MAGNETIC INDUCTION EFFECTS OF THE DIURNAL VARIATION. CASE STUDY – THE HOKKAIDO MAGNETOMETRIC ARRAY

VENERA DOBRICĂ[1], TORU MOGI[2], CRIŞAN DEMETRESCU[1], MASAMITSU TAKADA[2]

[1] *„Sabba S. Ştefănescu" Institute of Geodynamics of the Romanian Academy, Bucharest*
[2] *Institute of Seismology and Volcanology, Graduate School of Science, Hokkaido University*

Effets d'induction magnétique produits par la variation diurne. Etude de cas – le reseau magnétometrique de Hokkaido. La variation diurne régulée, representée par les moyennes horaires des éléments géomagnétiques enrégistrés dans le cadre du reseau tectono-volcano-magnétique de l'île de Hokkaido, le Japon, a été utilisée pour déterminer le signal induit dans les structures magnétiques et conducteures au-dessous de la surface de la Terre, produites par le champ variable externe lié à la variation diurne. Les enregistrements effectués chez deux observatoires géomagnétiques japonés – Memambetsu, qui se trouve dans la proximité du reseau, et Kakioka, amplasé 900 km sud-ouest du reseau, ont été utilisés pour representer le champ variable externe. La modalité du traitement des données utilise un modèle d'induction magnetique dont les valeurs calculées sont controlées par l'induction magnétique dans les roches crustales. Les résidus sont controlés par l'induction électromagnétique dans les structures conducteures dans la croûte et le manteau de la zone point d'observation. On démontre la stabilité de la méthode par l'analyse d'un nombre d'intervalles de sept jours d'enrégistrement du champ géomagnétique, choisis aléatoire. La méthode permet de déterminer les contrastes contenus par les propriétés magnétiques et électriques des roches du sous-sol des stations du reseau. L'information fournie par le modèle d'induction magnétique peut être utilisée autant pour cartographier les variations laterales des propriétés magnétiques et éléctriques du sous-sol (dans le cas des reseaux denses de stations magnétométriques), que dans une meilleure élimination (enlèvement) des effets de la variation du champ géomagnetique externe contenues par les données des reseaux tectono-volcano-magnétiques.

Key words: magnetic induction, electromagnetic induction, diurnal variation, magnetometric array, Hokkaido.

1. INTRODUCTION

It is common knowledge (*e.g.* Chapman and Bartels, 1940) that external variable magnetic fields induce a response of the Earth's interior. A rich literature has been devoted to electromagnetic induction in the Earth, from theory (*e.g.* Rokityansky, 1982; Schmucker, 1985) to sounding the internal structure of the Earth for general (Banks, 1969; Parker, 1970, 1980; Weidelt, 1972; Roberts, 1984) and/or applied purposes (Johnston, 1997; Larsen, 1997; Harada *et al.*, 2004; Demetrescu and Dobrică, 2003).

Demetrescu *et al.* (1985; 1988) and Demetrescu and Andreescu (1992) remarked that the variable external field induces in the rocks above the Curie temperature a response by magnetic induction and devised a method to separate the magnetic and the electromagnetic induction effects, method which also allows, in case of a network of geomagnetic observatories, mapping the lateral variation of the magnetic and electric properties of the underground. The method was applied to data from the European network of geomagnetic observatories (Demetrescu *et al.*, 1988; Demetrescu and Andreescu, 1992; 1994; Demetrescu and Dobrică, 2003) and to data from the Romanian network of repeat stations (Demetrescu *et al.*, 1985), using as inductive source the solar-cycle-related (SC) variation, present both in observatory data (Chapman and Bartels, 1940; Yukutake, 1965; Alldredge, 1976; Courtillot and Le Mouël, 1976; Alldredge *et al.*, 1979; Yukutake and Cain, 1979; Demetrescu *et al.*, 1988; Sabaka *et al.*, 2004; Verbanac *et al.*, 2007) and in repeat station data (Atanasiu *et al.*, 1976; Anghel and Demetrescu, 1980; Galdeano *et al.*, 1980, Demetrescu *et al.*, 1985).

In the present paper, we study the case when the inductive source is the regular daily variation, on data from the Hokkaido magnetometric array of the Institute of Seismology and Volcanology (ISV) of the Hokkaido University, Japan, in the frame of a scientific cooperation between the Institute of Geodynamics, Bucharest, and the ISV, Sapporo.

2. METHOD AND DATA

Our method is based on the observation that the variable external magnetic field related to the diurnal variation induces variable internal magnetic fields not only by electromagnetic induction, but also by magnetic induction. In case of pure magnetic induction, the temporal variation of the field components at a given observing site is a linear combination of the components of the magnetic force (Demetrescu *et al.*, 1985; 1988),

$$\Delta E^{(S)}(t) = \sum_{k=1}^{3} c_k^E \Delta F_k\,, \tag{1}$$

where Δ represents variations about temporal averages, $E^{(S)}$ is the geomagnetic field component at the station (E can be X, Y or Z), F_k, k = 1...3, are the components of the inductive magnetic force and c_k^E are coefficients that depend on the effective magnetic permeability characterizing the site. These coefficients can be derived by a least squares procedure; a map with their values would display the lateral variation of the magnetic properties of the underground. The calculated values ($\Delta E^{(S)}_{calc}$) of the model would represent the pure magnetic induction component of the observed signal and the residuals ($\Delta E^{(S)}_{res} = \Delta E^{(S)} - \Delta E^{(S)}_{calc}$) would contain information on electromagnetic induction in the Earth at the observing site.

The residuals can be used to infer information on the electric properties of the underground, within the frame of a model suggested by Demetrescu and Andreescu (1992) and applied to data from the European network of observatories by Demetrescu and Dobrică (2003). In terms of induced current loops flowing in the more conductive structures in the underground, having in view that the residuals should correlate with the negative time derivative of the variable external field, –F'(t), if they were produced as an electromagnetic induction effect, the instantaneous value of the tension *u* and intensity *i* in a R-L circuit, given by

$$u = L\frac{di}{dt} + Ri \tag{2}$$

reads

$$-\dot{F}(t) = L \cdot R\dot{e}s(t) + R \cdot Res(t) \tag{3}$$

given that the residuals could be viewed as a measure of the intensity of the current in an equivalent circular loop of radius unity surrounding the point of observation (Demetrescu and Andreescu, 1992). L and R, the inductance and, respectively, the resistance of the underground, can be derived from (3) by a least squares procedure and maps of their lateral variation could be drawn.

In the absence of independent data on the external geomagnetic field related to the variation observed (*i.e.* the field produced by the ionospheric current system responsible for the regular diurnal variation), we took as estimates for the components of the inductive magnetic force, the components of the variation at a nearby geomagnetic observatory (a reference station, as is usually done in the interpretation of data from magnetometer arrays (Gamble *et al.*, 1979; Gough and Ingham, 1983; Larsen, 1997; Ueshima *et al.*, 2001; Harada *et al.*, 2004)). In this study, the Memambetsu geomagnetic observatory has been used as the reference station, so the input magnetic force in the model is in fact a resultant of the external field and the induced response of the Earth beneath the observatory. The location of the magnetometric stations and Memambetsu geomagnetic observatory is shown in Figure 1. Three stations (ERM, NIJ, TNK) provide data since 2000, while URH started operation in 2001.

The data from the magnetometric stations of the Hokkaido array, sampled at 10 s, were worked out to obtain hourly averages of the northward (X), eastward (Y) and downward component (Z) of the geomagnetic field for each station. Shown in Figure 2 are the hourly averages at three of the recording stations, namely ERM, NIJ, and TNK, for the time interval May 1 – 7, 2000, in local time (LT).

3. RESULTS AND DISCUSSION

The diurnal evolution of the field is characterised by a pronounced minimum around 10 h LT and smaller amplitude variations during afternoon and night hours, more pronounced in X than in Z (Fig. 2). Also, amplitude and phase differences between the three stations, more pronounced in Z, can be noticed.

The contribution of the magnetic induction in crustal rocks to the diurnal variation of the geomagnetic elements, *i.e.* the calculated values of the model for the time interval May 1–7, 2000, is presented in Figure 3. The model residuals are shown in Figure 4. One can notice the more pronounced magnetic induction response in the horizontal components (X and Y) in comparison with the vertical one. On the contrary, the residuals are much more pronounced in Z than in X and Y, a behaviour also noticed in case of the solar-cycle-related variations (Demetrescu *et al.*, 1988; Demetrescu and Andreescu, 1992; Demetrescu and Dobrică, 2003).

The coefficients $c_1^{(X,Y,Z)}, c_2^{(X,Y,Z)}, c_3^{(X,Y,Z)}$ depend on the magnetic permeability of rocks under the observing point, down to the Curie temperature surface, but also on the magnetic properties of rocks under the MMB observatory, chosen as reference station. In turn, L and R, derived from the model residuals, depend on the electric properties of crustal and mantle conductive structures under the reference station. The contribution of these properties would result in certain phase and amplitude differences between the Z residuals and the proxy chosen for the variations of the electromagnetic inducing force, namely the time derivative of the vertical component at the reference station (Fig. 5). To test the stability of the method, the induction model was applied to data from several time intervals, both from the year 2000, when only three stations (ERM, NIJ, TNK) were in operation, and from 2001, when all four stations acquired data. Corresponding values for c_k, k = 1, 2, 3, were obtained. To test how the results depend on the reference station considered, data from another Japanese observatory, Kakioka (KAK), were also used as a proxy for the inductive external variation. MMB was in this case the fifth station of the network. Of course, the inferred coefficients will contain, this time, information from the rocks under the KAK observatory.

In Figures 6–9, we plotted the coefficients c_1^X, c_3^Z, L, and respectively R for the four magnetometric stations and one of the two geomagnetic observatories, as deduced using data of the other (MMB and KAK, respectively) as proxy for the external daily variation field, in case of several 7-day intervals from various months of the years 2000 and 2001, indicated in the figures. The plots illustrate, on one hand, differences in magnetic and electric properties of the underground between stations and, on the other, the stability of the method. No matter of the time interval and of the reference observatory considered, the tendency of variations from one station to another is preserved. This indicates that in case of a more dense network of stations operating simultaneously, one can derive robust maps of the lateral variation of magnetic properties, that do not change their shapes (the anomalies appear on the map in the same place) but only values, when data series are picked up from various common time intervals for which the analysis would be done. We point out here that such maps would, however, display magnetic and electric properties contrasts rather than actual permeabilities, resistance and, respectively, inductance of the underground.

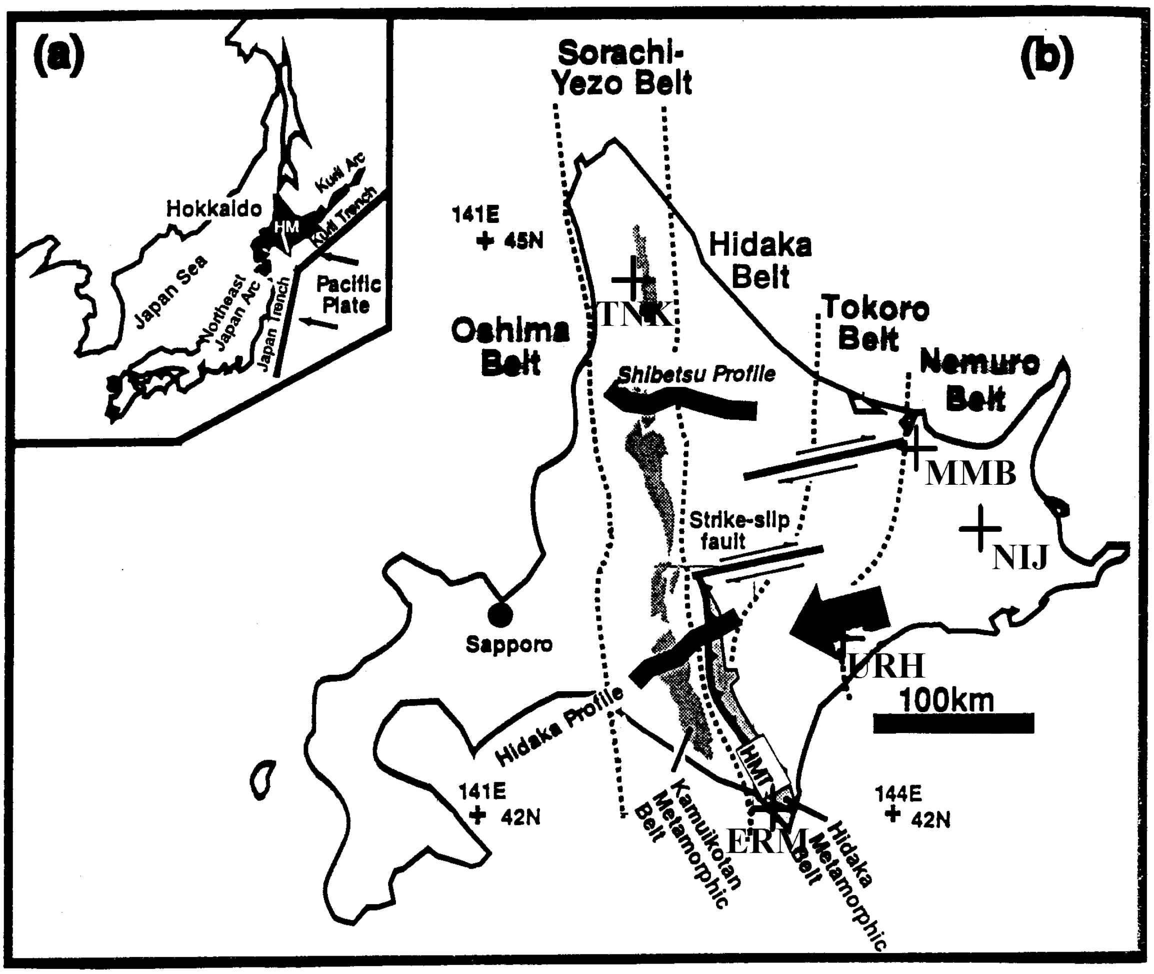

Fig. 1 – Location of the magnetometric stations and of MMB geomagnetic observatory.

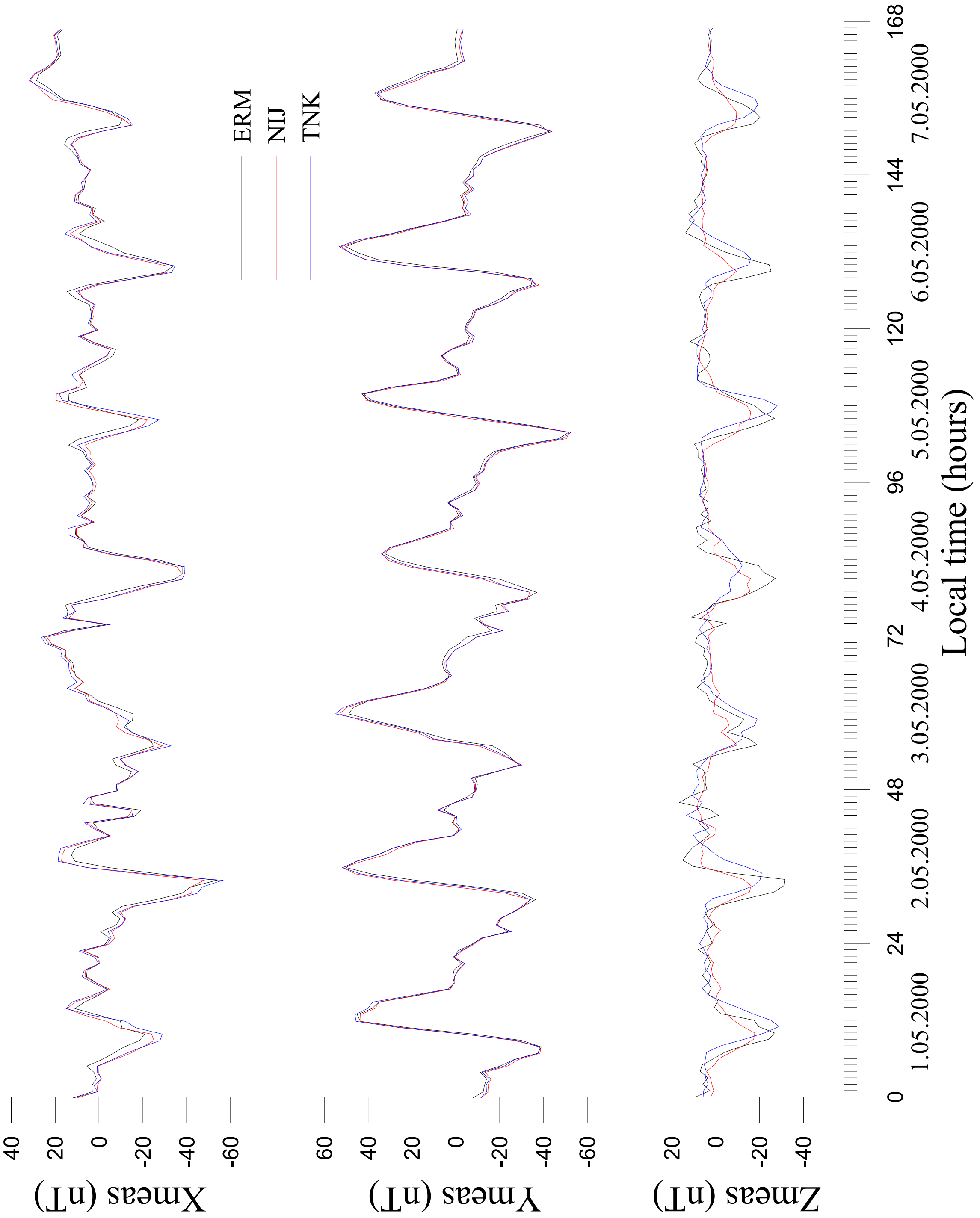

Fig. 2 – The diurnal variation of the X, Y, and, Z components of the geomagnetic field at ERM, NIJ, and, TNK magnetometric stations.

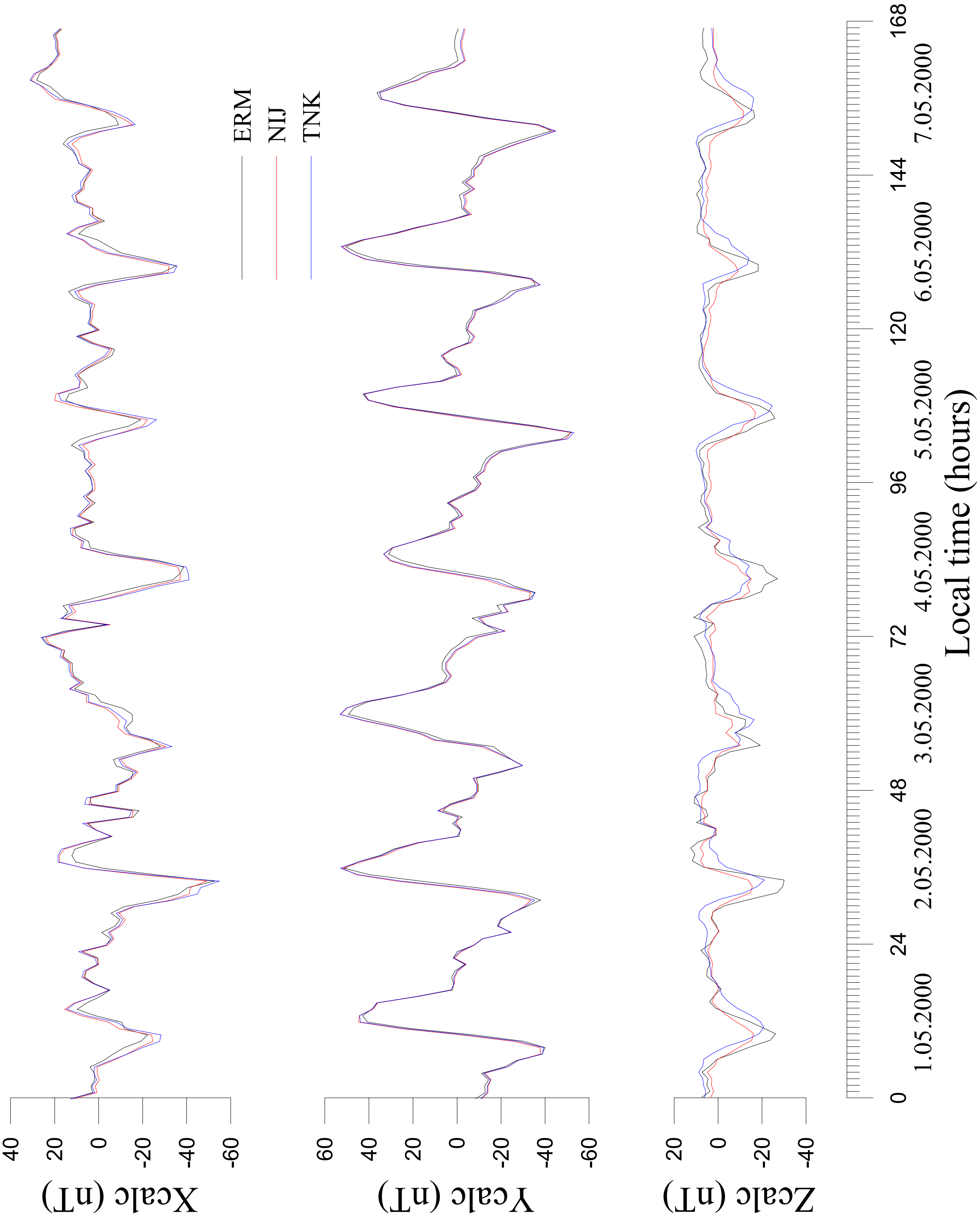

Fig. 3 – Calculated values of the induction model.

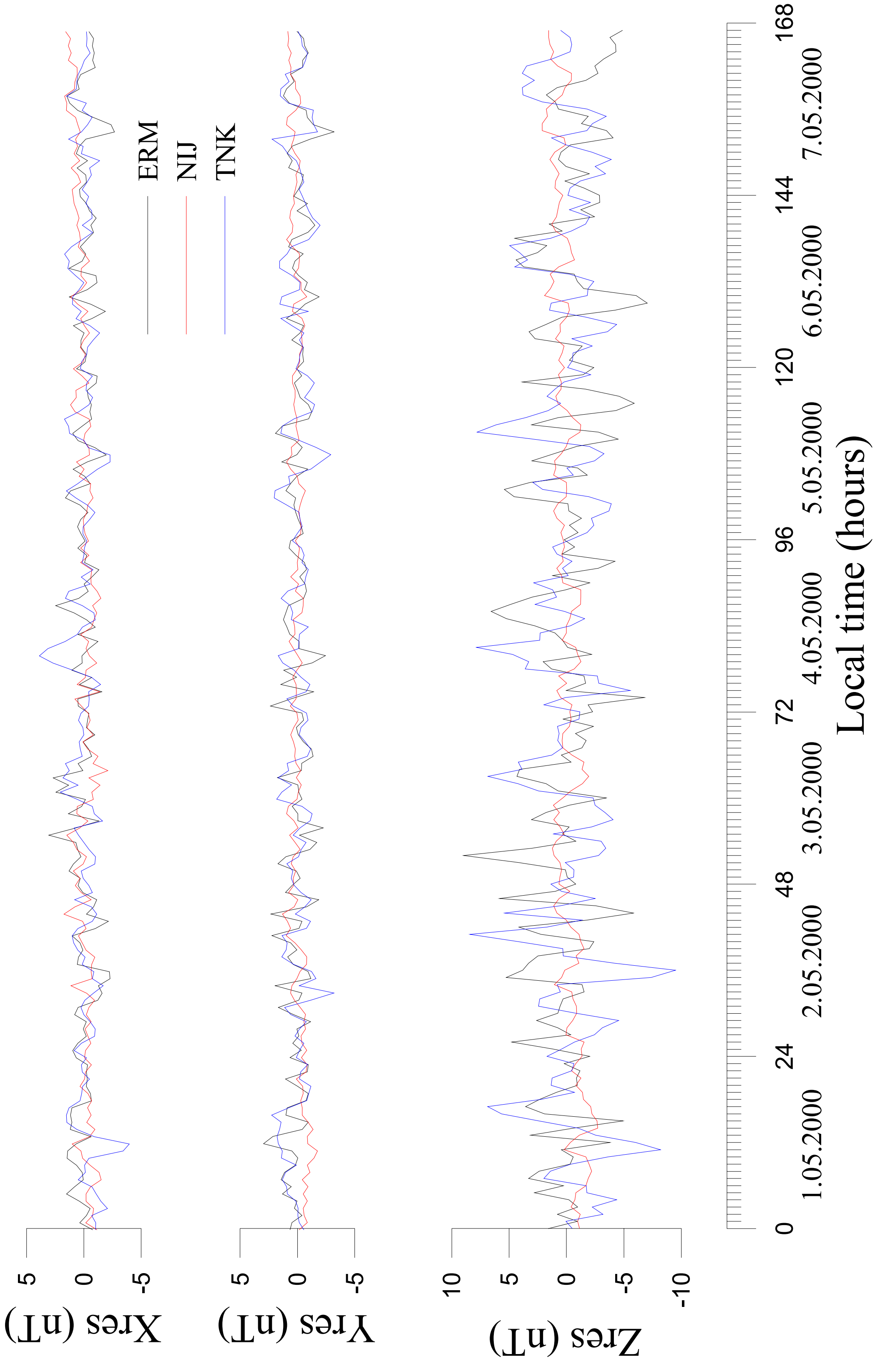

Fig. 4 – Residuals of the induction model.

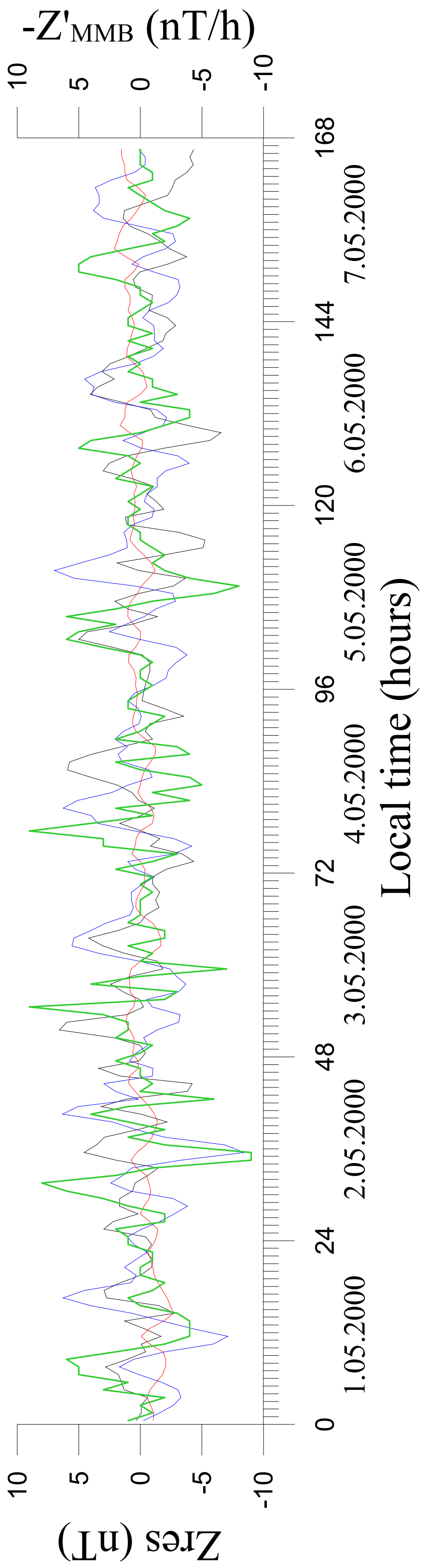

Fig. 5 – Residuals of the induction model in the Z component and the negative time derivative of Z component at the MMB geomagnetic observatory.

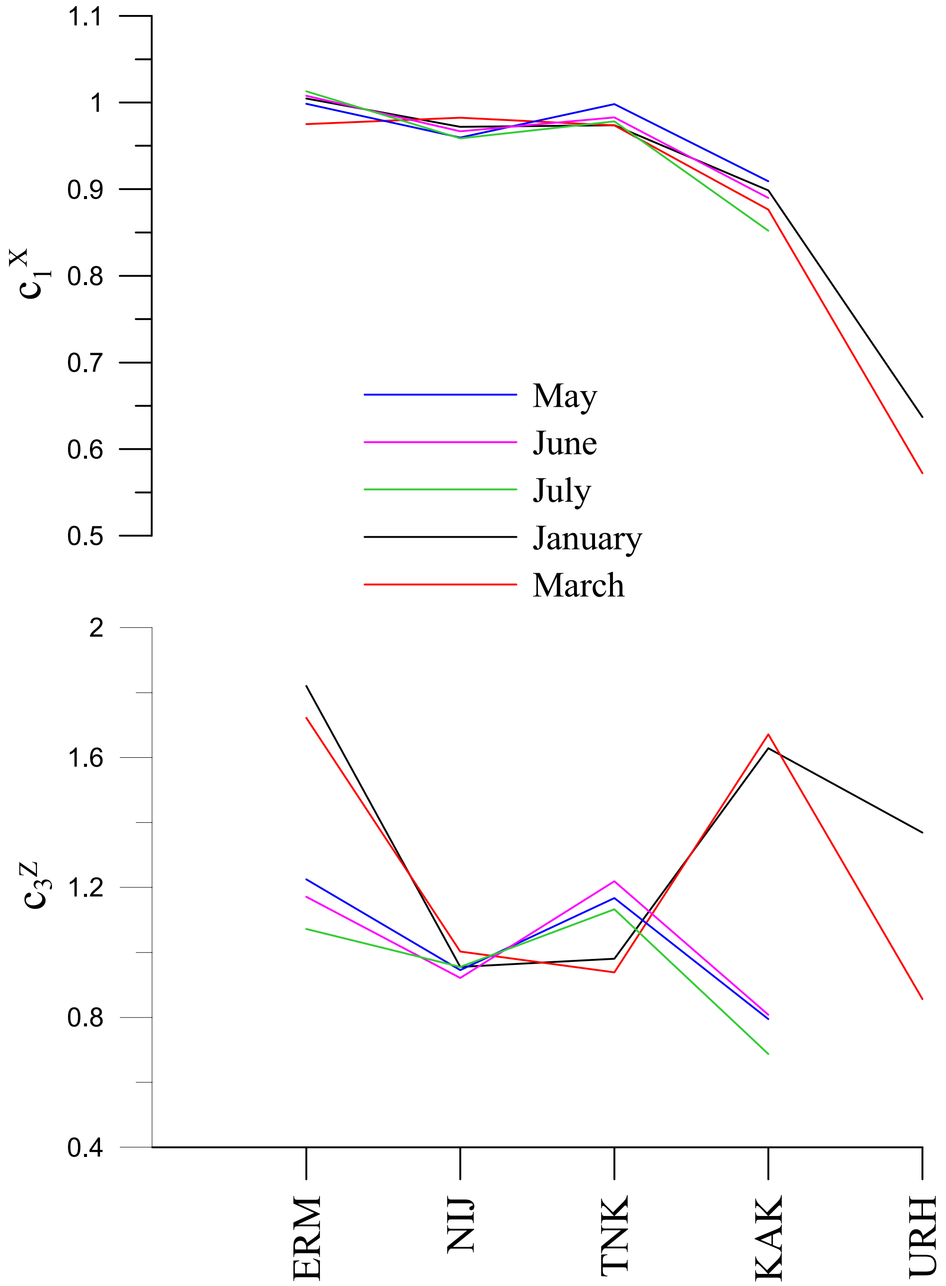

Fig. 6 – The coefficients c_1^X, c_3^Z at the magnetometric stations and KAK geomagnetic observatory.

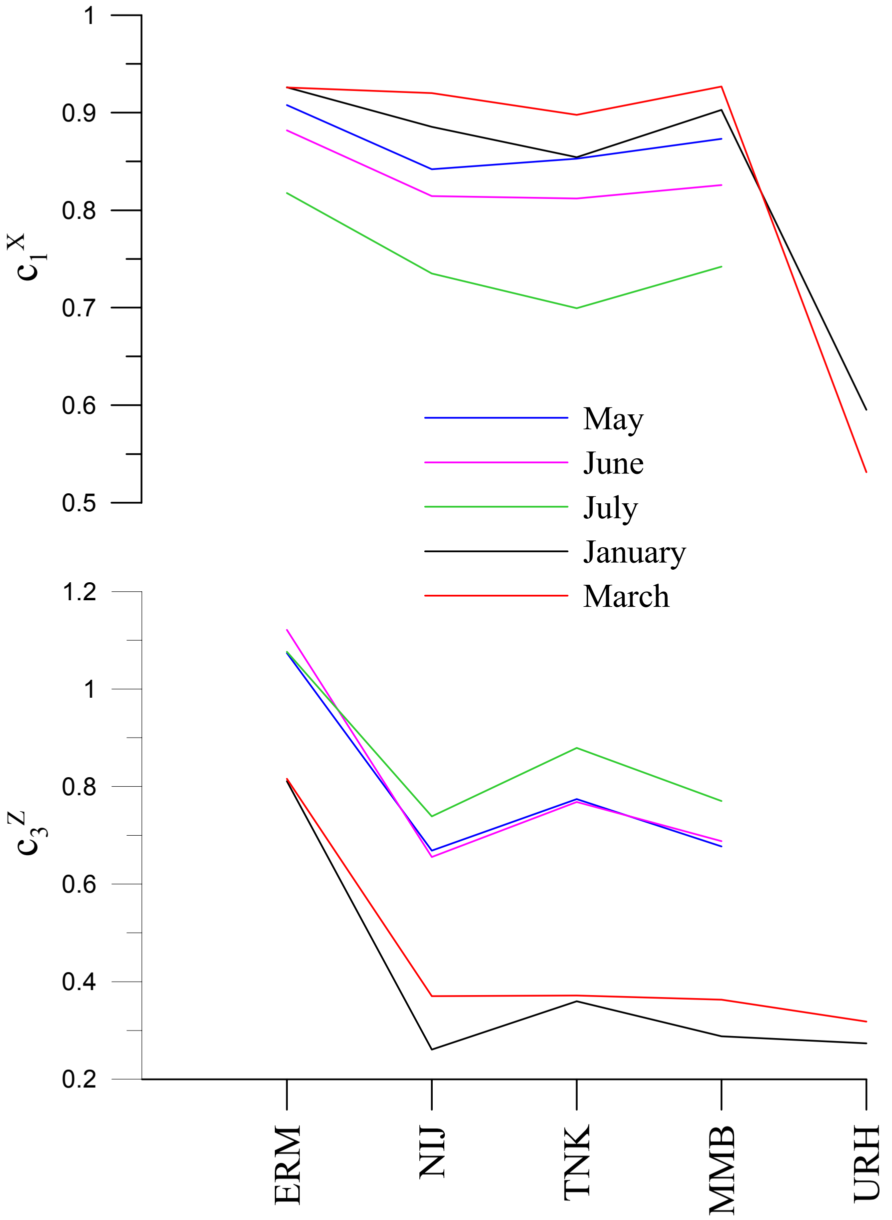

Fig. 7 – The coefficients c_1^X, c_3^Z at the magnetometric stations and MMB geomagnetic observatory.

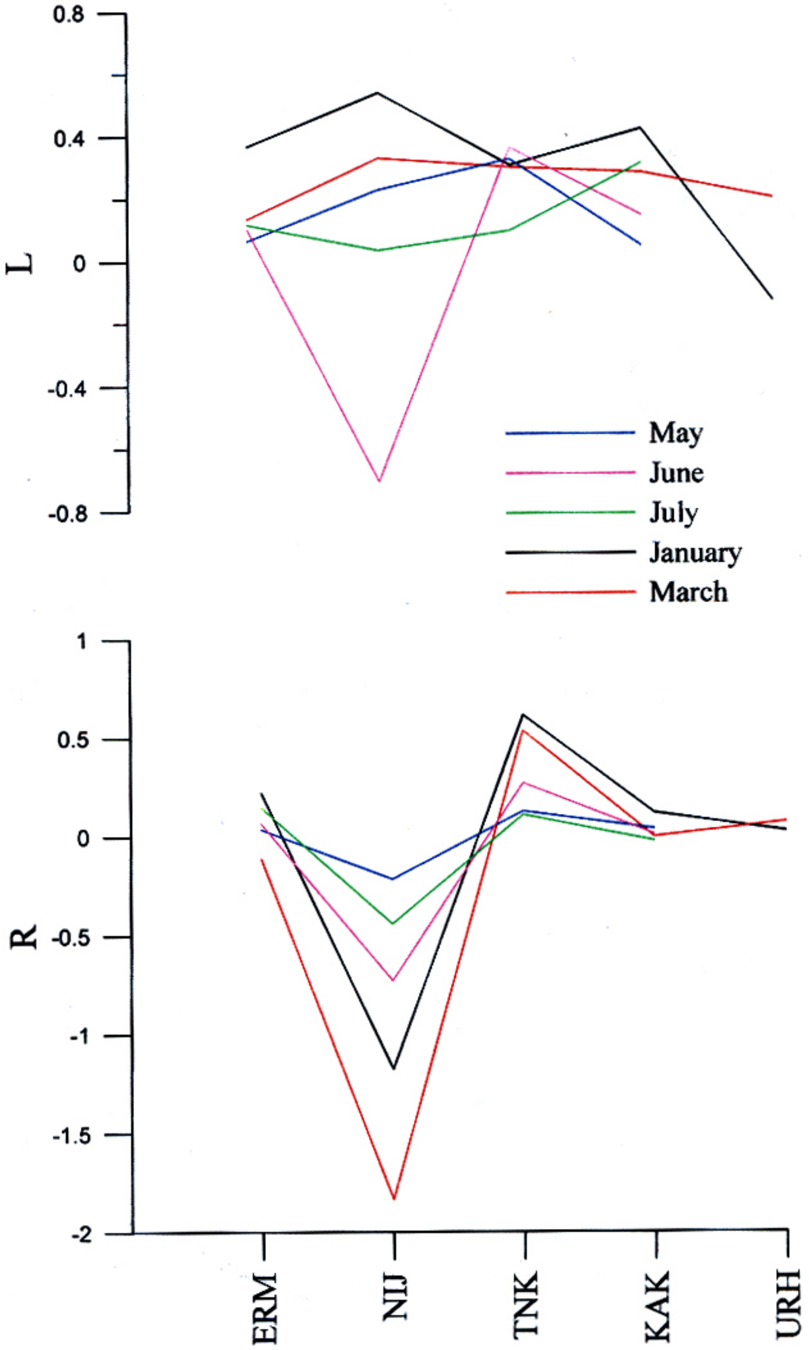

Fig. 8 – The coefficients L and R at the magnetometric stations and KAK geomagnetic observatory.

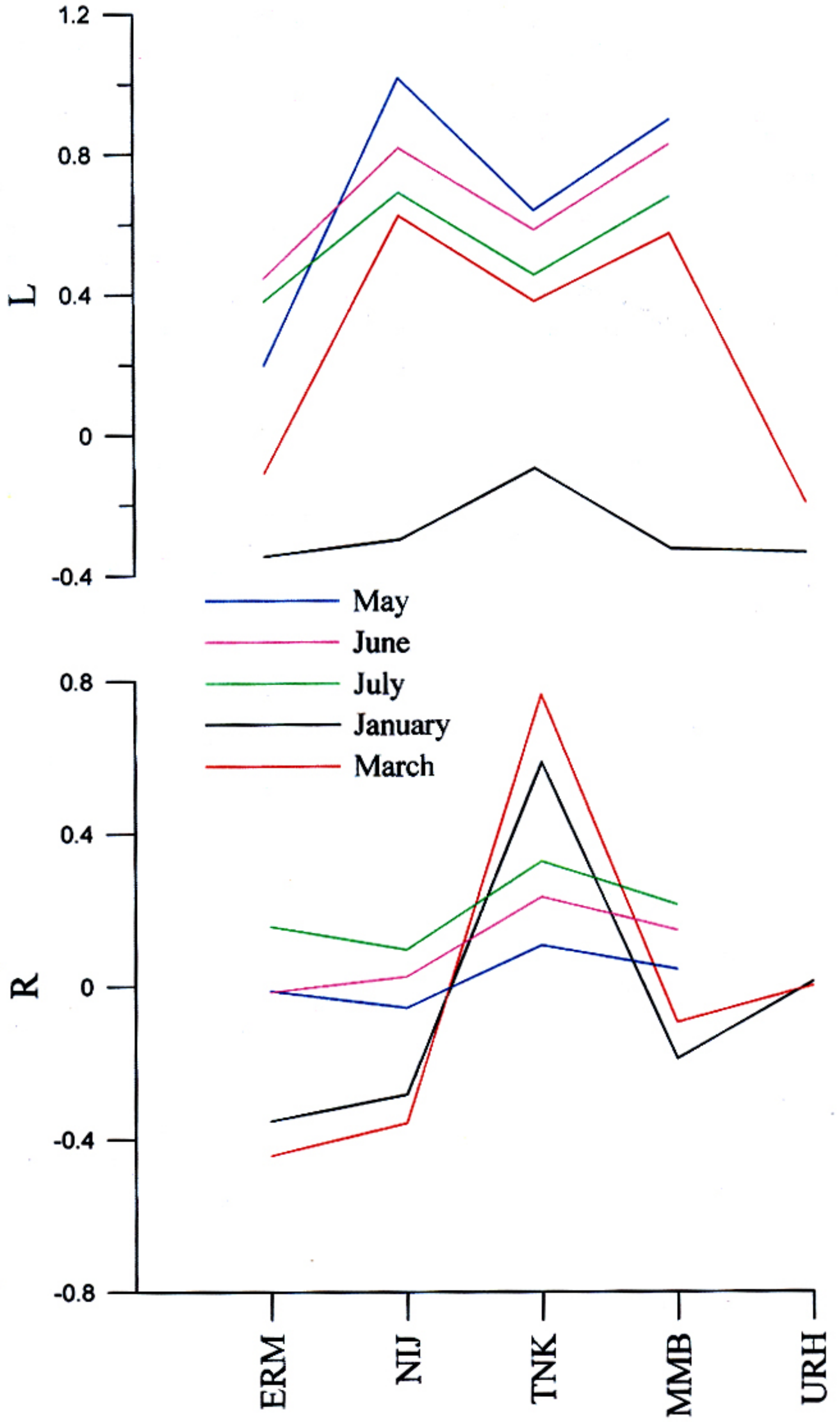

Fig. 9 – The coefficients L and R at the magnetometric stations and MMB geomagnetic observatory.

4. CONCLUSION

The present study aimed at extending to the regular daily variation data the method devised by Demetrescu *et al.* (1985, 1988) and Demetrescu and Andreescu (1992) to infer information on the lateral variation of the magnetic properties of crustal rocks and of the electric properties of crust and mantle rocks using a magnetic induction model and solar-cycle-related variation data.

The method was tested on data from the Hokkaido magnetometric array of the Institute of Seismology and Volcanology of the Hokkaido University. Records of a geomagnetic observatory in the region were used as a proxy for the external variable field source. The study performed on data from several 7-day time intervals showed that the method is stable in the sense that the inferred lateral variation of magnetic and electric properties of the underground would be robust – the anomalies keep their position on a map – no matter of the time interval and/or the reference station chosen. However, magnetic and electric properties contrasts rather than actual values are displayed by such maps.

Having in view the rock volumes sampled by the diurnal variation, going to depths of 2–3000 km, it would need external variable sources of higher frequency to model the vertical distribution of the magnetic and electric properties of the lithosphere. This would be a matter of future research.

The method described in the present paper could also improve the treatment of tectono- and volcano-magnetic array data.

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