of five stations in the locality of Mt. Etna, flanked by a sixth external reference station installed further west (about 50 km) on the Nebrodi Mountains. Local magnetic transients attributable to Etna volcano can thus be isolated. The stations on Mt. Etna are located along an N–S profile crossing the volcano summit. This layout is symmetrical with respect to the central craters and should allow continuous prospecting of the geomagnetic field along this section of Mt. Etna. The sites chosen were carefully tested before the stations were installed and the inspection revealed the presence of low magnetic gradient (less than 50 nT/m) and low local noise amplitude.

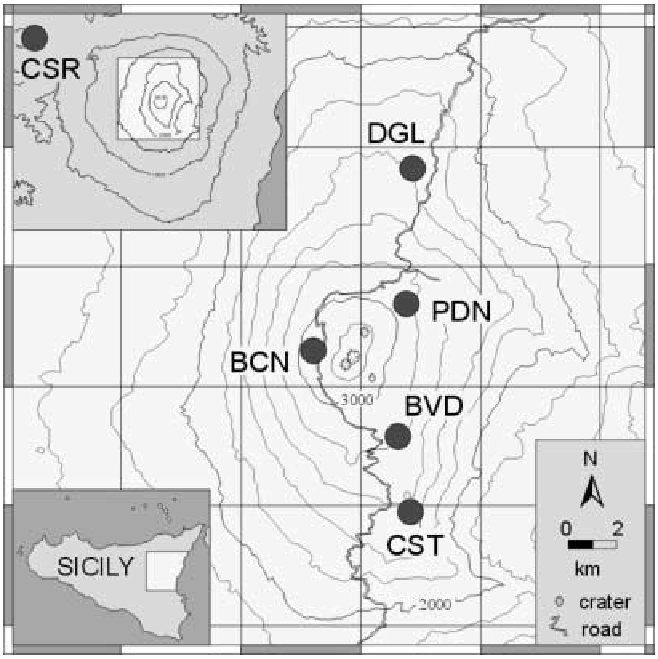


Fig. 1 Configuration of Mt. Etna magnetic network. Stations on Etna (*DGL*, *PDN*, *BCN*, *BVD*, and *CST*) are located at elevations ranging between 2,500 and 3,000 m a.s.l., while the CSR reference station was installed further west (about 50 km) on the Nebrodi Mountains

It is worth noting that automation in volcano monitoring also requires the transmission of an early warning signal if the activity of the local geomagnetic field exceeds some prescribed limits. At present, this step is not included in the Mag-Net system, because the definition of limits requires a database sufficiently great to characterize the behavior of the local geomagnetic field. The activity was mainly technical over the 3-year period 1996–1998 and led to an acceptable configuration of the monitoring network in the second half of 1998.

Remote station architecture

The remote stations were made using components with low energy consumption and a good cost-to-performance ratio. Their main characteristics are the following:

- Readings of the Earth’s magnetic field are executed by Overhauser effect magnetometers.
- The synchronization of readings at each station is controlled by a global positioning system (GPS) receiver.
- Data transmission is performed by mobile phones working in the global system for mobile communication (GSM) in the 900 MHz band.

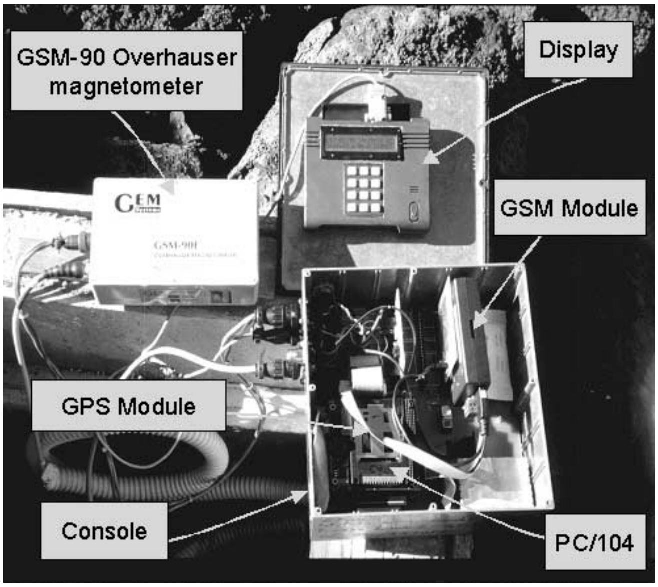


Fig. 2 Remote station console

- The management is realized by a microcomputer compliant with the PC/104 standard and compatible with PC/AT architecture.

All the electronic circuits are contained in a console (Fig. 2). The package consists of a rugged aluminum box (250×250×110 mm) with a connector leading to a remote terminal. All control of the unit is done by this terminal, with a removable display and keyboard. In particular, it is possible to ensure the correct operation of the station on-site with several operating tests on the magnetometer, clock, mobile phone, and energy supply (Fig. 3). Each station is powered by a solar cell with battery back-up.

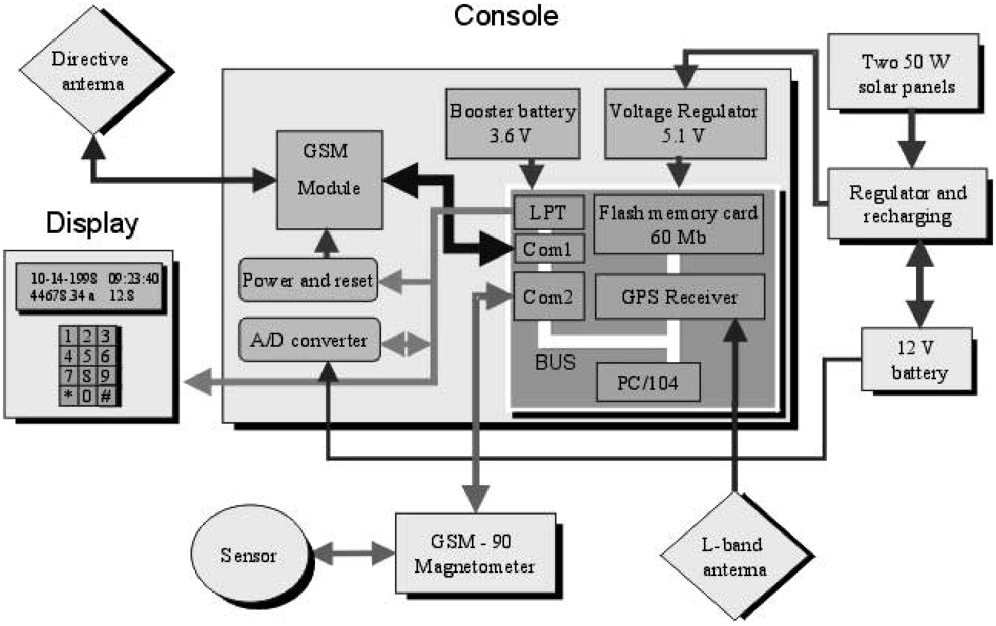
We introduced the Overhauser effect magnetometers to attain much higher performance than that of an ordinary proton precession magnetometer. In contrast to a standard proton magnetometer sensor, where only a proton-rich liquid is required to produce a precession signal, the Overhauser effect sensor must have a free radical added to the liquid. This free radical ensures the presence of free, unbound electrons that couple with protons to produce a two-spin system. A strong RF magnetic field is used to disturb the electron–proton coupling. By saturating free electron resonance lines the polarization of protons in the sensor liquid is greatly increased. The Overhauser effect offers a more powerful method of proton polarization than standard DC polarization, i.e., stronger signals are achieved from smaller sensors and with less power.

We employed the GSM-90 Overhauser magnetometer manufactured by GEM System Inc., which is microprocessor based with full remote control capability. The results of measurements are made available in serial form (RS-232-C interface) for collection by data acquisition systems. The GSM-90 is a high sensitivity instrument, having 0.01 nT resolution, 0.2 nT absolute accuracy over its full temperature range, sampling rates up to 3 s, and 10,000 nT/m gradient tolerance. Their characteristics of long-term stability and absolute accuracy turned out to be particularly suitable for continuous measurements in harsh environmental conditions.

Computer-based control center

The control center is a computer-based magnetic data acquisition system situated in a local observatory where electricity and telephone services are available. At this location a computer receives the data and performs data

Fig. 3 Remote station block diagram



sorting and reduction as well as limited evaluation to detect abnormal behavior or breakdown of remote sensors. Communication software, called MagTalk, between the control center (CC) and remote stations (RS) has been developed in C++ language with a client/server structure. At predetermined intervals (e.g., once a day) the client (CC) connects to the server (RS) to download the latest data. Data coming from each station are collected in the host computer at the observatory, where they are added to the local database.

The computer system is also programmed to calculate automatically and display in real time simple differences and spectral content of incoming signals, providing a quantitative measure of magnetic activity. These data can be the basis for rudimentary alarm systems, notifying observatory staff that something has happened that requires further evaluation. An operator can then investigate the problem and decide what further action is needed, such as changing the transmission frequency, if greater information is required, or correct some equipment failure.

The local control center has also been devised to upload data to a distant user immediately after acquisition and re-formatting. Data processed at the "distant desk" can be downloaded a few hours later and used by the personnel in charge of the volcano forecast. The online availability of crude or pre-processed data to authorized users connected to a wide-area network, fosters the possibility of monitoring active volcanoes without concentrating all human resources in a single observatory, at a given site. Provided that the field maintenance and support are available at the volcano observatory chosen, such a scheme would allow special instruments to be run even without any expertise in processing and interpretation of specific data.

To share the measurements throughout the world some new pages were added to the INGV website under the item Laboratory of Geomagnetism. At the address http://www.ct.ingv.it it is possible to examine geomagnetic observations carried out at Mt. Etna. In the website the 10 min average of the magnetic field total intensity and the related standard deviation for each station are plotted. In particular, external users having a password are able to download directly data acquired at the stations of the magnetic network of Mt. Etna.

Faster data processing

To handle rapidly the huge amount of data coming from stations of a monitoring network (e.g., 8,640 a day in each station, using a 10 s sample rate) and to apply different analysis techniques with the same speed we have developed a code, called MADAP (MAgnetic DAta Processing), which allows a high skill level to be achieved by the operator. The code was designed under LabVIEW (Laboratory Virtual Instrument Engineering Workbench).

MADAP contains an original graphic routine for speeding up the visualization of long data series, thus allowing one to obtain a general view of the signals in a short time. Once the time window is chosen, the routine automatically decimates the data from the original files creating a plot with a maximum number of points equal to the maximum resolution of the monitor used. It offers an immediate visual representation of any data period to facilitate the detection of possible anomalous behaviors; these can then be analyzed in more detail by selecting shorter and more appropriate time windows.

In addition to graphical capabilities, MADAP also includes a powerful, comprehensive package of analysis routines for processing acquired data. This package is rich in statistics, regressions, linear algebra, time and frequency domain algorithms, windowing routines, and digital filters. A number of dedicated routines to reduce magnetic disturbances are available in the package. Detection of volcanomagnetic events (a few nT or less) attributable to the dynamics of a volcano requires eliminating from measurements of the geomagnetic field variations with no geophysical significance. The most used and reliable method is the classical differential technique, based on simultaneous simple differences between the magnetic field amplitudes recorded at several points on a volcano. This method was implemented with the option to verify the synchronization between signals recorded at different stations by cross-correlation function. We included also Steppe's (1979) method to find differences between a given station and a weighted linear combination of the remaining stations of a total field array, where the weights are determined by linear regression. Recently, a vector magnetometer for continuous monitoring of the inclination and declination of the geomagnetic field has been tested in the reference station of Mag-Net. Thus, we added a more detailed data analysis by employing the method developed by Poehls and Jackson (1978), which relates the vector field at the reference site to the total field at the observation sites by empirical transfer functions to filter out residual variations caused by transitory fields. This method is effective in reducing the residuals associated with diurnal variations, thus allowing volcanomagnetic events, even shorter than a few days duration, to be detected. In order to distinguish between transients of volcanomagnetic origin and transients generated by strong variations in the external transitory magnetic field we implemented the method devised by Del Negro and Ferrucci (2000), which takes into account the correlation between the measurements at two stations. This method is useful when the observation sites are relatively few. Finally, given the intrinsically time-varying nature of magnetic signals, a module for the joint time–frequency analysis, a signal processing technique in which signals are analyzed in both the time and the frequency domain simultaneously, has been implemented. This module uses a rather sophisticated time-dependent spectrum analysis which allows us to examine the instantaneous spectrum of a signal and discover how it changes over time, thus providing a more complete representation of the signal and consequently a better understanding of its nature.

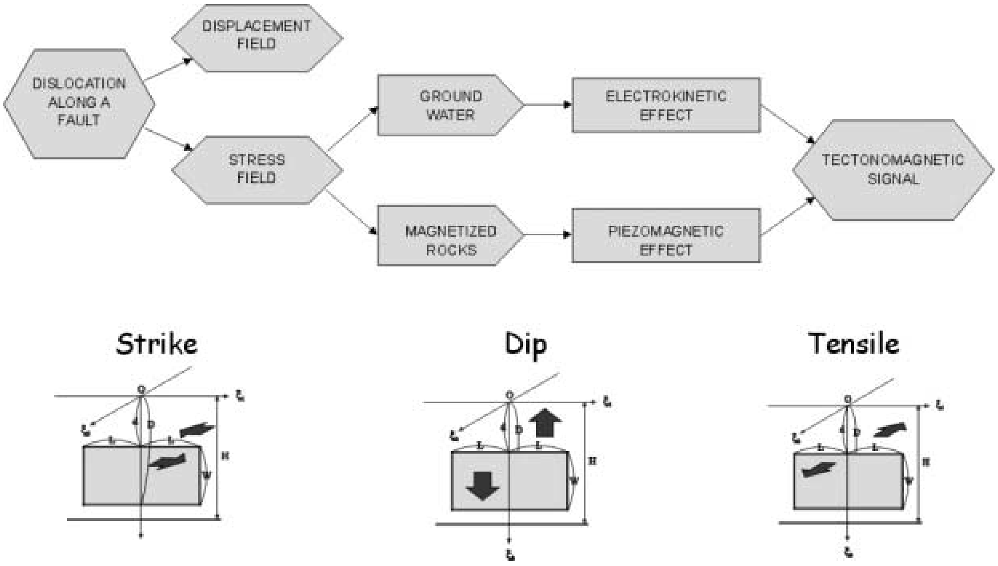


Fig. 4 Flow chart of the tectonomagnetic signals produced by a dislocation along a fault. Below it is shown the geometry of faults

Implementation of modeling techniques

Generally speaking, volcanomagnetic fields have three main endogenous causes: (1) thermomagnetic processes, (2) piezomagnetic effects and (3) electrokinetic phenomena, which are sometimes strictly linked to each other in real fields. For example, uprising of magma, which gives rise to thermal demagnetization process, will also cause the redistribution of the stress field at a shallow depth. Variation in the stress field may modify not only the magnetization of rocks but also the net of interconnected pores. Finally, circulation of groundwater driven by thermal energy will plausibly take place in dilated areas. The interstitial pressure gradients can generate electrofiltration currents, which cause the electrokinetic magnetic anomalies. All of these processes can produce a detectable intensity of geomagnetic field under a suitable condition.

Although there are some numerical and analytic solutions for volcanomagnetic modeling in the literature, they are rarely user-friendly for those not familiar with the research fields. In order to reduce the delay between observation and interpretation, and thereby improve the efficiency of volcano monitoring, we have implemented some of these solutions in a unified manner with the aid of graphical user interface under MatLab (The MathWorks, Inc.). Here we call this procedure VMM (Volcano Magnetic Modeling). The VMM basically consists of four modules for computation of magnetic fields associated with tectonic and volcanic activity (Fig. 4). The first is for the piezomagnetic effects due to a fault based on the analytic solutions by Sasai (1991b) and Utsugi et al. (2000). Computations for strike-slip, dip-slip, and tensile-opening of a rectangular fault with an arbitrary dip angle are available. The second is for the piezomagnetic effects due to a point pressure source (Mogi model in volcanology) based on the analytic solutions proposed by Sasai (1991a). The third is for the electrokinetic effects due to a rectangular fault using the analytic solutions by Murakami (1989). The fourth is for the thermomagnetic effects due to a spherical body using the analytic solution of a magnetic dipole. As an option, the displacement and stress fields, which are based on the analytic expressions of Okada (1992), are also available. In the present version of VMM (Del Negro and Hashimoto, unpublished) all fields are calculated in the plane of the ground surface. We have also installed the VMM code on our website for remote applications via the Internet.

Concluding remarks

In order to provide a basis for short-term decision-making in the forecasting and monitoring of volcanic activity, we developed the Mag-Net system which automates data acquisition, processing, and analysis. The Mag-Net system is designed to allow magnetic monitoring of the Etna volcano at great distances from a central observatory.

We developed new methodological and technological approaches to provide a system which could give near-real-time information to operators working on monitoring and forecasting of volcanic eruptions. It was necessary to speed up all the processes capable of refining the data acquisition techniques and improving recognition of the events among the signals. The main problems confronted by our system may be summarized as follows:

1. Development of instruments dedicated to working in volcanic areas and the implementation of measurement techniques aimed at reducing the effects of external noise phenomena.
2. Application of advanced statistical methods to evaluate the reliability of magnetic signals associated with volcanic events. In the study of volcanic areas a fundamental problem lies in evaluating whether one or more anomalous variations of the local geomagnetic

field is or is not related to processes observed before an imminent eruption and during the eruption.

3. Implementation of a procedure for modeling magnetic fields associated with volcanic activity. The correct identification and interpretation of the sources of a wide spectrum of geophysical signals associated with volcanic activity has always suffered from the inability to appropriately model the magnetic fields.

Our aim is that of achieving substantial improvements in the knowledge of the dynamics of the shallow plumbing system at Etna volcano and, consequently, to investigate any possible magnetic transients before and during volcanic eruptions. The expected results should allow the observation and evaluation in real time of typology and activity level of the volcano, which can be used to define the pre-alarm/alarm thresholds relevant for civil protection decisions.

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