Improved models of the piezomagnetic field for the 2011 Mw 9.0 Tohoku-oki earthquake

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ABSTRACT

To assess the feasibility of observing changes in the magnetic field produced by the piezomagnetic effect, an improved model of the piezomagnetic field corresponding to the Mw 9.0 Tohoku-oki earthquake is presented. In contrast to an earlier study, the proposed model explicitly considers the spatial distribution of slip on the seismic fault, and the results from this new model differ significantly from those of the previous model where slip distributions were ignored. Quantitative aspects of the piezomagnetic effect are discussed through comparisons of data and models. One feature clarified is that, because the fault rupture is so far offshore, the expected amplitudes are quite small at onshore existing observation sites; consequently, there would have been little chance of observing sizable piezomagnetic signals at inland sites during the Tohoku-oki earthquake. Nevertheless, piezomagnetic signals were reportedly detected at a few sites, possibly indicating that the stress sensitivity or the initial magnetization was larger (by several factors) than assumed. On the other hand, relatively large variations in the magnetic field of up to 10 nT may have occurred offshore. This means that if ocean-bottom sensors had been installed, larger piezomagnetic signals would have been detected. Moreover, the piezomagnetic field in offshore areas is sensitive to the detailed

slip distribution, suggesting that observations of the magnetic field at ocean-bottom sites might provide important constraints on determination of slip models.

Keywords: piezomagnetic effect; stress sensitivity; 2011 Tohoku-oki earthquake; slip distribution

1. Introduction

The piezomagnetic effect, which describes changes in magnetization caused by mechanical stress, predicts changes in the Earth's magnetic field following a major earthquake. In earlier studies (e.g. Sasai, 1991, 1994, and references therein), a constitutive law of the relation between stress changes and magnetization changes has been proposed, as follows:

$$\Delta M_i = \frac{3}{2}\beta \Delta T_{ij} M_j,\ (i, j = x, y, z) \qquad (1)$$

where ΔM_i is the change in remanent and induced magnetization, ΔT_{ij} is the deviatoric stress tensor, M_j is the initial total magnetization (i.e. the sum of induced and remanent magnetization without changes in stress), and β is a proportional coefficient that is usually referred to as the (piezomagnetic) stress sensitivity. Because of the piezomagnetic effect, it should be possible to monitor changes in stress in the Earth's crust with geomagnetic observations. Changes in the magnetic field that arise from the piezomagnetic effect are referred to as piezomagnetic fields. These fields are inverted to changes in magnetization in terms of the magnetic Coulomb’s law, and further inverted to changes in stress in terms of eq. (1).

However, the usefulness of the piezomagnetic effect as a tool for monitoring changes in stress is still not clear. Whether or not the piezomagnetic field can be observed depends on the spatial distribution of the piezomagnetic field which, in turn, depends on source type, depth and distance. If the piezomagnetic field has a detectable magnitude that is restricted to just a narrow area, then its detection will be difficult with poorly or sparsely spaced arrays of instruments. Numerical examinations of realistic source models need to be performed in order to assess the detectability of the piezomagnetic field.

The piezomagnetic stress sensitivity is another uncertain factor that determines whether or not the piezomagnetic field is detectable. While the proportional relation (i.e. eq. 1) is partially inferred from considerations based on thermodynamics (e.g. Nakamura and Nagahama, 1997), and the values of stress sensitivity can be determined by theoretical considerations (Stacey and Johnston, 1972), the actual magnetization fraction and type varies from rock to rock and representative values for a particular region must be determined from magnetic anomaly maps, geology and laboratory experiments. Laboratory experiments (e.g. Nagata and Kinoshita, 1967) suggest that stress sensitivities are on the order of 10^{-9} Pa^{-1}. A stress sensitivity of this order is usually assumed when the piezomagnetic effect is considered in studies of volcanoes (e.g. Currenti et al., 2005) and earthquakes (e.g. Okubo et al., 2011). However, these values are sometimes too small to explain the observed offsets in the magnetic field associated with stress changes (e.g. Nishida et al., 2004; Oshiman et al., 1990; Zhan, 1989). The effective values of the stress sensitivity on the geophysical scale (i.e. larger than the laboratory scale) should be evaluated by comparing observational and theoretical models.

The 2011 Mw 9.0 Tohoku-chihou Taiheiyou-oki earthquake (herein referred to as the Tohoku-oki earthquake), which occurred on the boundary between the Pacific and Eurasian plates, is one event for which the magnitudes of the piezomagnetic field can be examined. The Tohoku-oki earthquake is the largest seismic event to have been observed with a dense network of modern geophysical instruments. Along with seismological and geodetic data, geomagnetic data were obtained for this extreme event. Utada et al. (2011) presented a prompt and comprehensive report on observed variations in the geomagnetic field associated with the Tohoku-oki earthquake. Together with several types of geomagnetic variations that followed the earthquake, they also reported that magnetic field offsets, which probably arose from the piezomagnetic effect, are actually observed, but they are only up to 1.0 nT at the observation sites. In their conclusions, Utada et al. (2011) presented a negative view on the detectability of the piezomagnetic field.

Although the observations reported in Utada et al. (2011) provide constraints on the phenomena that actually occurred at the time of the earthquake, their conclusions about the piezomagnetic effect need to be reconsidered because they are based on oversimplified source models that ignore the spatial distribution of slip on the fault. Any reconsideration should incorporate improved piezomagnetic field models in the hope of clarifying the quantitative nature of the piezomagnetic field and evaluating the usefulness of observing it.

The aims of this study are to: (1) provide constraints on the piezomagnetic stress sensitivity around the Tohoku region, near the seismic fault of the Mw 9.0 Tohoku-oki earthquake; and (2) assess the usefulness of the magnetic observations as a tool for detecting stress changes. To these ends, improved models of the piezomagnetic field are presented, and the various models are compared and assessed using the data presented by Utada et al. (2011).

2. Procedures for modeling the piezomagnetic field

This study presents a new model of the piezomagnetic field in which the spatial distribution of slip on the plate-boundary fault is explicitly considered. In many studies of the piezomagnetic field in relation to earthquakes (e.g. Nishida et al., 2007), uniform slip models are employed. However, the slip on a fault is generally heterogeneous, and it is therefore preferable to explicitly consider the spatial distribution of slip. In a uniform slip model, the fault parameters are averaged to obtain a single slip parameter. Such a simplification is valid if the spatial scale of the slip on the fault is smaller than the distance between the observation site and the fault. This criterion is not satisfied in the case of the Tohoku-oki earthquake, for which the spatial scale of the slip and the distance from the surface expression of fault rupture to observational sites are of the order of 100 km. Therefore, the assumption of uniform fault slip used previously by Utada et al. (2011) is likely inadequate in the calculations of the piezomagnetic fields produced by the earthquake.

This study considers the heterogeneous fault slip models of Hayes (2011) and Shao et al. (2011) (herein, referred to as the USGS and UCSB models, respectively), which are derived from seismic wave inversion. Averaged slips from these models were used in the calculations of Utada et al. (2011). These models were published immediately following the Tohoku-oki earthquake and we can expect further refinements as more complete geophysical data sets are taken in account (e.g. Koketsu et al., 2011). Nevertheless, important characteristics of the Tohoku-oki fault slip are apparent in both the USGS and UCSB models. For example, both models indicate large slip near the trench axis. With these slip distributions, it is possible to evaluate the importance of heterogeneous slip distributions and to compare our results with those of Utada et al. (2011).

Piezomagnetic fields that correspond to a heterogeneous slip model are calculated according to the following procedure. The fault plane (i.e. plate boundary) is divided into sub-faults, and on each sub-fault the slip is assumed to be uniform. The total piezomagnetic signal at any point is the sum of the contributions from all sub-faults, and each contribution can be calculated by analytical formulae (Utsugi et al., 2000). Using this procedure, we can calculate the piezomagnetic signals that correspond to heterogeneous slip models for the Tohoku-oki earthquake.

Because the above procedure involves formulae derived by Utsugi et al. (2000), all the assumptions involved in the formulations of Utsugi et al. (2000) are also used in the present models. The initial total magnetization of the crust is assumed to be uniform between the ground surface and a constant Curie point depth. The Earth's crust is approximated by elastic half-space, surface of which locates at sea level. These assumptions are not satisfied in reality, thus producing some uncertainty in the models obtained for the piezomagnetic field. Errors should also be included in the slip models, as mentioned above. To estimate the importance of uncertainly in the slip models and Curie point depths, we calculate the piezomagnetic fields that correspond to the two slip models (USGS and UCSB) with two values of H (15 and 30 km). The values for H used here are the same as those used by Utada et al. (2011), and they provide reasonable estimates for the island arc of the Tohoku district and for the subduction zone east of the Tohoku district of Japan (Tanaka et al., 1999). The effects of heterogeneities in the initial magnetization will be discussed separately, later.

3. Features of the new piezomagnetic models

Using the above procedures, and the parameters listed in Table 1, models of the piezomagnetic field have been constructed. The spatial distribution of the expected amplitude of the piezomagnetic effect is shown in Fig. 1. Observations are assumed to have been made at sea level, i.e. the surface of a uniform elastic half-space. Below, I enumerate the features that are commonly observed in the results and which correspond to all sets of parameters. It should be noted that the absolute values given in the results are strongly dependent on the assumed sets of parameters. For this reason, this analysis focuses on relative rather than absolute values.

Relatively large signals of the piezomagnetic field are expected to occur in offshore areas in all cases. For the UCSB slip model, piezomagnetic fields larger than 3 nT are predicted in offshore areas. For the USGS slip models, the predicted piezomagnetic fields are smaller than those for the UCSB model, yet changes larger than 1 nT are predicted.

In contrast, the expected amplitudes of piezomagnetic signals over the more distant onshore, including the sites of observation, are rather small. Over a vast part of the land area, the predicted amplitudes of the piezomagnetic field are up to 0.4 nT. Precise values of the expected changes at the observation sites are listed in Table 2, together with the observed changes reported by Utada et al. (2011). In some models, the changes predicted at some locations are as large as 0.6 nT. For example, the predicted change at the ESA site is 0.6 nT for model b (i.e. UCSB slip model with H = 30 km) whereas the predicted change at the same site is zero for other models. There is no location where all the models predict changes greater than 0.4 nT.

It should be pointed out that these models are quite different from those that use uniform slip distribution. Figure 2 shows the calculated piezomagnetic field intensities that correspond to uniform slip models where the slip parameters are averaged over the fault plane. Numerous differences can be observed between Figs. 1 and 2. For example, the amplitudes of the signals predicted with the uniform slip model do not exceed 1.0 nT, except for some localized areas. If we focus on this result, the impression is that the detection of coseismic piezomagnetic signals is a hopeless task, even if the observational area is extended to the seafloor. However, the amplitudes of signals predicted by the heterogeneous slip model are larger than 1–2 nT across a wide area of ocean. In this case, the amplitudes of the coseismic piezomagnetic signals would have been detected, if suitable magnetometers had been installed in the region.

The large differences that exist between the uniform and heterogeneous slip models highlight the importance of considering the heterogeneous model for the Tohoku-oki earthquake. The large differences also indicate that many of the conclusions about piezomagnetic signals by Utada et al. (2011) need to be reconsidered and probably changed.

4. Discussion

The goals of this study were to provide constraints on stress sensitivity, and to assess the usefulness of magnetic observations as tools for monitoring stress. The former can be accomplished by comparing the data with the models. The latter can be achieved by analyzing the constructed model. These matters are further discussed below.

4.1. Possible values of the piezomagnetic stress sensitivity

To provide constraints on the stress sensitivity using the results of piezomagnetic modeling, I make reference to the data presented by Utada et al. (2011). The idea is as follows. In the proposed model, the stress sensitivity (β) and the intensity of the initial total magnetization ($M = (M_x^2 + M_y^2 + M_z^2)^{1/2}$) are assumed to be given as in Table 1. The assumed values are possibly different from the actual values. As the calculated value of F_p (denoted by $F_\mathrm{p}^{\mathrm{calculated}}$) is proportional to the assumed value of βM, [$(\beta M)^{\mathrm{assumed}}$], the difference between $(\beta M)^{\mathrm{assumed}}$ and the actual value of βM [$(\beta M)^{\mathrm{actual}}$] yields the disparity between the observed value of F_p ($F_\mathrm{p}^{\mathrm{observed}}$) and the calculated F_p

($F_p^{\mathrm{calculated}}$). The value of $(\beta M)^{\mathrm{actual}}$ is given by

$$(\beta M)^{\mathrm{actual}} = \frac{F_p^{\mathrm{observed}}}{F_p^{\mathrm{calculated}}} \times (\beta M)^{\mathrm{assumed}}. \qquad (2)$$

If F_p^{observed} and $F_p^{\mathrm{calculated}}$ correlate well, it is possible to determine a plausible value of $(\beta M)^{\mathrm{actual}}$.

Regrettably, the correlation between observed and calculated signals of the piezomagnetic field is not good (Fig. 3). This means that assumptions of a uniform Curie point depth, a uniform initial total magnetization, and/or an assumed slip model, are inadequate. In particular, ignoring the heterogeneity of the initial magnetization is possibly problematic because it is known to enhance the piezomagnetic field (e.g. Oshiman, 1990). Aeromagnetic surveys over the Tohoku region have shown that magnetic anomalies in this region are rather strong (i.e. 10–100 nT) (Fig. 4), raising the possibility of a strong heterogeneity in the initial total magnetization. Consideration of the heterogeneity of the initial magnetization is clearly important if we are to calculate the piezomagnetic field accurately. However, an accurate determination of the structure of the initial magnetization is generally laborious and full of possible errors; hence, an accurate determination of a generated piezomagnetic field is difficult in the presence of a strong heterogeneity in the initial magnetization (e.g. Yamazaki, 2011).

Nevertheless, we can attempt to provide constraints on the possible values of the stress sensitivity using data just from sites KAK and KTR. Around these sites, the gradient of the magnetic anomaly is relatively small (Fig. 4), and we can therefore anticipate that the model with uniform initial magnetization will provide reasonable calculated results. The amplitude of the piezomagnetic signal observed at KTR was –0.8 ± 0.2 nT, whereas those predicted in the theoretical models (Fig. 1a–d) are between –0.2 and –0.3 nT. The piezomagnetic signal observed at KAK was –0.22, whereas those predicted by theoretical models are between –0.07 and –0.22. To explain the observations at KAK and KTR, the actual value of βM needs to be larger than the value assumed in the present calculation (i.e. 1.0 $Pa^{-1}Am^{-1}$) by factors of 2–3. Provided that the assumption of M = 1.0 A/m (Table 1) is correct, the above result means that the stress sensitivity is about 2.0–3.0 × 10^{-9} Pa^{-1}. This value is on the same order as that assumed in many piezomagnetic models (e.g. Johnston et al., 1989).

4.2 Potential usefulness of seafloor magnetic observations

In all the models of the piezomagnetic field shown in Fig. 2, the amplitudes of the piezomagnetic signals are expected to be small on land and relatively large offshore. Because the actual value of βM is possibly larger than assumed, as discussed in the previous subsection, the actual changes in the magnetic field are possibly larger than those shown in Fig. 1. In particular, large offsets in the magnetic field are expected near the trench axis. Although this result is obtained for an assumption that observations are made at sea level, piezomagnetic signals are also expected to be large at seafloor because the seafloor is rather closer to the rupture. If offshore ocean-bottom magnetometers had been installed, they would have detected significant amplitudes of piezomagnetic signals corresponding to the Tohoku-oki earthquake.

Observing piezomagnetic signals would not be very useful if the piezomagnetic signals were insensitive to details of the fault parameters, but the results of the piezomagnetic models demonstrate that this is not the case. Indeed, the spatial distributions of the piezomagnetic field are strongly dependent on the slip model that is adopted. It is possible that we could have improved the determination of earthquake source parameters if data from ocean-bottom magnetometers had been available, instead of relying solely on the results of inversions of seismic and geodetic data.

In general, it is difficult to measure accurately the distributions of slip for earthquakes that occur on an offshore plate boundary, because geodetic measurements are made mainly on land. In the case of the Tohoku-oki earthquake, extremely large slips near the trench axis have been suggested by inversions of the seismic data (e.g. Hayes, 2011; Shao et al., 2011), but better constraints on slip distributions could have been obtained from seafloor geodetic measurements (Sato et al., 2011). Given that seafloor geodetic equipment is costly and difficult to manage, geomagnetic observations might provide useful additional data for monitoring interplate earthquakes along subduction zones. This solution may still apply, even when we consider magnetic anomalies on the seafloor, because heterogeneities in the magnetization of the crust may possibly enhance the generated piezomagnetic field (e.g. Oshiman, 1990).

Regrettably, there are also drawbacks to making seafloor magnetic observations. First, seafloor observations are quite costly. Second, it may be difficult to keep the sensors stably located during quakes, and if a sensor is displaced during a quake, an apparent change in the magnetic field will be recorded. Even if it were possible to obtain accurate data of the geomagnetic field at a certain point, it would be necessary to consider heterogeneities of the initial magnetization and ocean-bottom topography when converting the observed changes in the magnetic field to fault source parameters. For these reasons, the usefulness of observing the piezomagnetic field remains uncertain. However, similar difficulties also exist with respect to making ocean-bottom geodetic observations. Not only are they are extremely costly, but monument stability during earthquakes is also a problem. It is also difficult to process the observations correctly and obtain precise geodetic information. A decision on prioritizing geodetic and geomagnetic techniques should be based on which drawbacks are most easily overcome. If costs allow, an integrated use of both techniques is most desirable because they independently bring useful information to bear on these tectonic phenomena.

5. Conclusions

To calculate the piezomagnetic field that corresponds to the 2011 Mw 9.0 Tohoku-oki earthquake, it is necessary to consider the best representation of the spatial distribution of slip along the fault, and in this paper, I demonstrate the importance of such a consideration, and construct an appropriate slip model. Although this model still cannot entirely explain the observed distribution of piezomagnetic signals, constraints are obtained from data at two onshore sites, where the model seems to provide adequate results. Comparisons between the data and the model show the stress sensitivity to be about 2–3 $\times 10^{-9}$ Pa^{-1}, which is on the same order as that assumed in many piezomagnetic models. Models of the piezomagnetic field predict that changes in the geomagnetic total forces, due to the piezomagnetic effect, will be relatively large in offshore areas closer to the rupture, and relatively small onshore, far from the rupture. Because the expected magnitudes of the piezomagnetic signals are small at existing sites, stress sensitivity of the piezomagnetic effect is likely to be on the order of 10^{-9}, though this is not tightly constrained. Nevertheless, the possibility of a large piezomagnetic field occurring at ocean-bottom stations is not excluded. Details of the spatial distribution of the piezomagnetic field in oceanic areas are highly dependent on the slip model used. The implication is that detection of the piezomagnetic field with ocean-bottom magnetometers might have provided constraints on the slip models of the Tohoku-oki earthquake, if such observations had been available.

Acknowledgments

Slip models proposed by Shao et al. (2011) and Hayes (2011), and a program coded by M. Utsugi, were used to calculate the piezomagnetic fields. Numerical data on the geomagnetic anomalies around Japan were provided by the Geospatial Information Authority of Japan through their Web site. Comments and advice from anonymous reviewers and the journal editor (P. Shearer) helped to improve an earlier version of the

manuscript. The software Generic Mapping Tools (Wessel and Smith, 1998) was used to prepare some of the figures, including maps.

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Figure captions

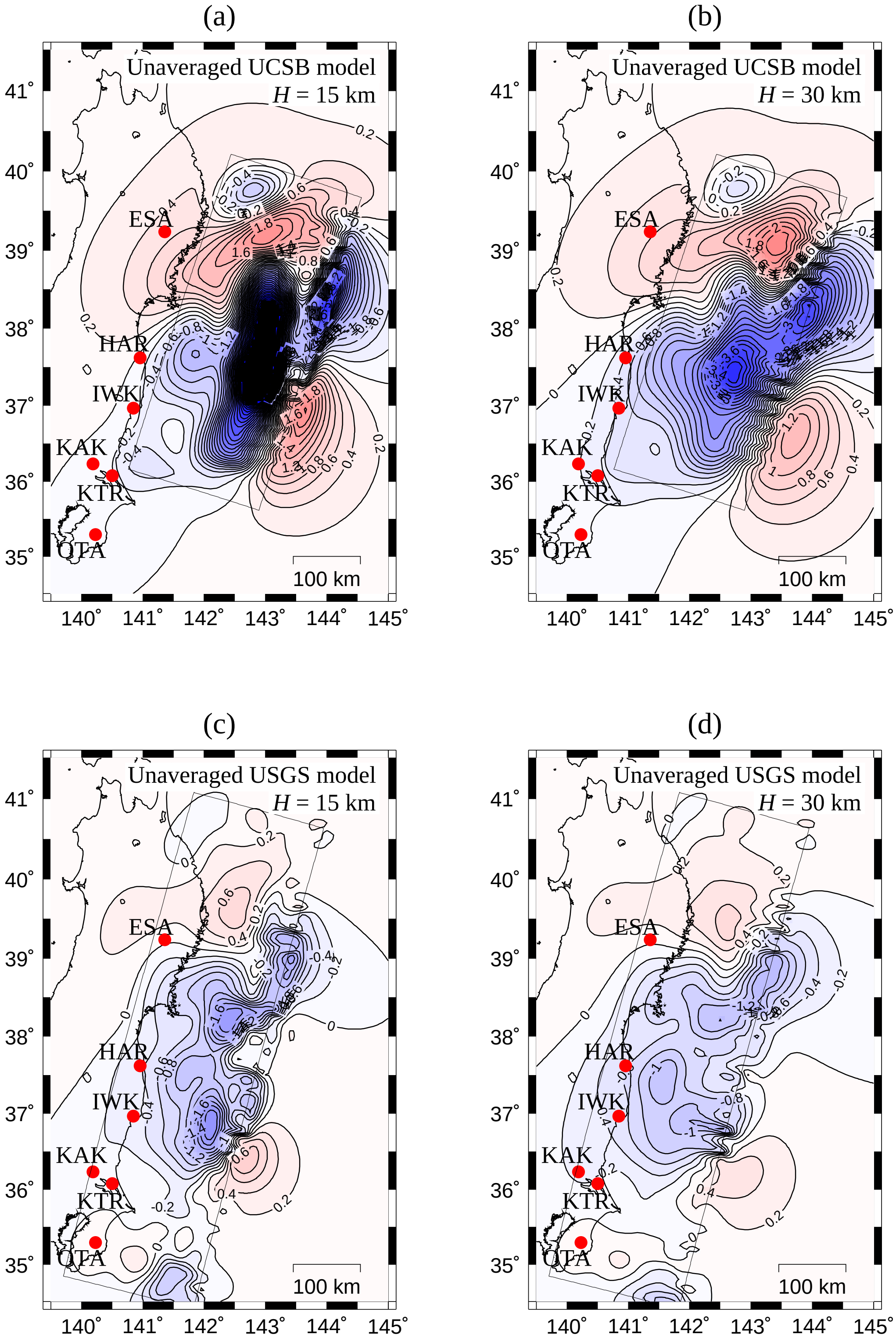
Fig. 1. Models of the piezomagnetic field corresponding to the UCSB and USGS slip models. (a) UCSB slip model with *H* = 15 km. (b) UCSB slip model with *H* = 30 km. (c) USGS slip model with *H* = 15 km. (d) USGS slip model with *H* = 30 km. The rectangle represents the fault plane on which heterogeneous slip is considered.

Fig. 2. Models of the piezomagnetic field corresponding to averaged versions of the UCSB and USGS slip models. (a) UCSB slip model with *H* = 15 km. (b) UCSB slip model with *H* = 30 km. (c) USGS slip model with *H* = 15 km. (d) USGS slip model with *H* = 30 km. The rectangle represents the fault plane on which uniform slip is considered.

Fig. 3. Comparisons between observed and calculated piezomagnetic signals. Calculated values in this figure are the averages of four piezomagnetic models. Error bars in calculated values represent maximum and minimum values for the four models. Error bars in observed values are from Utada et al. (2011). Open circles indicate the results at sites KAK and KTR, where the magnetic anomalies

are rather small, while solid circles indicate the results at other sites.

Fig. 4. The magnetic anomaly over the Tohoku region as observed by an aeromagnetic survey at a height of 5000 m. Contour intervals are 10 nT. Observations were conducted by the Geographical Survey Institute (predecessor of the Geospatial Information Authority) of Japan in 1990, and the data are available on their Web site, in Japanese (http://vldb.gsi.go.jp/sokuchi/geomag/menu_03/aeromag_data.html; last access: 26 October 2012).



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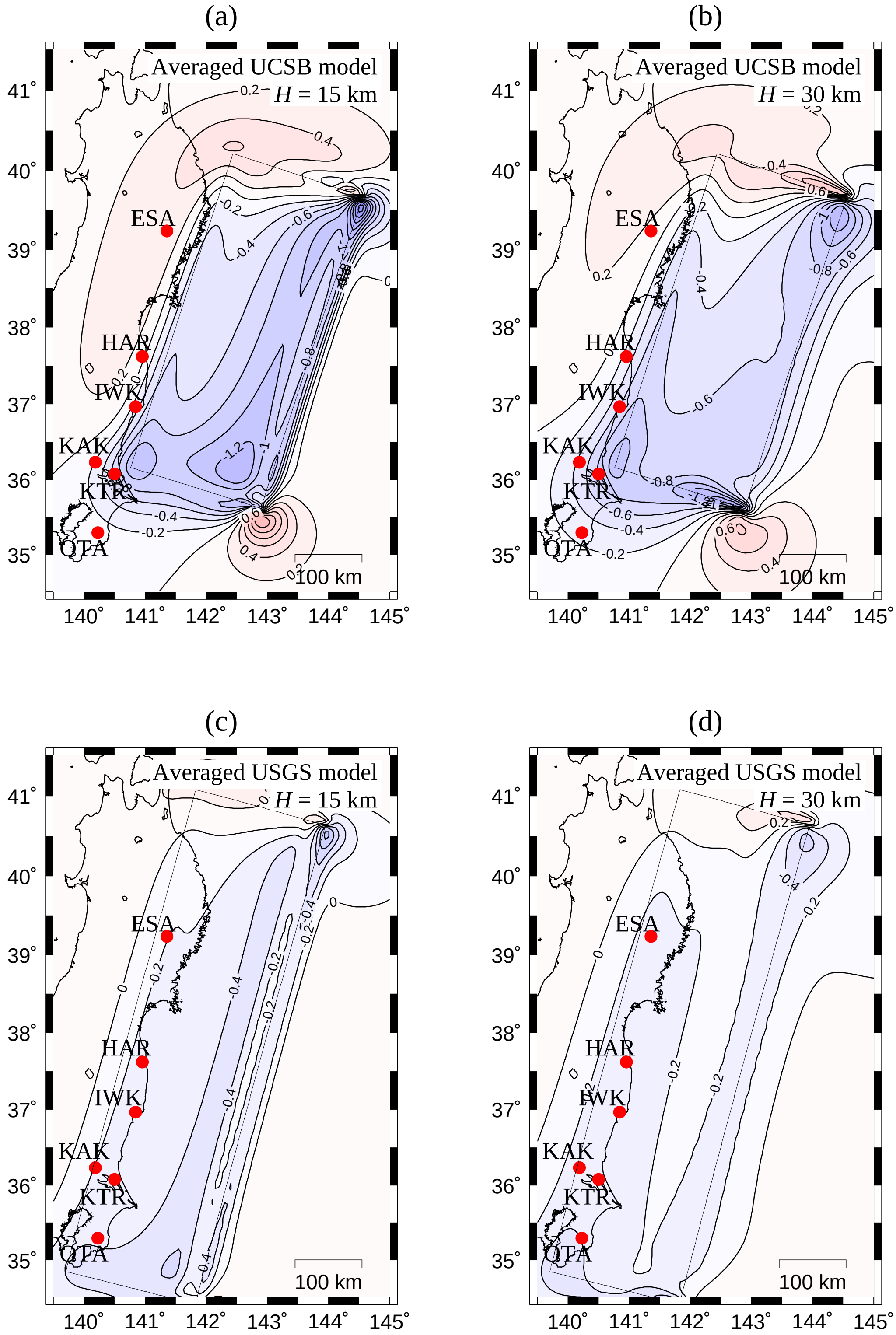

Figure 2 Models of the piezomagnetic field corresponding to averaged versions of the UCSB and USGS slip models. (a) UCSB slip model with $H = 15$ km. (b) UCSB slip model with $H = 30$ km. (c) USGS slip model with $H = 15$ km. (d) USGS slip model with $H = 30$ km. The rectangle represents the fault plane on which uniform slip is considered.

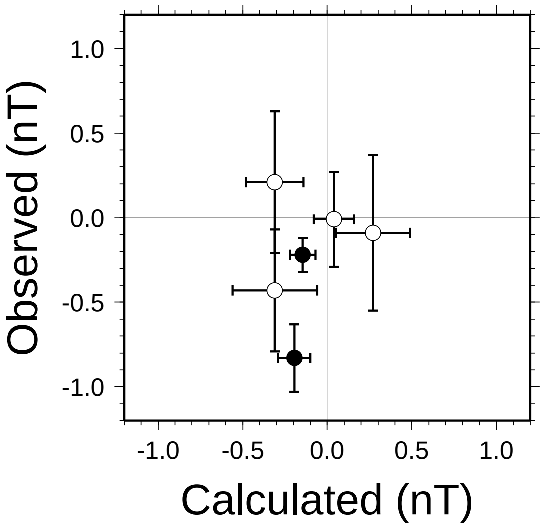

Figure 3 Comparisons between observed and calculated piezomagnetic signals. Calculated values in this figure are the averages of four piezomagnetic models. Error bars in calculated values represent maximum and minimum values for the four models. Error bars in observed values are from Utada et al. (2011). Solid circles indicate the results at sites KAK and KTR, where the magnetic anomalies are rather small, while open circles indicate the results at other sites.

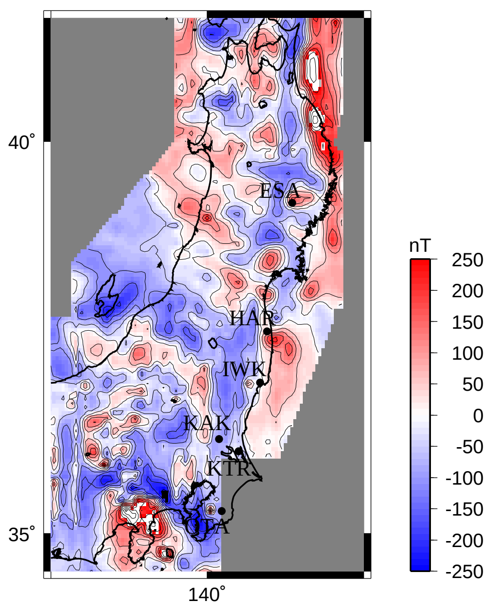

Figure 4 The magnetic anomaly over the Tohoku region as observed by an aeromagnetic survey at a height of 5000 m. Contour intervals are 10 nT. Observations were conducted by the Geographical Survey Institute (predecessor of the Geospatial Information Authority) of Japan in 1990, and the data are available on their Web site, in Japanese (http://vldb.gsi.go.jp/sokuchi/geomag/menu_03/aeromag_data.html; last access: 26 October 2012).

Table 1

Parameters assumed in the modeling of the piezomagnetic field.

Parameter	Value
Rigidity	57(53) × 10^9 Pa
Poisson's ratio	0.25
Magnetization	1.0 A m^{-1}
Piezomagnetic stress sensitivity	1 × 10^{-9} Pa^{-1}
Curie point depth	15 and 30 km
Inclination of the ambient geomagnetic field	51.0 degree
Declination of the ambient geomagnetic field	–7.5 degree
Observation altitude	0 m

Table 2

Comparisons of coseismic changes in the geomagnetic total intensity, as predicted by the piezomagnetic models versus those calculated from data reported in Utada et al. (2011). Piezomagnetic field models are determined for Curie point depths of 30 and 15 km together with two slip models (USGS and UCSB).

Station code	USGS slip model		UCSB slip model		Observed (error)	
	30 km	15 km	30 km	15 km		
ESA	+0.05	+0.05	+0.55	+0.49	–0.09	(0.46)
HAR	–0.56	–0.37	–0.40	–0.06	–0.43	(0.36)
IWK	–0.48	–0.28	–0.44	–0.14	+0.21	(0.42)
KTR	–0.18	–0.10	–0.29	–0.18	–0.83	(0.20)
OTA	+0.14	+0.16	–0.08	–0.03	–0.01	(0.28)
KAK	–0.22	–0.14	–0.19	–0.07	–0.22	(0.10)