

# Strong earthquakes associated with high amplitude daily geomagnetic variations

Taha Rabeh · Miguel Miranda · Milan Hvozdara

Received: 20 October 2008 / Accepted: 9 August 2009 / Published online: 3 September 2009  
© Springer Science+Business Media B.V. 2009

**Abstract** In this work, we attempt to quantify forces that result from the interaction between the induced Sq-variation currents in the Earth's lithosphere and the regional Earth's magnetic field, in order to assess its influence on the tectonic stress field and on seismic activity. The study area is the Sinai Peninsula, a seismically active region where both seismic and magnetic data are available. We show that both short-term and long-term magnetic changes correlate with the seismic activity extending to this area in other previous studies. We also analyze a set of large earthquakes and magnetic data from observatories around the world to deduce a relationship between earthquake magnitude and maximum distance up to which precursory variations of the magnetic field are observed.

**Keywords** Sq-variations · Diurnal variations · Earthquake's epicenter · Magnetic signal

## 1 Introduction

Coupling between processes within the earth's crust and the troposphere over regions of seismic activity is known for a long time (Nagata 1976), and that anomalous variations within the ionosphere are observed several days/hours before strong earthquakes (e.g., Yamazaki and Rikitake 1970; Smith and Johnston 1976; Zhu 1976; Honkura 1985).

---

T. Rabeh (✉)  
NRIAG, Helwan, Cairo, Egypt  
e-mail: taharabeh@yahoo.com

*Present Address:*

T. Rabeh · M. Miranda  
CGUL, IDL, University of Lisbon, Lisbon, Portugal

M. Hvozdara  
Geophysical Institute of SAS, Dubravska 9, 845 28 Bratislava, Slovakia

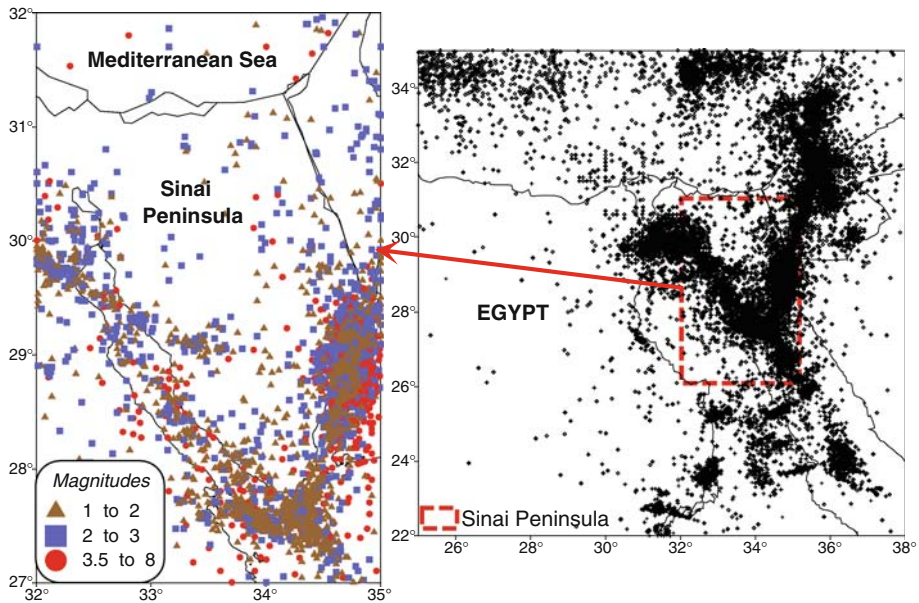
Sasai (1980, 1983) studied the tectonomagnetic field based on the linear piezomagnetic effect. He showed magnetic changes due to stress force. Chen et al. (1999) proved the statistical significance of the magnetic precursors on the background of day-to-day ionospheric variability for magnitudes larger than 5. They also concluded that the precursors were observed 5 days before the seismic shock, and that the probability of the precursor's identification increases with the magnitude of future event. Liu et al. (2004) studied pre-earthquake ionospheric anomalies using GPS signals and claimed that within 5 days prior to 16 of the 20  $M \geq 6.0$  earthquakes (80% success rate), these precursors could be observed. Similar observations were made for example by Yen et al. (2004) for the 1999 Chi-chi M7.3 earthquake and by Johnston et al. (2006) for Seismomagnetic effects from the long-awaited 28 September 2004 M6.0 Parkfield earthquake.

Liu et al. (2000) used critical plasma frequency as index of ionospheric anomalies, for F2, measured by ionospheric sounding instruments (ionosondes), corresponding to the maximum electron density of the ionospheric F layer (160–400 km in altitude). They found that this index significantly decreased locally during afternoons within a few days before  $M \geq 6$  earthquakes occurred.

Several mechanisms have been evoked to explain the lithosphere–atmosphere–ionosphere coupling. One is the chemical influence of emanations from the Earth's crust (radon, noble gases, and metallic aerosols) on the boundary layer of the atmosphere; these emanations change the conductivity of the layer, and as a consequence, modify the atmospheric electric field value within the active area (e.g., Pulinets et al. 1999). It has also been proposed that pre-seismic electric fields on the ground can be generated actively by plastic deformations during the slow cooperative build-up of stress (Freund 2000; Freund and Sornette 2007), but these currents prior to ionospheric anomalies have not yet been observed (Kamogawa 2006). Geomagnetic external disturbances like geomagnetic storms and cloud-to-ground lightning have also been proposed as a mean to trigger seismicity (e.g., Sobolev and Zakrzhevskaya 2003). Duma (1996, 1999) focused on the involvement of the regular diurnal variations of the Earth's magnetic field, known as Sq-variations in this process and Duma and Ruzhin (2003) attempted to quantify the forces which resulted from the interaction between the induced Sq-variation currents in the Earth's lithosphere and the regional Earth's magnetic to assess its possible influence on the tectonic stress field and, as a consequence, on seismic activity. They claim that Lorentz forces due to the interaction between the conductive lithosphere and the external field superimpose the tectonic stress field creating a so-called 'Magneto-Seismic Effect' that can efficiently trigger seismic activity, including strong earthquakes (Duma 2005).

In this paper, we study the seismically active Suez–Sinai area (see Fig. 1 for location). The region is dominated by the active boundary between the African and the Arabian plates that are separating one from the other along the Red Sea rift. Sinai Peninsula can be considered a sub-plate that accommodates the main motion of the Aqaba left-lateral transform fault (Le Pichon and Gaulier 1988) with the supposed extensional motion of the Suez Gulf (Jackson et al. 1988) and the opening of the Red Sea (Ben-Menahem et al. 1976). The seismicity of the region (see Fig. 1) indicates that the Gulf of Aqaba is presently the more active segment of the plate boundary.

In this area, seismic monitoring started in 1899 with the installation of a seismological station in Egypt (HLW), but most instrumental events have small magnitudes, with only two instrumental events with  $M > 6$  in the Dead Sea Transform fault (July 11, 1927 and November 22, 1995). Magnetic observations from Misallat observatory are available at World Data Centre for Geomagnetism since 1960.



**Fig. 1** Location of the study area

As both seismic and magnetic data are available, we check the existence of a temporal and spatial relationship between ionospheric magnetic disturbances and seismicity, and we can evaluate the Sq-affects along with the diurnal magnetic variations corresponding to the seismic activities. This mechanism was proposed by Duma (1999) and Duma and Ruzhin (2003) as a trigger of earthquake activity.

## 2 Comparison between Sq- and earthquake activity

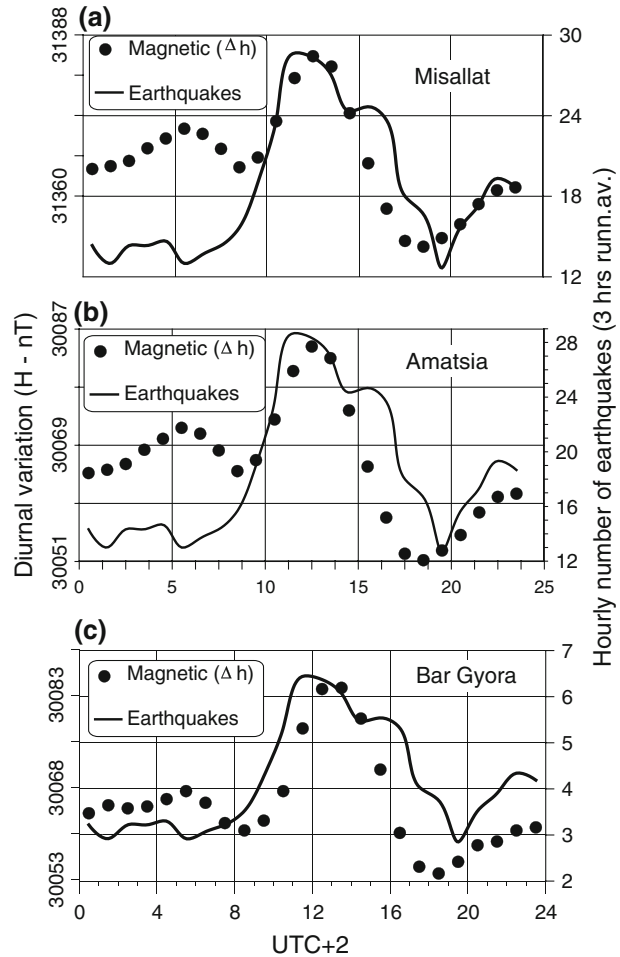
### 2.1 Diurnal and long-term comparison

The diurnal magnetic variations, Sq, also called “magnetic quiet-day solar daily variations” (Chapman and Bartels 1940) are generated in the Earth’s ionosphere, mainly by solar radiation and tidal forces. It can be computed by removing the absolute values of the horizontal magnetic field from the mean values of the horizontal magnetic component H along the daytime. This procedure was applied to the continuous magnetic data available at three Geomagnetic Observatories close to the study area: Misallat in Egypt and Bar Gyora and Amatsia in Israel. Their geographic latitudes are 29.515 N, 31.723 N, and 31.550 N, respectively.

Considering the seismicity of the study area, the seismic catalogue includes a group of about 34,559 seismic events with magnitudes ranging from >1 to <8 for which magnitudes have been computed by NRIAG along more than 100 years. From this dataset, we produced a 3 h running mean using local time for the three observatories in Local Time.

The comparison between average magnetic data and average seismic data is shown in Fig. 2a–c for each of the three observatories. It shows that earthquake occurrence and Sq depend on Local Time in the same way, as suggested before, pointing to the existence of a

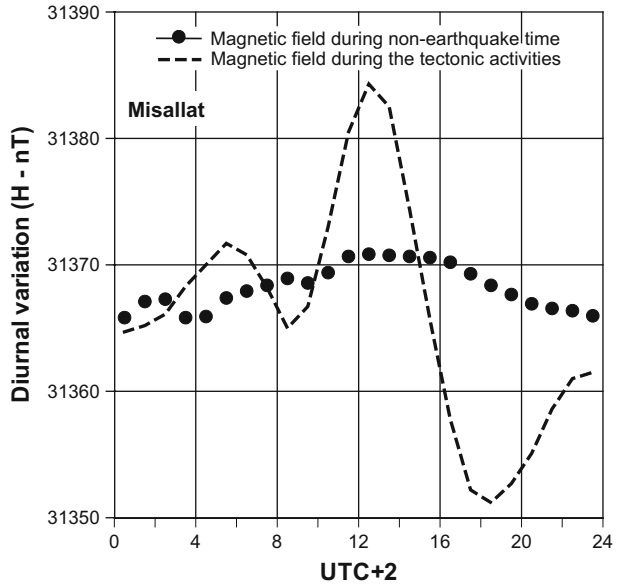
**Fig. 2** Correlation of a mean diurnal variation of the magnetic component (H) with 3 h mean values seismic activities for **a** Misallat, **b** Amatsia, and **c** Bar Gyora geomagnetic observatories



general relation between time-dependent earthquake activity and regional Sq-variation. Maximum values for the number of earthquake events are slightly lesser than the corresponding maximum of Sq, between 10 and 15 Local Time, whereas the minimum values are found between 0 and 5.

We can even emphasize the existence of magnetic signals related with seismic activity, if we consider the 2004 magnetic year from Misallat geomagnetic observatory, which is considered the year of small seismic activity, according to the Egyptian Seismic network records, and we compute the average value of the magnetic field removing the effect of the seismic active periods with a simple average of  $\pm 2$  weeks around the minor earthquakes. We can also retain only the seismically active periods and produce the complementary 3 h average magnetic field. Results shown in Fig. 3 indicate that deduced magnetic variations outside the seismic active periods are similar to the baseline for Misallat Geomagnetic Observatory, thus confirming that seismic activity increases the magnetic field variation.

**Fig. 3** The magnetic field variations for mean value of 1 year to the magnetic component (H) from Misallat geomagnetic observatory once during normal variations, and the other after removing 3 weeks before and after the Earthquake from the magnetic data



### 2.2 The magnetic signal as a seismic precursor

In a number of situations, it is possible to identify a sharp magnetic signal 24 h before a large earthquake. This signal appears often as an increase in the magnetic field ( $\Delta h$ ) reaching several tenths of nT more than normal daily variation.

One example is the 23 June 2001  $M_w$ 8.4 earthquake that took place near the coast of Peru, whose epicenter was located at  $16^{\circ}15'S$  and  $73^{\circ}40'W$ . It caused an increase in  $\Delta H$  of approximately 20 nT at Huancayo Geomagnetic Observatory on the preceding day, 22 June 2001 (cf. Fig. 4). Another example is the 2 November 2002 earthquake occurred in Sumatra, Indonesia, with  $M_w$ 7.4. Its epicenter was located at  $3^{\circ}24'N$  and  $96^{\circ}18'E$ .  $\Delta H$  reached 15 nT at Tonghai Geomagnetic Observatory the preceding day, 1 November 2002 (cf. Fig. 5). Similar situations were observed for the 5 September 2004  $M_w$ 7.4 earthquake of Honshu and the 15 November 2006  $M_w$ 8.3 earthquake at Kuril Islands causing in both cases an increase of near 15 nT at Kakioka Geomagnetic Observatory (cf. Figs. 6, 7).

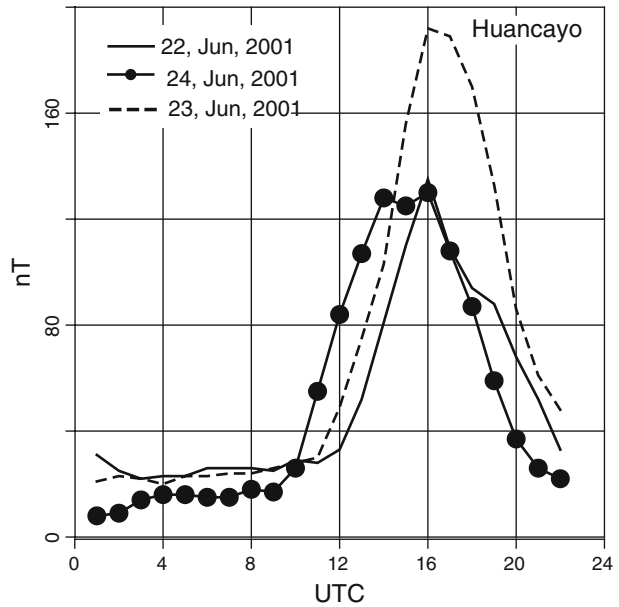
In our study area, we must refer the M5.3 earthquake that took place on the Red Sea on the 20 August 2004, which caused an increase in the magnetic field by approximately 25 nT, at Misallat (Fig. 8).

In all these cases, there is a consistent magnetic signal that can be detected 24 h before the earthquake.

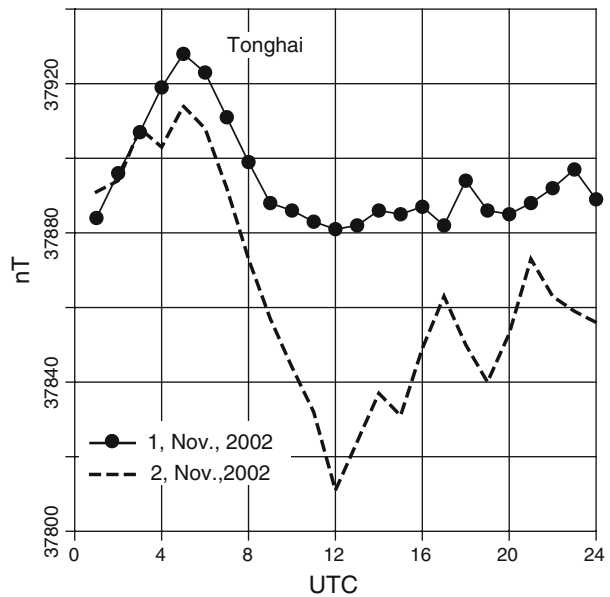
### 2.3 How far does the correlation go?

The maximum distance for the above-described relationship can be determined if we compare the observations corresponding to a large event for a set of magnetic observatories at increasing distances, in what concerns the diurnal correlation and the long-term correlation. To do so, we analyzed magnetic data from five different observatories: Misallat, Bar Gyora, Amatsia, Qsaybeh, and Istanbul-Kandilli.

**Fig. 4** 23-June Earthquake, 2001, near coast of Peru of  $M = 8.4$  showed the magnetic signal before the Earthquake



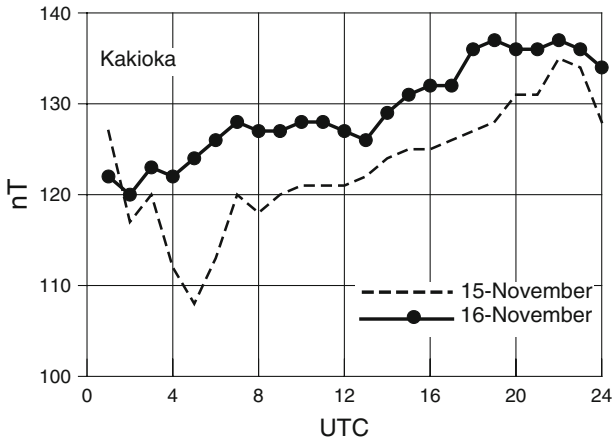
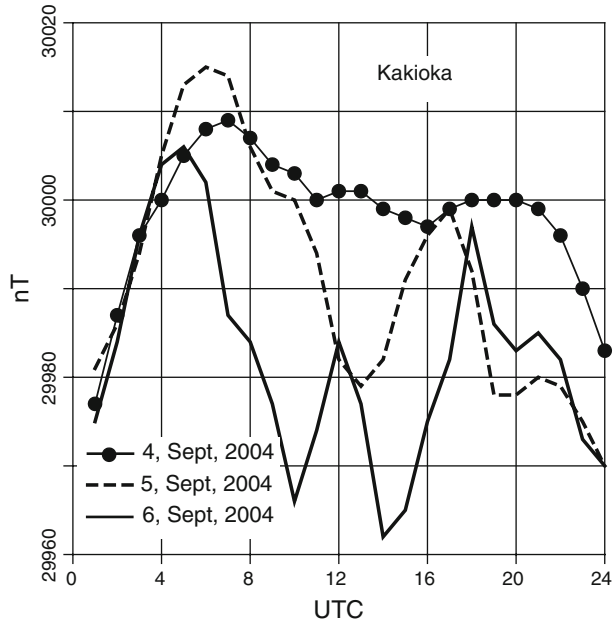
**Fig. 5** 2-November Earthquake, Sumatra, Indonesia, 2002 of  $M = 7.4$  showed the magnetic signal before the Earthquake



In analyzing what concerns the diurnal correlation, we can verify (cf. Fig. 9) that the similarity between magnetic and earthquake data is observed for the first four observatories, whereas in the case of Istanbul-Kandilli, this similarity vanished. In this case, we have an empiric determination of about 1,400 km as the maximum distance.

If we focus on a specific event like the 20 August 2004  $M5.3$  Aqaba earthquake (cf. Fig. 10), we get a similar conclusion as the increase in the magnetic field the day

**Fig. 6** 5-September Earthquake, near the south coast of Honshu, Japan with magnitude 7.4, showed the magnetic signal before the Earthquake

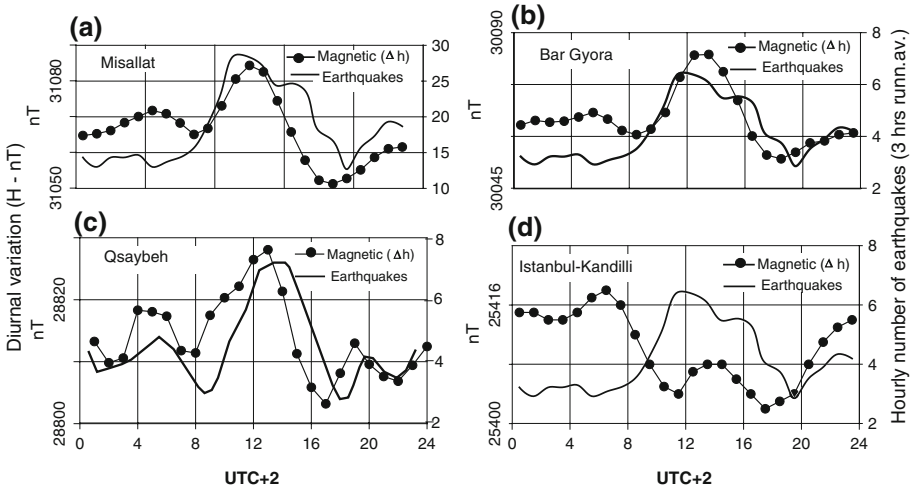
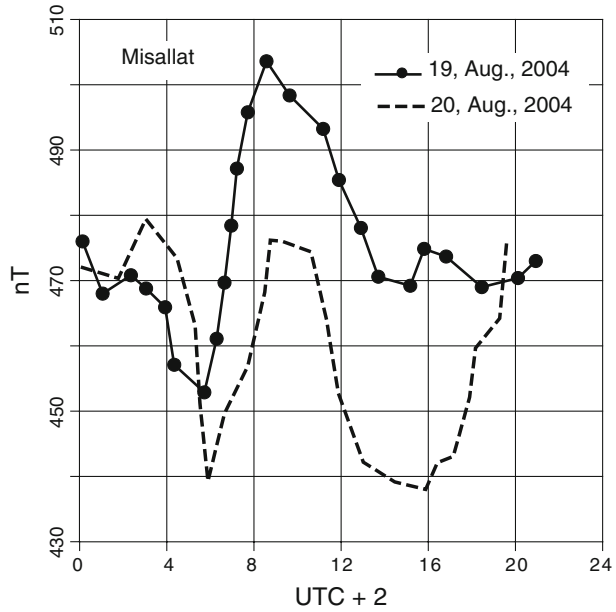


**Fig. 7** 15-November Earthquake, 2006, Kuril Islands of Magnitude = 8.3, showed the magnetic signal before the Earthquake

before is observed up to Qsaybeh geomagnetic observatory, thus corresponding to a maximum distance of about 600 km.

To look for other cases where the earthquakes have larger magnitudes and where we can hypothesize that the distance affected is larger, we considered three complementary cases. The first one is the  $M_w$ 8.3 15 November 2006 earthquake at Kuril Islands, whose epicenter was located at  $46^{\circ}60'N$   $153^{\circ}23'E$ , and where the magnetic signal can be detected at Kakioka geomagnetic Observatory, thus corresponding to a distance of about 1,200 km (cf. Fig. 11). The second one is  $M_w$ 8.7 28 March 2005 earthquake, Northern Sumatra,

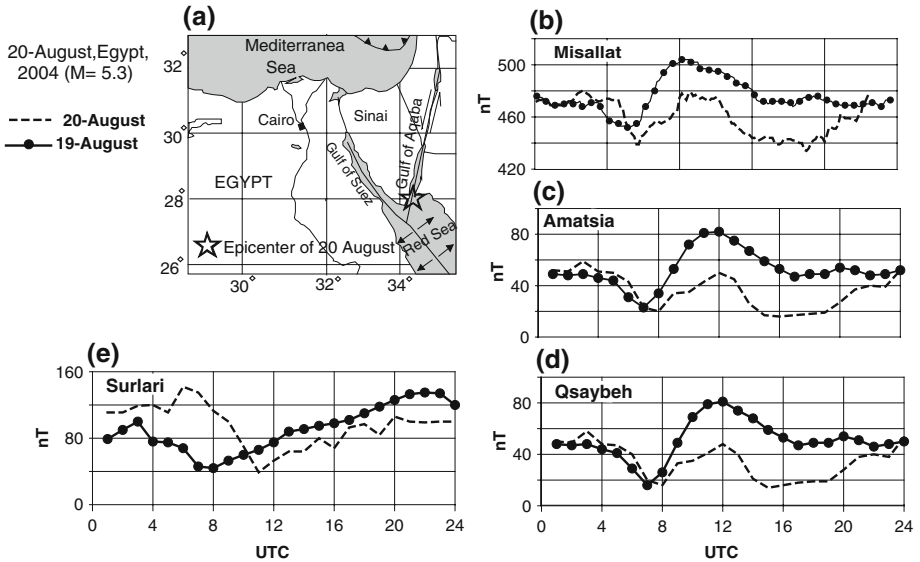
**Fig. 8** 20-August Earthquake, Egypt, 2004 of  $M = 5.3$  showed the magnetic signal before the Earthquake



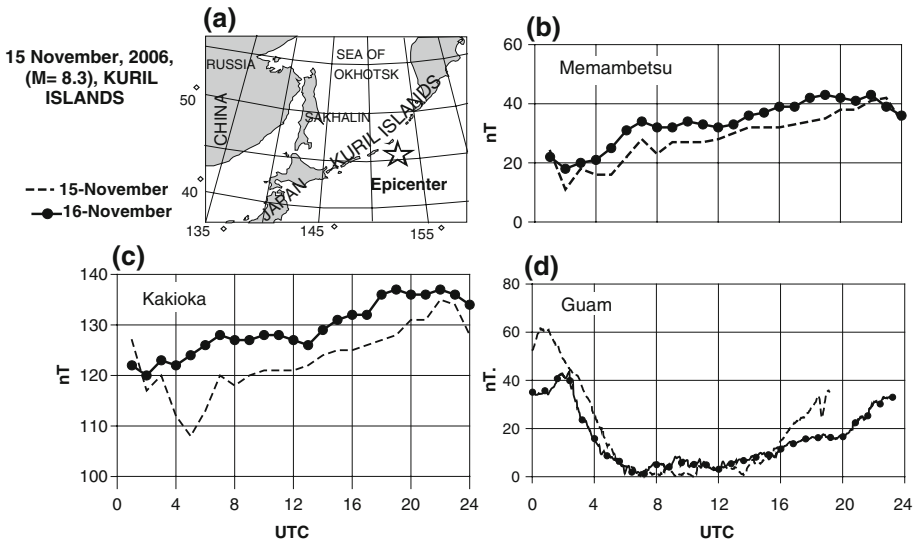
**Fig. 9** Ideal case for determining the diameter of the detected magnetic signal before the Earthquakes from **a** Misallat-Egypt, **b** Bargayora-Israel, **c** Qsaybeh-Lebanon, and **d** Kandilli-Istanbul, Turkey for long-period correlation

Indonesia with epicenter  $2^{\circ}07'N$   $97^{\circ}01'E$ , whose signal can be detected at Guangzhou geomagnetic observatory located at  $23^{\circ}09'N$ ,  $113^{\circ}34'E$ , which indicates a distance of about 2,300 km (cf. Fig. 12). The third one is the  $M_w$ 7.9 3 November 2002 earthquake that took place in Alaska at  $63^{\circ}51.4'N$ ,  $147^{\circ}45'W$ , and whose signal becomes weak at Sitka geomagnetic observatory ( $57^{\circ}06'N$  and  $135^{\circ}33'W$ ), thus corresponding to a distance of about 700 km (cf. Fig. 13).



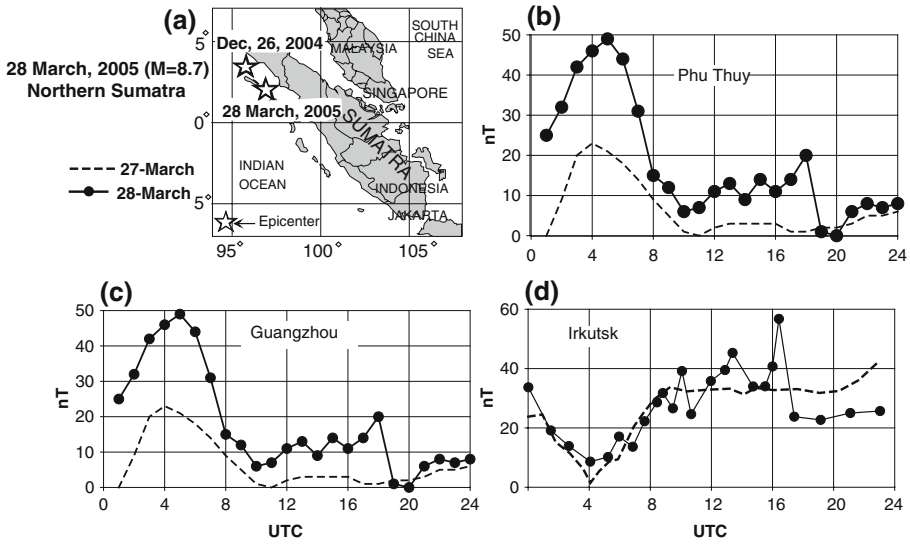


**Fig. 10** Tracing the diameter of the magnetic signal due to 20-August Earthquake, Egypt, 2004 of  $M = 5.3$

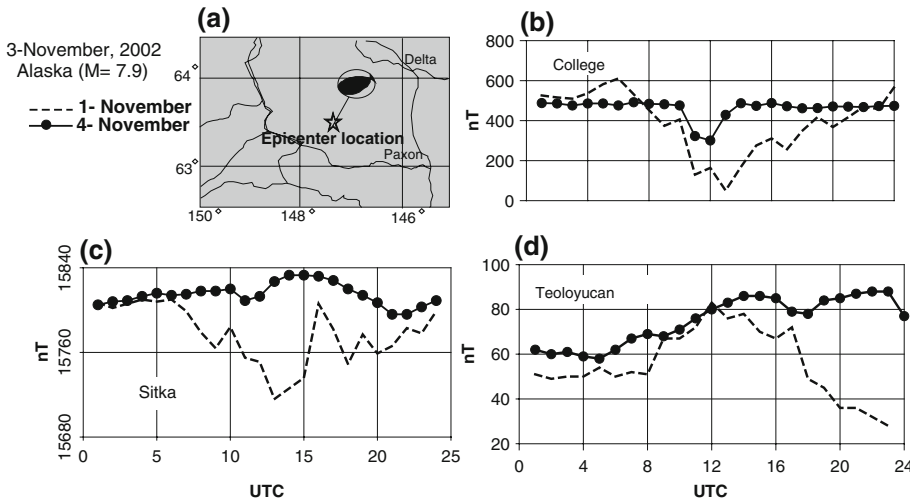


**Fig. 11** Tracing the diameter of the magnetic signal due to 15-November, 2006, Kuril Islands of Magnitude = 8.3

From all the above observations, we can conclude that the anomalous variations of the magnetic field that take place about 1 day before the strong earthquakes are observed up to a distance that is dependent on the magnitude of earthquake.



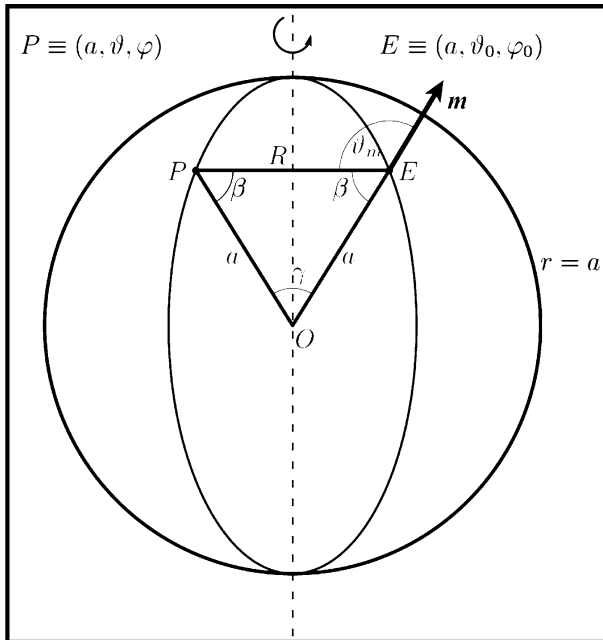
**Fig. 12** Tracing the diameter of the magnetic signal due to 28-March, 2005, Northern Sumatra, Indonesia of Magnitude = 8.7



**Fig. 13** Tracing the diameter of the magnetic signal due to 3-November, 2002, Alaska of Magnitude = 7.9

### 3 The algorithm of the method

In our algorithm, we present a simple formula for the calculation of the magnetic disturbance due to static radial magnetic dipole induced for example by piezomagnetic effects at the epicenter  $E$  (Fig. 14). The observation point is  $P$  at the angle epicentral distance  $\gamma$  (e.g.,  $83^\circ$ ). The triangle  $OEP$  we suppose to draw in the plane of great circle radius  $a$  connected the points  $EP$  and the center  $O$ . Then the distance of the  $EP$  is  $R = (2a^2 - 2a^2 \cos \gamma)^{1/2} = a[2(1 - \cos \gamma)]^{1/2}$  and  $\sin \gamma = (1 - \cos^2 \gamma)^{1/2}$ .



**Fig. 14** A schematic shows the magnetic field due to static radial magnetic dipole at the epicenter of the earthquake

It is known that  $\cos \gamma = \cos \vartheta \cos \vartheta_0 + \sin \vartheta \sin \vartheta_0 \cos(\varphi - \varphi_0)$ . The magnetic potential at the point  $P$  will be:

$$U(P) = \frac{\mu_0 m \cos \vartheta_m}{4\pi R^2} \tag{1}$$

where  $\vartheta_m$  is the angle reckoned by magnetic moment  $m$  and segment  $EP$ .

Using triangle geometry formulae, we see that  $\vartheta_m = \pi - \beta$  so,  $\cos \vartheta_m = -\cos \beta$ . The sinus theorem gives  $R/\sin \gamma = a/\sin \beta$ ,  $\sin \beta = (a/R) \sin \gamma$ , and  $\cos \beta = [1 - (a/R)^2 \sin^2 \gamma]^{1/2}$ .

Then, we have more complicated formula for  $U(P)$ :

$$U(P) = -\frac{\mu_0 m}{4\pi} \frac{[1 - (a/R)^2 \sin^2 \gamma]^{1/2}}{2a^2(1 - \cos \gamma)} \tag{2}$$

Using expressions for  $\cos \gamma$  and  $\sin \gamma$ , we can calculate components of the magnetic disturbance due to  $m$  at the point  $P$ ,  $\Delta X = a^{-1} \partial U / \partial \vartheta$ ,  $\Delta Y = -(a \sin \vartheta^{-1}) \partial U / \partial \varphi$  and  $\Delta Z = \partial U / \partial a$ .

The formula for modulus of the disturbance due to magnetic dipole  $\Delta B = \mu_0 m/R^3$  (Tesla) is used for the calculation of  $\Delta H$ .

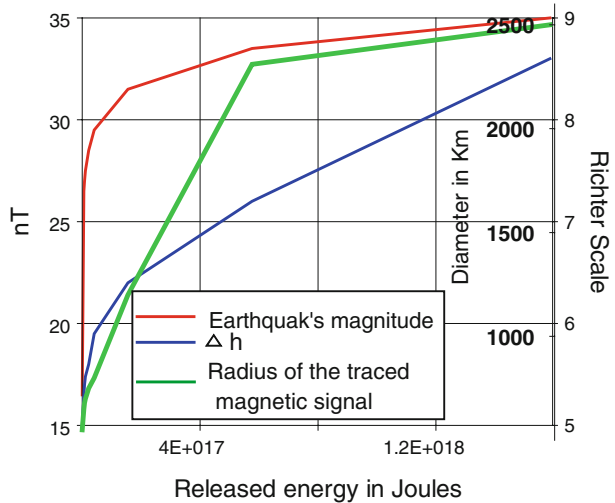
The torque acts on the ambient magnetic field,  $T$  is the magnetic moment that affects the magnetic field  $H$ . It can be expressed as:

$$T \text{ (in Joules)} = m \times H \tag{3}$$

**Table 1** Magnetic and the torque parameters related to the earthquakes

Diameter (km)	Magnetic moment ( $10^{13}$ Am <sup>2</sup> )	Torque ( $10^{13}$ J)	Earthquake magnitude in Richter (lgE = 4.8 + 1.5 M)	$\Delta H$ (nT)
100	13.96	209.4	5.3	15.0
1,000	22.8	456	6	20
2,300	26.4	871.2	9	33.0

**Fig. 15** Curves model illustrate the relation between Earthquake’s magnitude,  $\Delta h$ , and radius of the traced magnetic signal



**Table 2** Relationship between the distance of the earthquake’s epicenter, magnitude, distance, and the magnetic signal

Earthquake	Epicenter		Observatory	Distance (km)	$\Delta H$ (nT)
	Latitude	Longitude			
20-August, Egypt, 2004 ( $M = 5.3$ )	28.01	34.28	Qsaybeh	1,807	15.0
3-November, Alaska, 2002 ( $M = 7.9$ )	63.51	147.45	Victoria	3,360	19.5
15-November, Kuril Islands, 2006 ( $M = 8.3$ )	46.60	153.23	Kakioka	4,440	22.0
28-March, N. Sumatra, 2005 ( $M = 8.7$ )	2.07	97.01	Novosibirsk	5,330	26.0

We calculated the magnetic moment and the torque parameters related to the earthquakes. The results are listed in Table 1.

A statistical calculation for several major earthquakes (<5 magnitudes) was studied in detail to model the final results. The results (cf. Fig. 15; Table 2) agree with the results calculated by the algorithm. They show that if we have  $\Delta h$  of 15 nT, then we can expect earthquake with magnitude 5.3 Richter, which generates energy of  $6.927 \times 10^{12}$  Joules in an area of 550 km diameter. It can be concluded that there is an electromagnetic coupling that occurs between the processes within the earth’s crust and the troposphere over the regions of seismic activity and anomalous variations within the ionosphere several days/

hours before the strong earthquakes. These emanations change the conductivity of the layer and, as a consequence, modify the atmospheric electric field and hence the magnetic field values within the active area.

#### 4 Discussion and conclusions

In this study, we investigated the relationship between the diurnal and the long-term variations of the magnetic field with seismic activity within a study area encompassing the Sinai sub-plate. Diurnal and long-term Sq-magnetic variation showed a good correlation with seismic activity. In order to show that changes in the magnetic field are due to seismic activities, mean values of 1 year from the Misallat geomagnetic were selected and  $\pm 3$  weeks before and after the earthquakes has been removed from the magnetic data. The comparison between the Sq-variation during the seismic active periods and the Sq-variation during seismic quiet periods shows that both the phenomena are related.

We also studied the magnetic field variations for several days before and/or after the major earthquakes occurred along the last 26 years. The investigation showed a clear magnetic signal 1 day before the occurrence of a major earthquake. We also compared the magnitude of the earthquake to come with the maximum distance until which it is possible to identify the magnetic signal, and we concluded that it is a function of the earthquake magnitude. This conclusion was extended to a larger number of events for major earthquakes to obtain a relationship between earthquake magnitude, distance, and maximum  $\Delta h$ . These results show a good agreement with the conclusions of Duma and Ruzhin (2003) for small magnitude earthquakes (M5–M6) and differ in the case of larger magnitude earthquakes, mainly because large magnitude earthquakes generate larger quantity of energy more than estimated by Duma and Ruzhin (2003).

**Acknowledgments** The Authors deeply thank Professor Mioara Manda (Professor of geomagnetism at IGP and Potsdam) for her great efforts to revise the part of this work on magnetic variations. Also, we thank Dr. Gerald Duma (Professor of geophysics at ZAMG) for his efforts to revise the manuscript especially the seismic and magnetic variations.

#### References

- Ben-Menahem A, Nur A, Vered M (1976) Tectonics, seismicity and structure of the Afro-Eurasian junction—the breaking of an incoherent plate. *Phys Earth Planet Inter* 12:1–50
- Chapman S, Bartels J (1940) *Geomagnetism*. Oxford University Press (Clarendon), London and New York
- Chen YI, Chuo JY, Liu JY, Pulinets SA (1999) Statistical study of ionospheric precursors of strong earthquakes at Taiwan area, XXVI URSI General Assembly, Toronto, 13–21 August 1999. Abstracts, p 745
- Ding J, Liu J, Yu S, Xiao W (2004) Geomagnetic diurnal-variation anomalies and their relation to strong earthquakes. *Acta Seismologica Sin* 17(Suppl):85–93
- Duma G (1996) Seismicity and the Earth's magnetic field a clear relation demonstrated for several seismic regions, XXV General Assembly of the European Seismological Commission ESC, Reykjavik, Island, 1996, Icelandic Meteorological Office (Abstracts)
- Duma G (1999) Regional geomagnetic variations and temporal changes of seismic activity: observations of a so far unknown phenomenon, attempts of interpretation, 22nd general assembly of IUGG, Birmingham, England, Session JSA15 (Abstract)
- Duma G (2005) A significant electromagnetic process controls earthquake activity. *Geophys Res Abstr* 7:02860
- Duma G, Ruzhin Y (2003) Diurnal changes of earthquake activity and geomagnetic Sq-variations. *Nat Hazards Earth Syst Sci* 3:171–177

- Freund F (2000) Time-resolved study of charge generation and propagation in igneous rocks. *J Geophys Res* 105:11001–11019
- Freund FT (2007) Pre-earthquake signals—part I: deviatoric stresses turn rocks into a source of electric currents. *Nat Hazards Earth Syst Sci* 7:535–541
- Freund F, Sornette D (2007) Electro-magnetic earthquake bursts and critical rupture of peroxy bond networks in rocks. APS preprint
- Gauss CF (1839) Allgemeine Theorie des Erdmagnetismus. Resultate aus den Beobachtungen des magnetischen Vereins im Jahre 1838, Leipzig. Reprinted In: Gauss CF (ed) 1877. Werke, vol 5, pp 119–193. Königlichen Gesellschaft der Wissenschaften, Göttingen
- Honkura Y (1985) Some results from measurements of the geomagnetic field and the electrical resistivity in the Izu-Tokai region, Japan. In: Kisslinger L, Rikitake T (eds) Practical approaches to earthquake prediction and warning, pp 365–378
- Jackson JA, White NJ, Garfunkel Z, Anderson H (1988) Relations between normal-fault geometry, tilting and vertical motions in extensional terrains: an example from the southern Gulf of Suez. *J Struct Geol* 10(2):155–170
- Johnston MJS, Sasai Y, Egbert GD, Mueller RJ (2006) Seismomagnetic effects from the long-awaited 28 September 2004 M 6.0 Parkfield earthquake. *Bul Seism Soc Am* 96:206–220
- Kamogawa M (2006) Preseismic lithosphere-atmosphere-ionosphere coupling. *Eos* vol 87, No. 40, 3 October 2006
- Le Pichon X, Gaulier J-M (1988) The rotation of Arabia and the levant fault system. *Tectonophysics* 153:271–294
- Liu JY, Chen YI, Pulinets SA, Tsai YB, Chuo YJ (2000) Seismo-ionospheric signatures prior to  $M \geq 6.0$  Taiwan earthquakes. *Geophys Res Lett* 27:3113–3116
- Liu JY, Chuo YJ, Shan SJ, Tsai YB, Chen YI, Pulinets SA, Yu SB (2004) Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. *Ann Geophys* 22:1585–1593
- Mandea M, Macmillan S, Bondar T, Golokov V, Langlais B, Lowes F, Olsen N, Quinn J, Sabaka T (2000) International geomagnetic reference field 2000. *Phys Earth Planet Inter* 120:39–42 Also in *Pure and Applied Geophysics*, vol 157, pp 1797–1802
- Naaman SH, Alperovich LS, Wdowinski Sh, Hayakawa M, Calais E (2001) Comparison of simultaneous variations of the ionospheric total electron content and geomagnetic field associated with strong earthquakes. *Nat Hazards Earth Syst Sci* 1:53–59
- Nagata T (1976) Seismo-magnetic effect in a possible association with the Niigata earthquake in 1964. *J Geomag Geoelectr* 28:99–111
- Pulinets SA, Alekseev VA, Boyarchuk KA, Hegai VV, Depuev VKh (1999) Radon and ionosphere monitoring as a means for strong earthquakes forecast. *Il Nuovo Cimento* 22C(N3–4):621–626
- Russell HD (2002) The earth's magnetic field is still losing energy. *Creat Res Soc Q* 39:1–11
- Said R (1990) The geology of Egypt. Elsevier, Amsterdam
- Sasai Y (1980) Application of the elasticity theory of dislocations to tectonomagnetic modeling. *Bul Earthq Res Ins* 55:387–447
- Sasai Y (1983) A surface integral representation of the tectonomagnetic field based on the linear piezomagnetic effect. *Bul Earthq Res Ins* 58:763–785
- Smirnova N, Hayakawa M, Gotoh K, Volobuev D (2001) Scaling characteristics of ULF geomagnetic fields at the Guam seismoactive area and their dynamics in relation to the earthquake. *Nat Hazards Earth Syst Sci* 1:119–126
- Smith BE, Johnston MJS (1976) A tectonomagnetic effect observed before a magnitude 5.2 earthquake near Hollister California. *J Geophys Res* 81:3556–3560
- Sobolev G, Zakrzhevskaya N (2003) Magnetic storm influence on seismicity in different regions. *Geophys Res Abstr* 5:00135
- Tzani A (2003) Can earthquakes be triggered by diurnal geomagnetic variations? Observational evidence from Greece and abroad. *Geophys Res Abstr* 5:13108
- Xue S-X (1989) The evaluation of earthquake prediction ability [A]. In: Department of science, technology and monitoring, State Seismological Bureau (ed) The practical research papers on Earthquake prediction methods (seismicity section) [C]. Seismological Press, Beijing, pp 586–589 (in Chinese)
- Yamazaki Y, Rikitake T (1970) Local anomalous changes in the geomagnetic field at Matsushiro. *Bull Earthq Res Inst Univ Tokyo* 48:637–643
- Yen H-Y, Chen C-H, Yeh Y-H, Liu J-Y, Lin C-R, Tsai Y-B (2004) Geomagnetic fluctuations during the 1999 Chi-Chi earthquake in Taiwan. *Earth Planets Space* 56:39–45
- Zhu FM (1976) Prediction, warning, and disaster prevention to the Haicheng earthquake of magnitude 7.3. Proceedings of Lectures by the seismological delegation of the People's Republic of China, Seismol. Society of Japan Special Publication, pp 15–26 (in Japanese)