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A tectonomagnetic effect detected in Central Italy

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Abstract
Significant variations in the absolute value of the geomagnetic field intensity related to tectonic events, as earthquakes and volcanic eruptions, have been observed in several cases. To detect such a *tectonomagnetic effect* related to seismic activity, a seismomagnetic network was installed by the Istituto Nazionale di Geofisica (ING) in the Abruzzi region (Central Italy), in July 1989. This area is being uplifting since the Pliocene. A logistic compromise between geophysical requirements and the electrified railway system tracks distribution led to the installation of five total magnetic field intensity data acquisition sites. From July 1989 to September 1992 geomagnetic intensity data were simultaneously recorded at all stations and compared to that recorded at the L'Aquila Observatory, located in the same area. A variation of about 10 nT in the absolute level of the geomagnetic field was measured at two stations located on the eastern side of the network. We suggest that the detected magnetic anomaly could result from aseismic changes in crustal stress during this time.

Key words *tectonomagnetism – seismomagnetic network – seismic activity – Central Italy*

1. Introduction

The term *tectonomagnetism* has been proposed by Nagata (1969) for a research field dealing with geomagnetic changes due to stress variations (natural or not) in the upper part of the Earth's crust. In particular the term *seismomagnetism* is used when the observed geomagnetic changes are associated with the earthquake occurrence (Stacey, 1963, 1964). Examples of geomagnetic phenomena, possibly related to a seismomagnetic effect, are described in literature, even in the early scientific researches in geomagnetism and seismology. Rikitake (1976) reports an excellent review of magnetic measurements and theories in the field of historical seismomagnetic effects.

The seismomagnetic effect is generally ascribed to stress induced variations in the magnetic susceptibility of rocks, *i.e.* the piezomagnetic hypothesis, and to electrokinetic phenomena (Stacey and Johnston, 1972; Mizutani *et al.*, 1976; Fittermann, 1979; Guseva *et al.*, 1984; Dobrovol'skiy *et al.*, 1989). Their experimental observations and theoretical models show that the expected amount of change for a tectonomagnetic or seismomagnetic effect should be of the order of 10 nT at most and usually is less than that, therefore a very high accuracy in the measurements is required.

Only after the introduction of the first reliable drift free instrument for the absolute measurement of the Earth's total magnetic field, *i.e.* the Proton Precession Magnetometer (PPM), measurements were considered accurate enough to detect absolute level changes of the geomagnetic field (Packard and Varian, 1954). Also optical pumping magnetometers based on the Zeeman effect (Parsons and Wiatr, 1982; Usher *et al.*, 1964) have been recently used

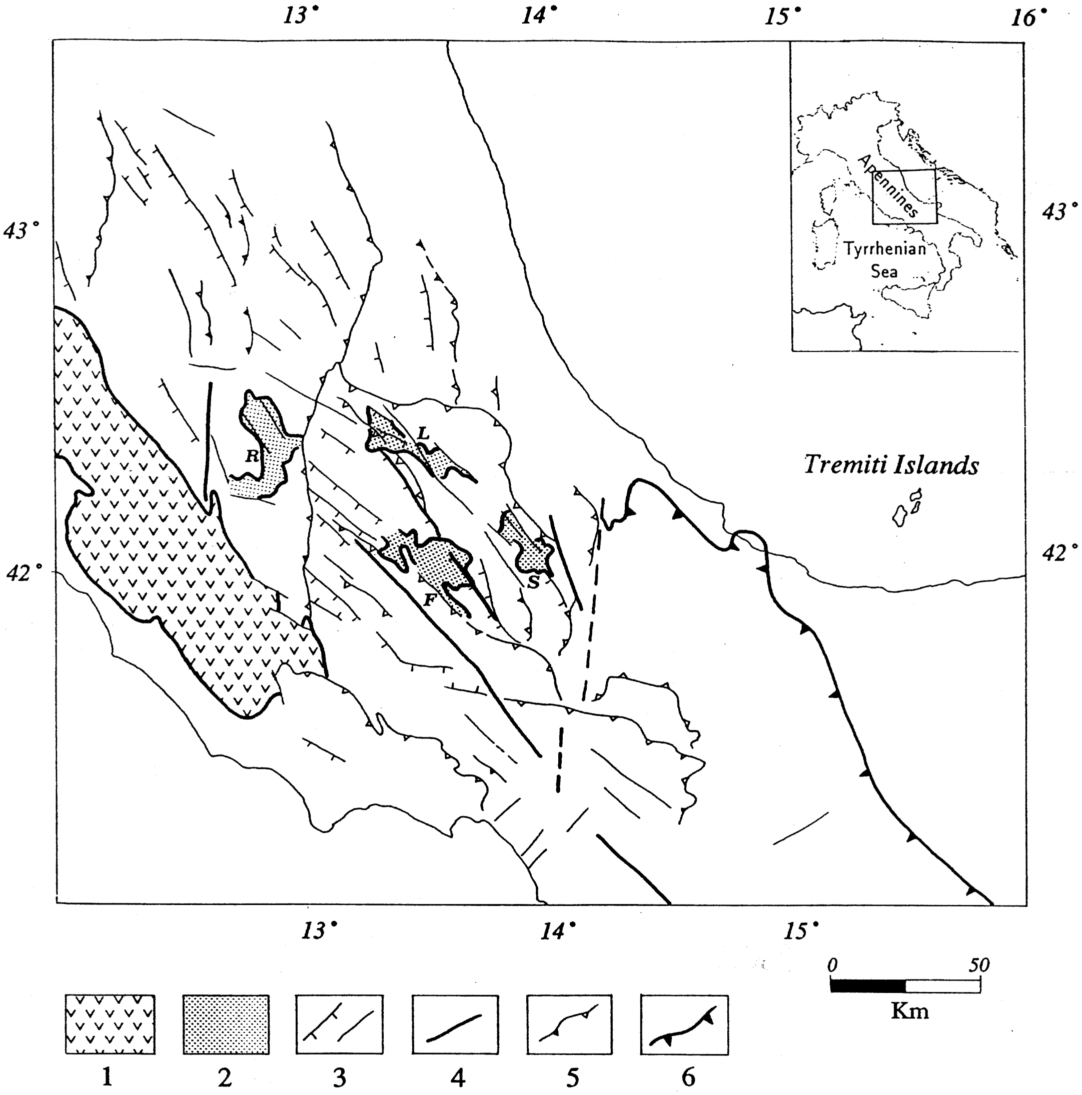

Fig. 1. Structural sketch of Central Italy (after Carraro *et al.*, 1981). 1: Quaternary volcanic deposits; 2: Plio-Quaternary extensional basins: L'Aquila (L), Fucino (F), Sulmona (S) and Rieti (R); 3: extensional faults; 4: strike-slip faults; 5: thrust faults; 6: Apennine thrust front.

for reliable tectonomagnetic studies. Modern tectonomagnetism starts with the use of such instruments. Following these considerations all correlation results between seismic activity and geomagnetic field perturbations reported before the Sixties should be considered with great care.

In the last decades networks of synchronous magnetometers were set up in seismogenic areas in U.S.A., Japan and

U.S.S.R. In order to detect local anomalous magnetic field changes related to tectonic or seismic activity, geomagnetic data from neighbouring sites are differenced. For recent results see for example: Smith and Johnston, 1976; Johnston, 1978; Davis *et al.*, 1980; Sasai and Ishikawa, 1980; Honkura, 1978; Shapiro and Abdullabekov, 1982; Sumimoto and Noritomi, 1986; Johnston and Mueller, 1987; Mueller and Johnston, 1990.

A network for seismomagnetic studies has been installed in Central Italy following some successful methodologies used in other countries. The very high artificial electromagnetic noise level restricts the choice of seismic areas for geomagnetic measurements to only a few locations. The Abruzzi region in Central Italy was found to be a good compromise for the installation of the network. In this paper the realization of the seismomagnetic network and the results of three years and a half of geomagnetic field absolute level measurements are discussed.

2. Tectonic evolution and seismic activity in Central Italy

Italy and its surrounding regions have a complex tectonic history that was accomplished mainly during the last 10 My. In fact, during upper Miocene-lower Pliocene time, extension leading to the accretion of new oceanic crust gave rise to the present Tyrrhenian basin, west of Italy, while a simultaneous shortening episode occurred throughout the Italian peninsula and originated the Apennine thrust-and-fold belt.

The Lazio-Abruzzi Apennine, where the study area is located, is the central section of the Apennine chain. From the geomorphologic point of view this area is characterized by NW-SE ridges in Meso-Cenozoic carbonatic sequences, adjacent to valleys excavated in Miocene clayey-arenaceous flysch. The structural continuity of the carbonatic ridges is often interrupted by major transversal structural elements or by topographic depressions filled with Plio-Quaternary sediments; some are very large like Fucino, Rieti, Sulmona and L'Aquila plains. In fig. 1 the main structural features of Central Italy based on the tectonic map of Italy (Carraro *et al.*, 1981) are drawn.

The Central Apennine is a tectonically active area, characterized by nearly continuous Pliocene and Quaternary uplift. Regional-scale volumes of fractured rocks have been widely recognized, suggesting the prior occurrence of large stresses. A post-middle Pliocene extension is indicated by steeply-dipping normal faults and by tilted blocks. The general orientation of the tectonic features is NW-SE and many of the large and destructive earthquakes occurred in the region are due to slip on NW-SE normal faults (Bosi, 1975). A seismogenic fault responsible for the surface wave magnitude $M_S = 6.9$ earthquake in 1915 is recognized along the eastern flank of the Fucino plain (Ward and Valensise, 1989).

Moderate seismicity is common in the Abruzzi region, most of the focal depths ranging to a maximum of 30 km. In this century three major earthquakes occurred: the 1915 Avezzano (Fucino plain) earthquake, mentioned above, and the 1984 S. Donato Val di Comino sequence main shocks ($M_S = 5.8$ and 5.2); all involved normal faulting. The L'Aquila plain is also an important center of seismic activity both for the intensity of historical earthquakes (up to X degree of Mercalli-Cancani-Sieberg scale) and for their frequent occurrence. Destructive events of 1349 (X), 1462 (X), 1703 (X) and 1762 (IX) occurred in this area (Istituto Nazionale di Geofisica, 1992).

3. The seismomagnetic network

Many field data acquisition systems devoted to seismomagnetic effect studies consist of an array of PPMs located in a seismically active area, a few or tens kilometers distant from each other. The sensors simultaneously detect the total geomagnetic field intensity at a few minutes time sampling rate. Comparison of time variations averaged over long term, in order to exclude rapid variations, is used as a key to detect internal Earth effects.

Earth's total magnetic field variations of the order of a few nT should be detected in order to reveal a seismomagnetic effect. In some areas, especially in Italy, this amplitude is smaller than the background noise level due to artificial effects, *i.e.* electrified railway lines (running on DC in Italy), power lines, urbanization, traffic, etc. This inconvenience restricts the possible areas for the installation of seismomagnetic networks.

The Abruzzi-Molise region, in Central Italy, is a seismically active area, that is at the same time rather noise free for magnetic measurements. The main Italian Geomagnetic L'Aquila Observatory (see Meloni *et al.*, 1984; Meloni and Palangio, 1990) is located here.

On the basis of the electrified railway system tracks distribution, the most suitable area for the installation of 4 total field monitoring stations is that encircling the two areas north and south of the main east-west railway line bordered by the Adriatic Sea and the Rome-Florence Rome-Naples lines. The minimum acceptable distance to the line for the station installation inside the two areas was considered to be 25 km.

In fig. 2 this century earthquakes with local magnitude greater than 4.0 (Istituto Nazionale di Geofisica, 1992) are plotted. The PPM locations and the National Geomagnetic Observatories of L'Aquila (AQU) and Castel Tesino (CTS) are also shown.

We use the Total Magnetic Field Anomaly Map of Italy (Molina *et al.*, 1994) to determine the total field crustal magnetic anomalies. The Abruzzi-Molise magnetic anomaly level is rather low indicating low average crustal magnetization. While larger amplitude seismomagnetic effects are expected in high crustal magnetization areas, a low electromagnetic artificial noise level was considered of highest priority in order to detect the unambiguous effects.

Table I. Acronyms and geographic coordinates of the Geomagnetic Observatories and seismomagnetic stations used in this work.

Acronym	Station	Lat.	Lon.
AQU	L'Aquila	42.38°N	13.32°E
CTS	Castel Tesino	46.05°N	11.65°E
CVT	Civitella Alfedena	41.78°N	13.88°E
LEO	Leonessa	42.55°N	13.70°E
MDM	Monte di Mezzo	41.76°N	13.08°E
RIT	Rieti	42.34°N	12.92°E
TER	Teramo	42.65°N	13.70°E

The chosen sites were tested on the basis of preliminary background noise level measurements, both in the higher frequency band of recording and in the magnetometer precession signal frequency band (1.8-2.3 kHz). Since 0.1 nT resolution was considered necessary, signal-to-noise ratio measurements lower than 8 must be excluded; for this reason a PPM offering the choice of two time windows for the precession signal measure was chosen and the lowest noisy window was selected for this experiment.

Magnetic field spatial gradients in the area must be lower than 1 nT/m since the frequency dispersion introduced by spatial gradients on total field measurements would affect the measured frequency and consequently the final value. A homogeneity test was done before installing all network stations in order to exclude high gradient areas and final location was selected also on the basis of this test.

The final logistic compromise led to the sites shown in fig. 2. The installation was completed in the first half of 1989 and, including L'Aquila Observatory, a number of 5 data acquisition sites have been working (see table I).

4. Seismomagnetic data analysis

Variations in the difference fields as recorded by single stations composing an

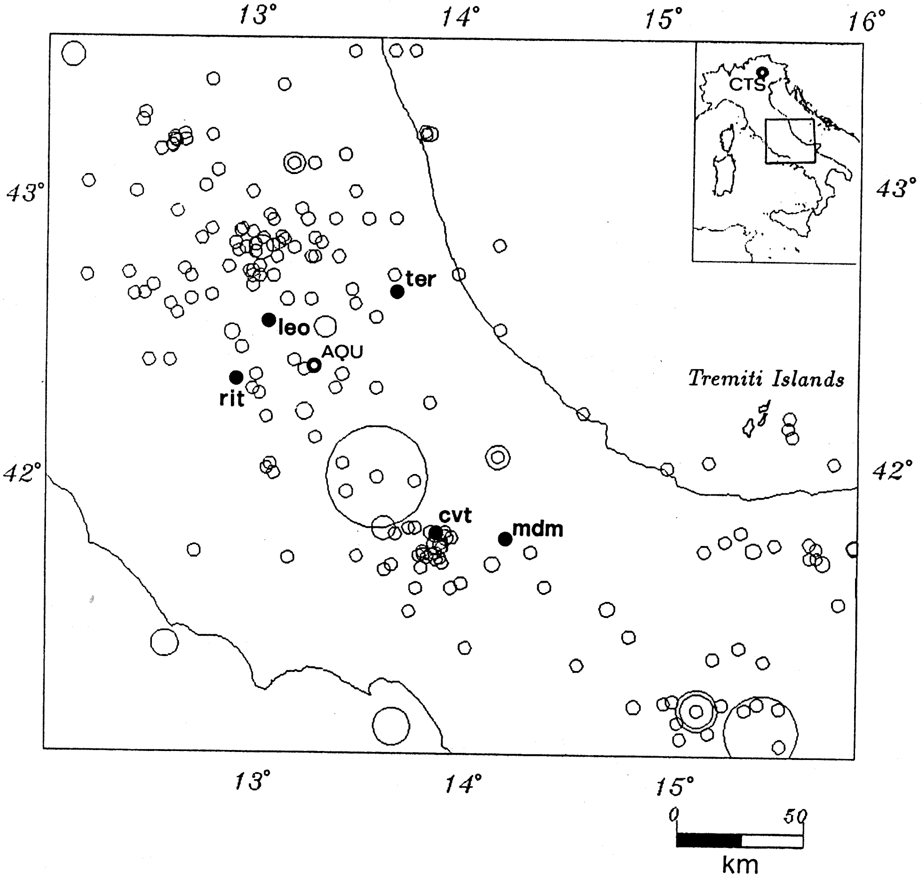

Fig. 2. Epicenters distribution of this century earthquakes (M_l > 4.0) from the ING Seismic Catalogue. L'Aquila (AQU) and Castel Tesino (CTS) Geomagnetic Observatories and the magnetometer sites are shown.

array of magnetometers arise mainly from four different sources:

a) magnetic field effects due to Earth external electric currents;
b) induced fields in the Earth's interior from point (a) source;
c) rapid variations of the internal Earth's core electric currents (non uniform secular variation);
d) changes in crustal magnetization due to stress (*e.g.* seismomagnetic effect).

To be sure to detect only the stress induced magnetization anomaly, the first three source effects must be eliminated from the data.

Most of the external electric currents noise can be removed if the data set is long enough in time to average over long term (a few to several days for example). If the investigated area does not have a large spatial extent and in particular if it lies at intermediate latitudes, iono-magnetospheric currents and their induction effects can be largely eliminated, particularly if the time scale of ionospheric and magnetospheric currents is short compared to the tectonic stress accumulation time (Rikitake, 1976).

Non uniform secular variation is probably one of the major problems to solve in tectonomagnetic studies: observed values reach at times 1 nT/yr per 100 km in latitude or more, for example along the San Andreas fault (Johnston *et al.*, 1985), with a small dependence also in longitude. The difference fields recorded by an array of magnetometers related to this effect could be confused with tectonomagnetic effects. However the secular variation pattern is generally rather regular and smooth and can be, if necessary, predicted and removed in order to determine the local effect for every station in the network.

5. Magnetic observations from 1989 to 1992

Starting from July 1989 four magnetometer stations were operational in the Abruzzi region network so that more than three years of geomagnetic total intensity measurements were available for this study.

Synchronously sampled (4 min) values from each site (see table I for acronyms) were collected and averaged on a daily basis. All-day (24 h data) and night-time

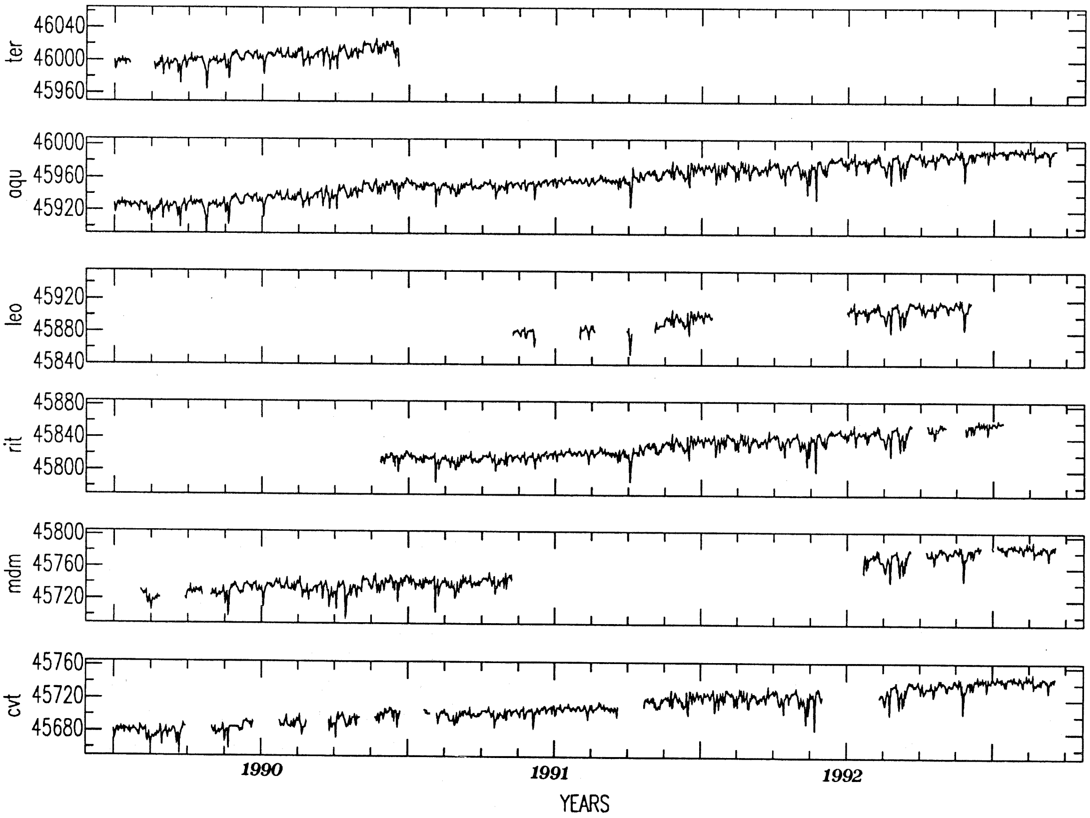

Fig. 3. Daily mean values (nT) of the total magnetic field at the geomagnetic stations.

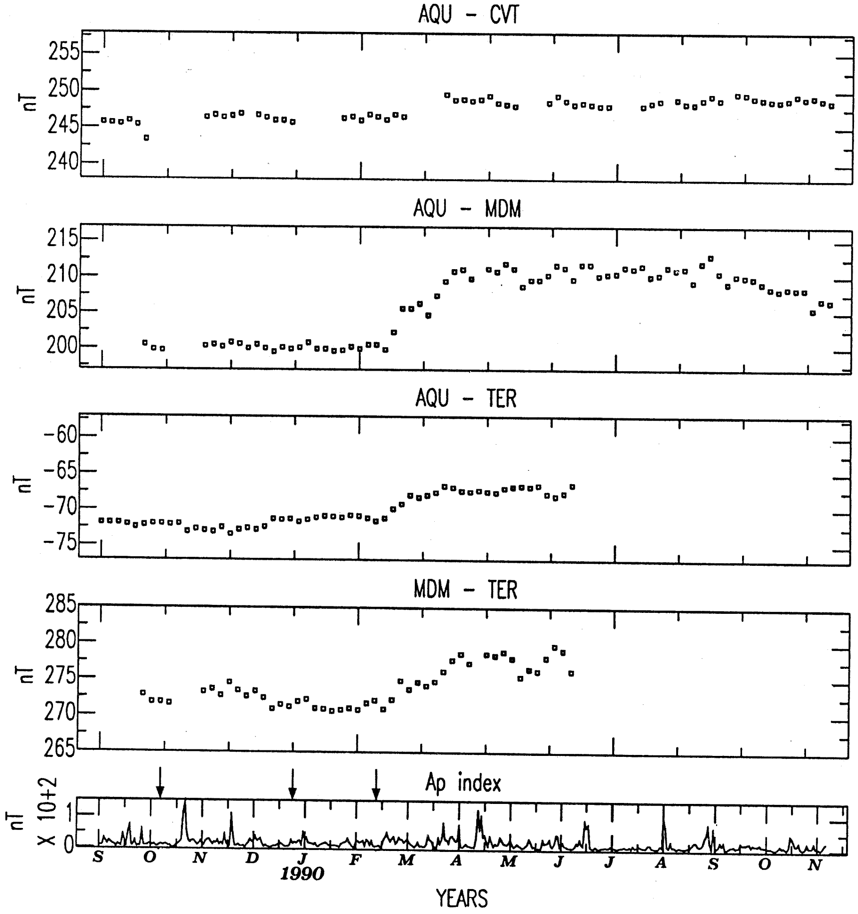

Fig. 4. 5-days mean of simple differences of the total geomagnetic field between CVT, MDM, TER stations and the AQU reference Observatory. The difference between TER and MDM is shown for comparison. The magnetic planetary activity Ap index is also plotted. The arrows at the bottom of the figure indicate the earthquakes occurrence.

mean values, centered at 02:00 UT, from all stations of the network were computed. In fig. 3 all-day mean values are reported for all stations, for the whole recording period.

Since very bad weather conditions arose during the '89-'90 winter, the stations located at high elevations in the network have some data missing during that time. A few gaps in the data set are due to instruments not properly working, as in CVT, or to a complete removal of the station, as in the case of TER, moved to RIT for logistic problems.

Figure 3 shows a regular steady secular variation pattern for total field values in all stations data with an average increase of 25 nT/year. The average spatial gradient of this variation is less than 1 nT/year/100 km. Many synchronous spikes are due to solar activity effects, mainly storms, which were very frequent in these years. A quick look at the data does not reveal much difference in response between the stations.

In fig. 4, 5-day differences between L'Aquila Observatory and the stations CVT, MDM and TER are shown.

Starting in February 1990 an anomalous variation of the absolute field level occurred in both stations that are located on the eastern side of the array, *i.e.* MDM and TER. 02:00 UT averaged values, not shown here, and all-day mean differences between AQU and MDM and between AQU and TER show similar changes: an increasing trend starts around the end of 1989 and goes through 1990 for about two months; the normal field level seems to be recovered in a few months. The amount of the anomalous change detected is of about 10 nT.

In order to exclude L'Aquila Observatory data, TER and MDM were also differenced and plotted. Unfortunately the move of TER station for logistic problems does not allow to follow the effect after June 1990 for this station. Looking at the AQU-MDM differences, however, a clear return to the 1989 level appears for MDM station. At the bottom of fig. 4 the geomagnetic planetary activity, *i.e.* the Ap index, and the earthquakes occurrence ($M_l \geq 4.0$) are shown.

There was no evidence of any artificial disturbances at all stations, since the sensors and the magnetometers hardware have been regularly inspected by specialized technicians.

6. Conclusions

The Abruzzi region is characterized by active faulting and rather intense seismicity: several destructive earthquakes occurred in the L'Aquila basin and surrounding areas (Istituto Nazionale di Geofisica, 1992).

In order to investigate the possible correlation between the detected anomalous changes in the geomagnetic intensity and the seismic activity, the earthquakes occurrence in the 1989-1992 period was examined. Three earthquakes with $M_l \geq 4.0$ and several with M_l ranging 3.0 to 4.0 occurred in Central Italy in this period: in January-February 1990 a seismic sequence with a $M_l = 4.0$ main shock occurred in the Tremiti Islands area (Adriatic Sea), about 100 km ESE of the study area. Since the two stations detecting the geomagnetic anomalous variation are both on the eastern (Adriatic) side of the network, the anomalous change in the total geomagnetic field intensity could have been the result of perturbations in crustal stress, following the Tremiti Islands event. On the other hand it is more likely that since the Tremiti Islands event is rather small and distant, the anomalous magnetic event in the Abruzzi region, *i.e.* the MDM and TER changes, were caused solely by a tectonomagnetic aseismic effect. Unfortunately there are no evidences of enhancement of tectonic stresses in the Abruzzi region at the time of this anomalous variation, since no geodetic or other geodynamic data are available at the present time to support this study.

REFERENCES

BOSI, C. (1975): Osservazioni preliminari su faglie probabilmente attive nell'Appennino Centrale, *Boll. Soc. Geol. It.*, **94**, 827-859.

CARRARO, F., A. CASTELLARIN, R. CATALANO, T. COCOZZA, G. I. ELTER, R. FUNICIELLO, G.O. GATTO, E. LOCARDI, M. PAROTTO, A. PRATURLON, R. SARTORI, P. SCANDONE, E. SEMENZA, C. STURANI and L. VEZZANI (1981): Tectonic map of Italy, 1:1500000, CNR, Geodynamical Project, Publication N. 269, GEO, Roma.

DAVIS, P.M., D.D. JACKSON and M.J.S. JOHNSTON (1980): Further evidence of localized geomagnetic field changes before the 1974 Thanksgiving Day Earthquake, Hollister, California, *Geophys. Res. Lett.*, **7**, 513-516.

DOBROVOL'SKIY, I.P., N.I. GERSHENZON and M.B. GOKHBERG (1989): Theory of electrokinetic effects occurring at the final stage in the preparation of a tectonic earthquake, *Phys. Earth Planet Inter.*, **57**, 144-156.

FITTERMANN, D. V. (1979): Theory of electrokinetic-magnetic anomalies in a faulted half-space, *J. Geophys. Res.*, **84**, 6031-6041.

GUSEVA, T.V., I.P. DOBROVOL'SKIY, I.L. NERSESOV and YU.P. SKOVORODKIN (1984): Vertical movements and magnetic variations preceding earthquakes, *Izv. Earth Phys.*, **20** (1), 37-40.

HONKURA, Y. (1978): On a relation between anomalies in the geomagnetic and telluric fields observed at Nakaizu and the 1978 Izu-Oshima Kinkai earthquake, *Bull. Earthquake Res. Inst.*, **53**, 931-937.

ISTITUTO NAZIONALE DI GEOFISICA (1992): Seismic Catalogue, Roma.

JOHNSTON, M.J.S. (1978): Local magnetic field variations and stress change near a slip discontinuity on the San Andreas fault, *J. Geomagn. Geoelectr.*, **30**, 511-522.

JOHNSTON, M.J.S., S.A. SILVERMAN, R.J. MUELLER and K.S. BRECKENRIDGE (1985): Secular variation, crustal contributions and tectonic activity in California, 1976-1984, *J. Geophys. Res.*, **90**, 8707-8717.

JOHNSTON, M.J.S. and R.J. MUELLER (1987): Seismomagnetic observation during the July 8th, 1986, magnitude 5.9 North Palm Spring earthquake, *Science*, **237**, 1201-1203.

MELONI, A., F. MOLINA, P. PALANGIO, Q. TACCETTI and A. DE SANTIS (1984): Automatic digital recording of geomagnetic elements by means of a proton precesssion magnetometer, *Geophys. Surv.*, **6**, 339-350.

MELONI, A. and P. PALANGIO (1990): Improvements of automatic Magnetic Observatories in Italy, in *Proceedings of the International Workshop on Geomagnetic Observatory Data Acquisition and Processing, Helsinki, May 15-25, 1989*.

MIZUTANI, H., T. ISHIDO, T. YOKOKURA and S. OHNISHI (1976): Electrokinetic phenomena associated with earthquakes, *Geophys. Res. Lett.*, **3/7**, 365-368.

MOLINA, F., E. ARMANDO, R. BALIA, O. BATTELLI, E. BOZZO, G. BUDETTA, G. CANEVA, M. CIMINALE, N. DE FLORENTIIS, A. DE SANTIS, G. DOMINICI, M. DONNALOIA, A. ELENA, V. ILICETO, R. LANZA, M. LODDO, A. MELONI, E. PINNA, G. SANTARATO and R. ZAMBRANO (1994): Geomagnetic survey of Italy at 1979.0. Repeat station network and magnetic maps, *Istituto Nazionale di Geofisica*, **554**, 32.

MUELLER, R.J. and M.J.S. JOHNSTON (1990): Seismomagnetic effect generated by the October 18th 1989, M_l 7.1 Loma Prieta, California, earthquake, *Geophys. Res. Lett.*, **17/8**, 1231-1234.

NAGATA, T. (1969): Basic magnetic properties of rocks under the effect of mechanical stresses, *Tectonophysics*, **21**, 427-445.

PACKARD, M. and M. VARIAN (1954): Free nuclear induction in the Earth's magnetic field, *Phys. Rev.*, **93**, 941-944.

PARSONS, L.W. and Z.M. WIATR (1982): Rubidium vapour magnetometer, *J. Sci. Instrum.*, **39**, 292-299.

RIKITAKE, T. (1976): Earthquake prediction (Elsevier, Amsterdam), pp. 357.

SASAI, Y. and Y. ISHIKAWA (1980): Tectonomagnetic event preceding a $M=5.0$ earthquake in the Izu Peninsula – aseismic slip of a buried fault?, *Bull. Earthq. Res. Inst.*, **55**, 895-911.

SHAPIRO, V.A. and K.N. ABDULLABEKOV (1982): Anomalous variations of the geomagnetic field in East Fergana – magnetic precursor of the Alay earthquake with $M=7.0$ (1978 November 2), *Geophys. J.R. Astron. Soc.*, **68**, 1-5.

SMITH, B.E. and M.J.S. JOHNSTON (1976): A tectonomagnetic effect observed before a $M=5.2$ earthquake near Hollister, California, *J. Geophys. Res.*, **81**, 3556-3560.

STACEY, F.D. (1963): Seismomagnetic effect and the possibility of forecasting earthquakes, *Nature*, **200**, 1083-1085.

STACEY, F.D. (1964): The seismomagnetic effect, *Pure Appl. Geophys.*, **58**, 5-22.

STACEY, F.D. and M.J.S. JOHNSTON (1972): Theory of the piezomagnetic effect in titanomagnetite-bearing rocks, *Pure Appl. Geophys.*, **97**, 146-155.

SUMIMOTO, N. and K. NORITOMI (1986): Synchronous precursors in the electrical Earth resistivity and the geomagnetic field in relation to an earthquake near the Yamasaki fault, Southwest Japan, *J. Geomagn. Geoelectr.*, **38**, 971-989.

USHER, M.J., W.F. STUART and S.H. HALL (1964): A self-oscillating rubidium vapour magnetometer for geomagnetic measurements, *J. Sci. Instrum.*, **41**, 544-547.

WARD, S.N. and G.R. VALENSISE (1989): Fault parameters and slip distribution of the 1915 Avezzano, Italy, earthquake derived from geodetic observations, *Bull. Seismol. Soc. Am.*, **79** (3), 690-710.

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