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Localized changes in geomagnetic total intensity values prior to the 1995 Hyogo-ken Nanbu (Kobe) earthquake

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ABSTRACT

Changes in total geomagnetic field intensity, of 2–3 nT, were observed prior to the 1995 Hyogo-ken Nanbu (Kobe) earthquake at the Amagase (AMG) site, located approximately 70 km from the epicenter. We examined whether the observed variations are local signals arising from the Earth's crust, or global variations that are unlikely to originate from the crust. To remove global-scale variations in total geomagnetic intensity data, we employed a regional geomagnetic field model. Using data recorded at five reference sites in Japan, we estimated global-scale variations in total geomagnetic intensity, and removed them from the observed total geomagnetic intensity at the AMG site. The reminder still showed variations during the period prior to the Kobe earthquake. In addition, these pre-seismic variations include two of the largest shifts recorded during the entire observation period at the AMG site, raising the possibility that these variations were indeed related to the earthquake. These variations cannot be interpreted as signals arising from the area close to the seismic source because of the large distance between the epicenter and the site. Therefore, our results raise the possibility that the physical state of the Earth's crust shows marked changes over a wide region in the lead-up to a seismic event.

1. Introduction

Anomalies in the geomagnetic field associated with or prior to large earthquakes were first reported more than a century ago by Tanakadate and Nagaoka (1893), who documented magnetic field variations associated with the 1891 Great Mino-Owari earthquake (M 8.0), Central Japan. Rikitake (1968) reported that the amplitude of change in the geomagnetic field associated with earthquakes showed a marked decrease since the invention of the proton magnetometer, which measures absolute values of total magnetic field intensity. The author attributed the large amplitudes of pre-seismic and co-seismic variations in the magnetic field to the low accuracy of the early observations. However, in conclusion, the author did not discount the existence of co-seismic variations in the geomagnetic field.

The reliability of geomagnetic observations has been improved with the use of modern instruments. In fact, geomagnetic observations synchronous with tectonic events are now used in studies of corresponding events (e.g., Napoli et al., 2008; Sasai et al., 2002). If pre-seismic variations in the geomagnetic field can be detected, and if they are related to the seismic event itself, then such variations would also provide information on the physical state of the Earth prior to the event, which is important in understanding the controls on the occurrence of earthquakes. In this sense, it is important to investigate the relation between geomagnetic variations and earthquakes, even if such pre-seismic variations cannot be used for earthquake prediction.

Sakanaka et al. (1998) reported possible precursory variations in the total geomagnetic field intensity prior to the 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake) (Mw. 7.1). This event was one of the most devastating intra-plate earthquakes in Japan for several decades, resulting in severe damages, more than 6400 deaths, and motivating intensive research on the event itself. In addition to the studies on purely seismological aspects of the event, some studies have been devoted to the detection of precursory phenomena, including changes in seismicity (Enescu and Ito, 2001), geochemistry (Igarashi et al., 1995), ground surface temperature (Tronin et al., 2002), and electromagnetic fields across a wide range of frequencies (Nagao et al., 2002).

Sakanaka et al. (1998) visually inspected the total geomagnetic field intensities recorded at the Amagase (AMG) magnetic station (N34°52′48″, E135°50′09″), with reference to the Kakioka Magnetic Observatory (KAK, N36°13′56″, E140°11′11″) (Fig. 1a), during the period from the end of 1992 to 1997, and stated that "one of the

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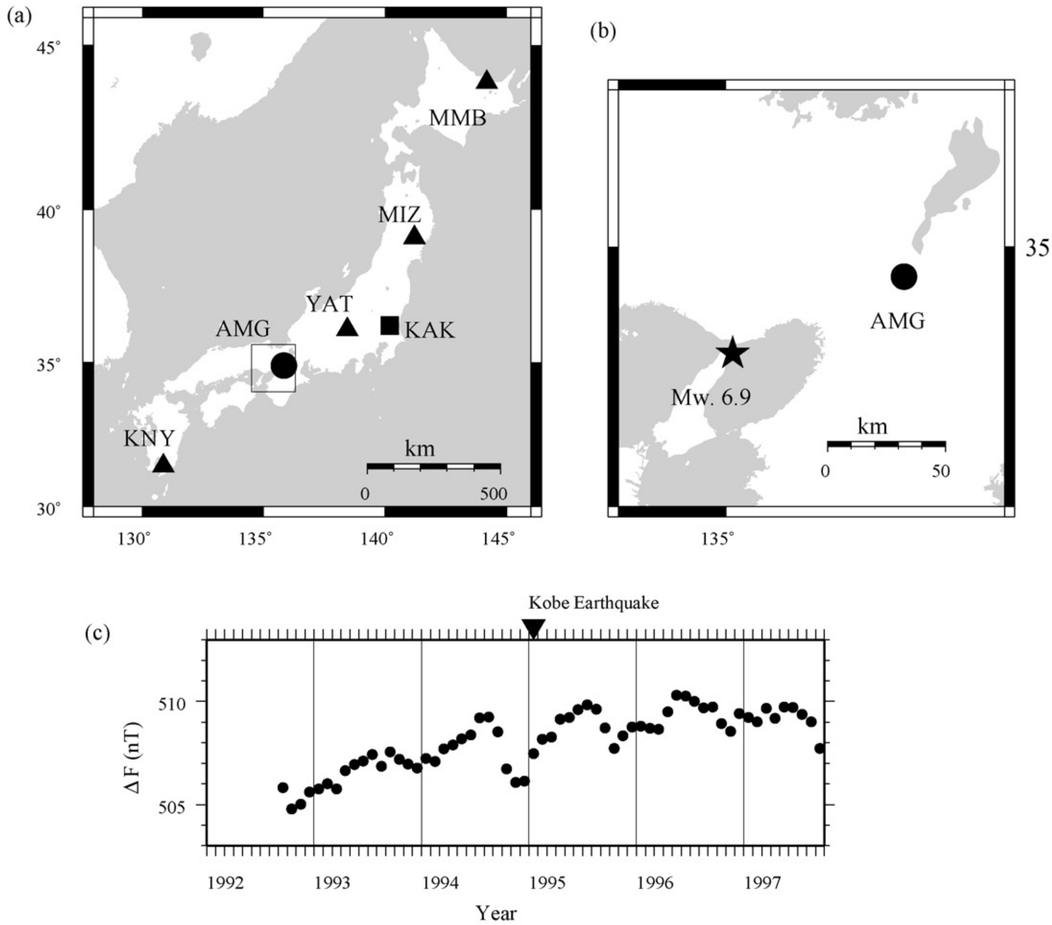

Fig. 1. (a) Map showing the locations of magnetic observation sites used in the present study. The solid circle indicates the location of the Amagase (AMG) magnetic observation site, and the solid square indicates the Kakioka (KAK) magnetic observatory. The open square indicates the area enlarged in (b). Triangles indicate observatories at Memambetsu (MMB), Mizusawa (MIZ), Yatsugatake (YAT), and Kanoya (KNY), whose data were used to estimate variations in the regional geomagnetic field. (b) Map of the AMG site. The star symbol indicates the epicenter of the 1995 Hyogo-ken Nanbu (Kobe) earthquake. (c) Monthly means of total geomagnetic field intensities (ΔF) recorded at AMG, with reference to KAK, during the period from 1992 to 1997 (modified after Sakanaka et al., 1998). Also shown is the timing of the Kobe earthquake.

anomalies is possibly related to the occurrence of the 1995 Hyogo-ken Nanbu earthquake, although the cause is unknown". Fig. 1c summarizes the reported variations in the geomagnetic total intensity values.

However, it is generally difficult to identify pre- or co-seismic variations in the geomagnetic field, as such variations arise from a variety of sources. To understand the relation between variations in the geomagnetic field and earthquakes, it is first necessary to distinguish variations arising from tectonic activity from those arising from other sources. The difference in spatial scales is a useful criterion in this regard. Generally, geomagnetic variations arising from the Earth's crust are localized within a restricted area, whereas those arising from Earth's outer core, ionosphere, and magnetosphere occur at regional or global scales. In the report by Sakanaka et al. (1998) and in Fig. 1c, simple differences between the AMG site and a reference site are calculated in order to remove global variations. However, this method is somewhat crude when seeking to detect variations as small as several nanotesla. Hence, a more accurate procedure of data correction is required. Fujiwara et al. (2001) attempted to represent spatio-temporal variations in total geomagnetic field intensity around Japan in order to extract only those variations from the crust. The use of such a method will enable the results presented by Sakanaka et al. (1998) to be reliably corrected.

In the present study, we attempt to clarify whether the anomalies in the total geomagnetic field intensity recorded at the AMG site prior to the Kobe earthquake are a local feature, and whether they are related to the earthquake itself. The remainder of the paper is organized as follows. In Section 2, we outline the magnetic observations undertaken at the AMG site. This information was provided by Sakanaka et al. (1998), although in Japanese; hence, it is reproduced here in English. In Section 3, we describe the methods and present the results of data correction to extract only the local changes in total geomagnetic field intensities. The method is based on the concept proposed by Fujiwara et al. (2001), although with some modifications. Section 4 considers the implications of the results, and proposes future research. Finally, the main conclusions are presented in Section 5.

2. Outline of observations

The AMG geomagnetic observation site was established in August 1992. A magnetic sensor is installed in a disused tunnel of a hydro-electric power station; the sensor is located approximately 300 m from the tunnel entrance at a depth of 140 m below the surface. A proton precession magnetometer is mounted on a plastic pillar at a height of 2 m, and absolute values of the total geomagnetic field intensity are recorded at 1-min intervals. The stored data are collected every 4 or 6 weeks. Proton magnetometers are only able to measure the total intensity of the geomagnetic field, whereas the geomagnetic field is of course a vector field. Nevertheless, proton magnetometers have the advantage of being able to measure absolute values without any drift in values due to, for example, changes in temperature or degradation over time. Based on the results of a magnetic survey in the vicinity of the sensor, we confirmed that the spatial gradient of the total geomagnetic field intensity around the sensor of the magnetometer at the AMG site is less than 1 nT/m, implying negligible seasonal variations due to variations in ground temperature (Utada et al., 2000). Unfortunately, in 2002 the tunnel walls collapsed near the site at which the sensor was installed. Although observations continued until the end of 2004, the collapse prevented us from undertaking periodic maintenance of the facility, resulting in periods of missing data. Therefore, continuous data at AMG were obtained over a period of 10 years, from 1992 to 2002.

The AMG site was not originally intended to observe localized changes in the total geomagnetic field intensity arising from tectonic activity: it was designed to provide reference data for the estimation of the spatio-temporal pattern of daily and secular variations in the geomagnetic field in Central and Western Japan. For this purpose, it was important that sensors should be installed at sites free of tectonomagnetic sources such as active volcanoes and faults. The location of the AMG site satisfies this condition. The sedimentary rocks in the area contain low concentrations of ferromagnetic minerals. The piezomagnetic and thermo-magnetic effects would only lead to changes in the geomagnetic field if the crust contains ferromagnetic minerals in rocks at temperatures below the Curie point; consequently, the AMG site is largely unaffected by piezomagnetic and/or thermo-magnetic effects.

The observation environment of the AMG site during the day-time is not ideal, as two electric railways exist within approximately 5 km of the site. Current leakage from the trains generates persistent noise during their operation, preventing reliable measurements of the geomagnetic field. However, the trains cease running at midnight, and the electric power supply is completely shut off between 01:30 and 03:29 LT (between 16:30 and 18:29 UT on the previous day); consequently, during these hours we could obtain data free from artificial noise.

To extract localized variations in the total geomagnetic field intensity at AMG, we took the simple differences between total intensity values at AMG and those at a reference site, and then calculated daily means for the period during the middle of the night (01:30–03:29 LT). As a reference, we used geomagnetic total intensity values recorded at the Kakioka Magnetic Observatory (KAK) (Fig. 1), operated by the Japan Meteorological Agency (JMA). The distance between AMG and KAK is rather large (~500 km). Consequently, we cannot expect that data correction based on the difference in values between the two sites would be sufficiently accurate. Nevertheless, such an approach provides a useful, although tentative, initial result. The use of KAK as a reference site has advantages because data at KAK are obtained in an ideal setting. The magnetic sensor at KAK is installed in a building which contains no magnetized materials such as iron spikes. In addition, the construction of DC electric railways within 35 km of KAK is prohibited by a law, in order to avoid noise from current leakage. It is likely that the magnetic data recorded at KAK provide the most reliable reference values of geomagnetic field variations in Japan, with minimal noise.

Fig. 2a shows daily means of the simple differences between AMG and KAK (ΔF) during the period from January 1994 to December 1995. Two prominent trends are apparent: a gradual decrease in values starting in September 1994 (i.e., 3 months before the Kobe earthquake) and a sudden increase in values approximately 10 days before the earthquake. However, because AMG is located far from KAK, the simple differences show both local and regional/global variations in the geomagnetic field. Further analysis is therefore required to extract the local variations.

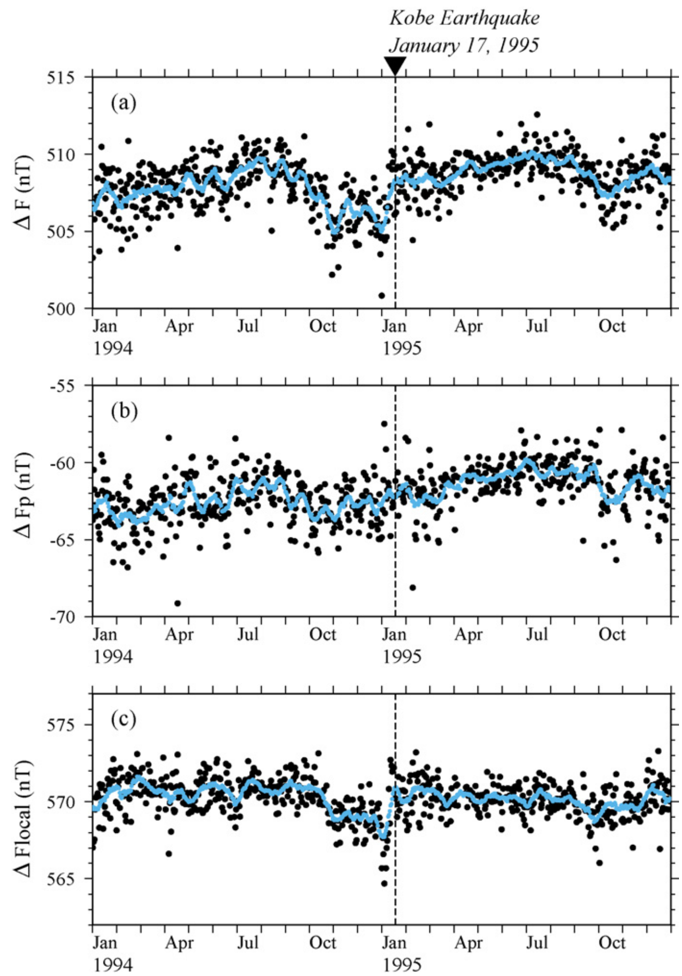

Fig. 2. (a) Night-time daily mean values of total geomagnetic field intensities at Amagase (AMG), with reference to those at Kakioka (KAK) (ΔF), during the period from January 1994 to December 1995. (b) Daily values of the total geomagnetic field intensity model at the AMG site with reference to those at KAK (ΔF_p). (c) Localized variations in the geomagnetic total force values (ΔF_{local}), as defined by $\Delta F - \Delta F_p$. In each panel, solid circles and the blue curve represent daily values and the 15-day running mean, respectively. Also shown is the timing of the Kobe earthquake.

3. Distinguishing between real and apparent signals

3.1. Method

To extract only the localized variations from the simple differences of the total geomagnetic field intensity (Fig. 2a), we used geomagnetic field models. Geomagnetic field models, including the well-known International Geomagnetic Reference Field (IGRF) (Macmillan and Maus, 2005), describe reference values of the geomagnetic field as a function of location and time (e.g., Olsen et al., 2007). By choosing appropriate geomagnetic field models, only those variations of global or regional extent are expressed. Therefore, localized signals in variations of the geomagnetic field are obtained as differences between the observed values of the geomagnetic field and the values predicted by the model. An attempt to extract crustal magnetic fields with the regional geomagnetic field models is currently underway in Japan (e.g., Ishii et al., 2008; Yamazaki and Oshiman, 2006).

Geomagnetic field models are generally based on vector magnetic field data because the physical law governing magnetic fields is described by vector equations. However, in the present study, we consider only total intensity values of the geomagnetic field. Several authors have attempted to represent the spatio-temporal distribution of total geomagnetic field intensity in a small region based solely on the total geomagnetic field intensity at several reference sites. For example, Fujiwara et al. (2001) represent the daily means of the total geomagnetic field intensity (F_p) around Japan in the form of

$$F_p(x, y, t_n) = \sum_{k=1}^{K} X_k(x, y)T_k(t_n) \quad (j = 1, \ldots, J), \tag{1}$$

where T_k is a numerical function of time and $X_k(x,y)$ is a second-degree polynomial of longitude x and latitude y. They showed that F_p given by Eq. (1) reproduced variations in the total geomagnetic field intensity observed at 15 stations in Japan, with accuracies of 0.41 nT for $K = 3$ and 0.25 nT for $K = 5$.

Eq. (1) has an inherent limitation that arises from the fact that only total geomagnetic field intensities are considered. Variations in total geomagnetic field intensity at a single location would be significantly different from those at adjacent locations in the case that the directions of the geomagnetic field vector are markedly different among the locations (e.g., Davis et al., 1981). Such differences are obviously not represented by a second-order polynomial (i.e., X_k in Eq. (1)). Fortunately, the AMG site is not located in an area of strong magnetic anomalies, meaning that we can expect Eq. (1) to be applicable to variations in the total geomagnetic field intensities at the AMG site.

In Eq. (1), X_k is expected to be invariant over time. Because the AMG site is located in the area considered by Fujiwara et al. (2001), we use the value of X_k determined in this earlier study. T_k is determined empirically using reliable, reference time series of total geomagnetic field intensities. For the period 1992–2002 in Japan, continuous total geomagnetic field intensity data are available from the Memambetsu (MMB: N43°55′, E144°11′) and Kanoya (KNY: N31°25′, E130°52′) observatories of JMA, the Mizusawa (MIZ: N39°07′, E141°12′) observatory of the Geographical Survey Institute of Japan (GSI), and the Yatsugatake (YAT, N36°04′, E138°27′) observatory of the Earthquake Research Institute of the University of Tokyo, along with the data recorded at KAK. The locations of these stations are shown in Fig. 1a. Using data at these reference sites, T_k is determined in a least-squares sense as follows:

$$F_p(x, y, t_n) = \sum_{m=1}^{M} w_m(x, y)F(x_m, y_m, t_n), \tag{2}$$

where (x_m, y_m) is the location of the mth reference site, and w_m is a weighting coefficient. A detailed explanation of the derivation of Eq. (2) is provided in Appendix A.

Note that Eq. (2) has the same form as that given by the regression method (Steppe, 1979), although it differs in the way in which the determination of coefficients (w_m) is obtained. In the regression procedure, w_m is determined using a set of data at the corresponding locations (x_m, y_m). In contrast, in our procedure, w_m can be determined without using actual data at the corresponding sites, and only the location (x_m, y_m) is used to determine w_m with the help of X_k, which is given *a priori*. This procedure is invalid in the case that the total geomagnetic field intensity is not expressed by Eq. (1). However, our procedure has the advantage in the way that w_m is calculated.

3.2. Results

Fig. 2b shows variations in ΔF_p at the AMG site, and Fig. 2c shows local variations (ΔF_{local}) given as $\Delta F_{local} = \Delta F - \Delta F_p$, where ΔF_p is the difference between F_p calculated for AMG and that calculated for KAK. In terms of the simple differences (ΔF), seasonal variations are apparent in the data for both 1994 and 1995: decreasing values from August or September, followed by increasing values from October or November. These trends are less pronounced in 1995, indicating that they represent regional-scale variations in total intensity values, represented in turn by ΔF_{local}. Variations in ΔF observed at the end of 1994 are still seen in ΔF_{local}, indicating that these variations are local features rather than regional-scale secular variations. Therefore, it remains possible that the pre-seismic decrease in total geomagnetic field intensity and subsequent return to the former level at the AMG site was related to the Kobe earthquake.

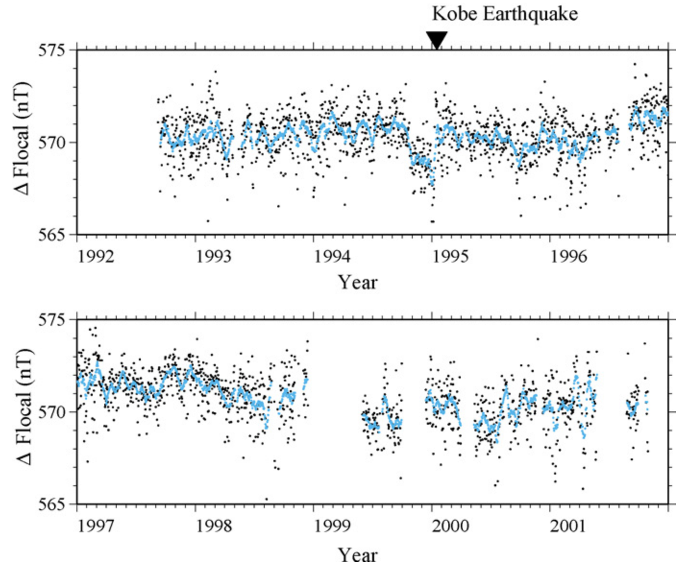

Fig. 3. Localized variations in total geomagnetic field intensities during the period from 1992 to 2002, during which time reliable observations were conducted at the AMG site. Black data points are daily values, and blue curves are 15-day running means.

4. Discussion

4.1. Significance of magnetic variations detected at AMG

To identify a possible relation between variations in total geomagnetic field intensities and the 1995 Kobe earthquake, it is necessary to consider the entire time series of ΔF_{local}. Fig. 3 shows variations in ΔF_{local} from 1992 to 2002. A visual inspection of the data reveals that the largest deviation from the long-term trend is that observed prior to the Kobe earthquake.

To quantitatively evaluate the amplitude of variations in ΔF_{local}, we consider the quantity *Amp*, defined as

$$Amp(L; t) = \frac{1}{L}\sum_{n=-L}^{-1} \Delta F_{local}(t_n) - \frac{1}{L}\sum_{n=0}^{L-1} \Delta F_{local}(t_n). \tag{3}$$

Amp expresses differences in L-day running means between two successive periods. According to the above definition, if some ΔF_{local} data are missing for $-L \le n \le L-1$, the denominator (L) for averaging is reduced accordingly. Fig. 4a and b shows *Amp* for timescales of $L = 30$ (days) and $L = 90$ (days), respectively. In the case of $L = 30$ (Fig. 4a), $|Amp|$ exceeds 2 nT only at the beginning of 1995, corresponding to the increase (i.e., return to the former level) in ΔF_{local} observed at that time. Similarly, $|Amp|$ in the case of $L = 90$ (Fig. 4b) exceeds 1.5 nT only at the end of 1994 and at the beginning of 1995, which correspond to a gradual decrease and subsequent increase in ΔF_{local}, respectively. Note that the function *Amp* has a time resolution longer than L days, as a consequence of its definition. The peak observed in mid-January 1995 (Fig. 4a and b) is reasonably interpreted to correspond to the increase in the geo-

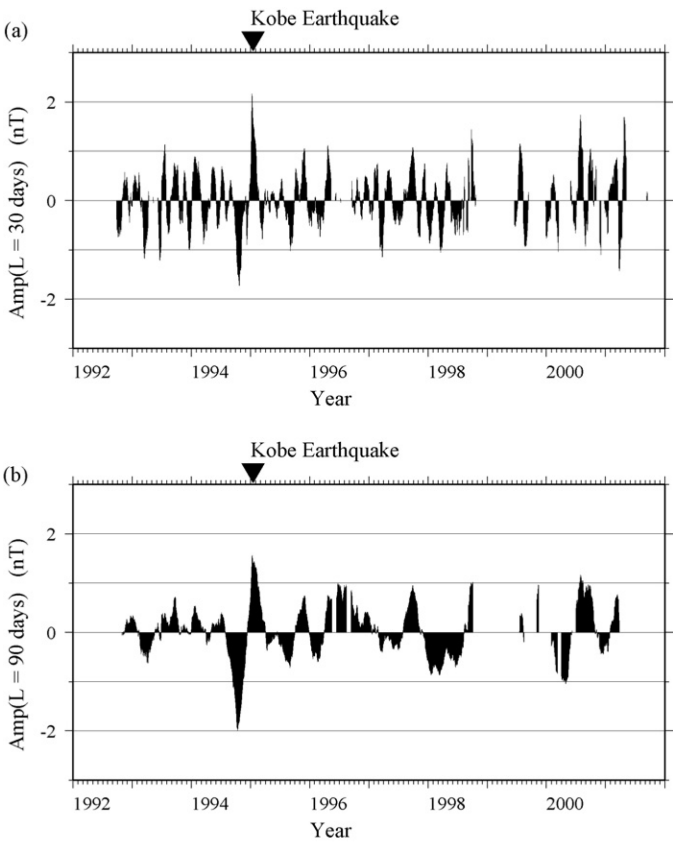

Fig. 4. "Amplitude" of variations in localized total geomagnetic field intensities shown in Fig. 3. Amplitudes are defined in Eq. (3). (a) and (b) show amplitudes for time-scales of $L = 30$ (days) and $L = 90$ (days), respectively.

magnetic total force recorded before the earthquake (see Fig. 2c). Therefore, the variations in ΔF_{local} observed prior to the Kobe earthquake represent two of the largest shifts in the local geomagnetic total intensity, based on an evaluation of *Amp* values calculated according to Eq. (3).

4.2. Interpretations of magnetic variations

If the detected anomalies in the localized variations in total geomagnetic field intensities (Fig. 2c) are in fact related to the Kobe earthquake, it would be important to identify the generating mechanism of the anomalies. Given that the intensity of magnetization is weak in the crust around AMG, it is logical that variations in the magnetic field should be attributed to electric currents in the crust. In addition, we note that even in the case of electric currents arising from unknown mechanisms in the vicinity of the fault that moved during the Kobe earthquake, such currents would make only a minor contribution to the magnetic anomalies observed at AMG prior to the Kobe earthquake. Following the Biot-Savart law of magnetostatics, the intensity of a magnetic field rapidly decays with increasing distance from the source, via a reverse-cubic relation. If magnetic anomalies of the order of 1 nT arose from the epicenter of the Kobe earthquake (Fig. 2c), then anomalies in the order of 10–100 nT would be expected to exist in the area close to the epicenter. In such a case, it would be natural to assume that such changes would also accompany other major earthquakes; however, this is inconsistent with the observations. Therefore, we cannot attribute the observed pre-seismic anomalies in the total geomagnetic field intensity to some precursory phenomenon that occurred near the seismic source. One possibility in this regard is that the detected anomalies in the magnetic field resulted from regional-scale changes in the physical status of the Earth's crust. The existence of regional-scale phenomena, including changes in elastic properties, has been suggested in previous works. For example, Enescu and Ito (2001) investigated the seismicity in a relatively large region surrounding the epicenter of the main shock of the Kobe earthquake, and reported anomalous pre-seismic changes in the *b*-values (which describe the frequency–magnitude distribution) and fractal dimensions (correlation dimensions) of the seismicity. Their results may indicate that the crust in the region showed anomalous behavior during the period prior to the Kobe earthquake. If such anomalies involve changes in the electromagnetic properties of the crust, they may also generate anomalous variations in the magnetic field. In fact, the area in which changes in seismicity were observed includes the location of AMG, although the starting time of changes in seismicity was earlier than the magnetic variations investigated in the present study.

Although the occurrence of regional-scale pre-seismic anomalies is not yet a widely accepted idea, recent studies have reported pre-seismic changes in crustal structures detected by passive image interferometry (e.g., Ohmi et al., 2008). Changes in seismic-velocity structures are considered to reflect changes in the stress field (e.g., Wegler and Sens-Schönfelder, 2007). Therefore, it is possible that the stress field in the crust shows a significant change prior to a major earthquake. In such a case, the existence of pre-seismic variations in electric current and consequently in the magnetic field would be less enigmatic.

One possible explanation in this regard is that changes in the stress field generate voltage differences in the crust. Experimental studies suggest that in the case of non-uniform mechanical stress, rocks behave as kinds of batteries (Freund, 2007a; Takeuchi et al., 2010), thereby generating an electrical circuit in the crust (Freund, 2007b). It may be important to note that the timing of the sudden increase (or recovery) in the total force value recorded just before the Kobe earthquake (Fig. 2c) is similar to the timing of electromagnetic waves reported by Nagao et al. (2002). This coincidence supports the hypothesis that a pre-seismic anomaly in the electrical properties of the crust is the sources of changes in the magnetic field. Another possible scenario is that changes in resistivity occurred in the crust. Since there may exist regional electric currents, changes in resistivity may result in changes in electric currents. Earlier studies reported that conductivity in the crust shows marked changes leading up to major earthquakes (e.g., Yanagihara and Nagano, 1976). Of note, the shape of variations apparent in Fig. 2c is similar to that of corresponding resistivity changes (Y. Sasai, personal communication).

4.3. Limitations of the results and perspectives on future work

Before we further interpret the present results, it is important to consider the possibility that the observed anomalies represent localized "noise", such as artificial noise, rather than localized geomagnetic changes. We attempted to distinguish localized and global variations in total geomagnetic field intensities with the help of a regional geomagnetic field model, but this procedure cannot distinguish localized "signals" from local "noises". We also checked the entire time series of ΔF_{local} (Fig. 3) and confirmed that the pre-seismic changes in the total geomagnetic field intensity are of greater magnitude than those observed at other times (Fig. 4a and b), but we cannot exclude the possibility that large noises were recorded at this time by chance. These uncertainties are inevitable given the reliance on data collected at only one site.

To test the existence of a relation between anomalies in the total geomagnetic field intensity and the earthquake event, it is straightforward in theory to examine magnetic field data recorded at other sites in the region. For forthcoming major earthquakes, it would be useful to deploy a dense network of magnetometers to detect pre-seismic magnetic signals, if indeed such signals can be detected. Inexpensive magnetometers would be sufficient because the signals are expected to be large near the source of the magnetic variations. Unfortunately, data analysis using multiple stations was not possible in the present case. Several proton magnetometers had been deployed near the epicenter of the Kobe earthquake, and total intensity values of the geomagnetic field had been recorded (Electromagnetic Research Group for the 1995 Hyogo-ken Nanbu Earthquake, 1997); however, the magnetometers were only installed after the main shock of the earthquake. Data prior to the earthquake were recorded only at the AMG site. Similar limitations are encountered by most studies concerning the relation between geomagnetic field variations and earthquakes, since we cannot predict the site of the epicenter in advance, and we cannot anticipate that multiple magnetometers will capture anomalies in total geomagnetic field intensities related to earthquakes, even if such anomalies actually exist.

As an alternative strategy for using data recorded at multiple stations, re-examinations of geomagnetic data accumulated by earlier observations are important to assess the existence of a relation between the geomagnetic field and seismic events. Although many such data have already been analysed, earlier investigations employed relatively crude procedures (e.g., the simple difference method) in identifying localized changes. The use of more sophisticated methods may reveal previously un-recognized local signals.

The method employed in the present study is based on a regional geomagnetic field model, and is insufficient in that it is based on total geomagnetic field intensities recorded at a small number of references sites. However, we can say that variations prior to the Kobe earthquake are localized changes, whereas those observed during other periods are not. Recent advances in the techniques available for modeling the geomagnetic field (e.g., Walker and Jackson, 2000) enable data correction with greater accuracy. Moreover, data processing methods have been proposed that take into account the induction effect in the Earth's crust (Fujii and Kanda, 2008). The use of such advanced procedures will produce reliable results regarding localized changes in the geomagnetic field, and possibly lead to a breakthrough in studies on the relation between tectonic activity and geomagnetic variations.

5. Conclusion

Prominent variations in total geomagnetic field intensities were observed by a proton magnetometer prior to the 1995 Hyogo-ken Nanbu (Kobe) earthquake, with the magnetometer located approximately 70 km from the event epicenter. Based on the difference between observed variations and those predicted by a regional total geomagnetic field intensity model, the variations observed prior to the earthquake are identified as local phenomena, possibly arising from the Earth's crust. The two anomalies observed prior to the earthquake are two of the largest localized variations in the total geomagnetic field intensities recorded at the observation site.

The observed variations in the magnetic field prior to the Kobe earthquake may reflect changes in the physical status of the crust over a wide region surrounding the epicenter. However, further investigation based on this event is difficult because we possess data from just one site in the region of interest; consequently, it would be premature to make definite conclusions based solely on the present results. This same difficulty would be encountered in dealing with any seismic event. A strategy to overcome this limitation is to re-examine geomagnetic data accumulated during earlier observations. Recent improvements in data processing will help in the identification of magnetic field variations prior to earthquakes.

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Appendix A. Determination of weighting coefficients $w_m(x, y)$

An initial premise is that variations in total geomagnetic field intensities, $F_{observed}(x,y,t)$, within the region of interest (i.e., in and around Japan), can be represented by a form of Eq. (1). We also assume that a set of spatial functions, $\Delta X_k(x,y)$, is given *a priori*. When the total geomagnetic field intensities at (x_m, y_m) $(m = 1, \ldots, M)$ are given, the temporal function, $T_k(t)$, is determined such that they satisfy the following equation:

$$\sum_{m=1}^{M}\left[F_{observed}(x_m, y_m, t_n) - \sum_{k=1}^{K} X_k(x_m, y_m) T_k(t_n)\right]^2 = \min. \quad (A.1)$$

The solution of this least-squares problem is given in the form of

$$T_k(t_n) = a_{km} F_{observed}(x_m, y_m, t_n). \quad (A.2)$$

Note that a_{km} is independent of t_n. Substituting Eq. (A.1) into Eq. (1), we obtain

$$F_p(x, y, t_n) = w_m(x, y) F_{observed}(x_m, y_m, t_n), \quad (A.3)$$

where

$$w_m(x, y) = \sum_{k=1}^{K} X_k(x, y) \cdot a_{km}. \quad (A.4)$$

Eqs. (A.3) and (A.4) give Eq. (2) in the main text.

The selection of K in Eq. (1) is an important problem. In the study of Fujiwara et al. (2001), $K = 5$ was employed to describe variations in total geomagnetic field intensities in Japan with an accuracy of 0.3 nT. If we were to use the same number of spatial and temporal functions as that employed by Fujiwara et al., we would achieve the same accuracy; however, in determining T_k we used data from just five reference sites. The least-squares problem, Eq. (A.1), is unlikely to be solved in a stable way if we set $K = 5$; therefore, we set $K = 3$. Based on the residuals shown in a table in Fujiwara et al. (2001), the accuracy of Eq. (1) with $K = 3$ is expected to be as good as 0.5 nT.

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