

LONG-TERM SEAFLOOR ELECTROMAGNETIC OBSERVATION IN THE NORTHWEST PACIFIC MAY DETECT THE VECTOR GEOMAGNETIC SECULAR VARIATION

H. Toh^{1*}, Y. Hamano², T. Goto³, and H. Utada⁴

^{*1} Data Analysis Center for Geomagnetism and Space Magnetism, Graduate School of Science, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 6068502 JAPAN

Email: toh@kugi.kyoto-u.ac.jp

² Basic Research Program, IFREE, JAMSTEC, Natsushima, Yokosuka, Kanagawa 2370061 JAPAN

Email: hamano@jamstec.go.jp

³ Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University, Katsura, Nishikyo-ku, Kyoto 6158540 JAPAN

Email: tgoto@tansa.kumst.kyoto-u.ac.jp

⁴ Ocean Hemisphere Research Center, Earthquake Research Institute, University of Tokyo, Yayoi, Bunkyo-ku, Tokyo 1130032 JAPAN

Email: utada@eri.u-tokyo.ac.jp

ABSTRACT

Sea Floor ElectroMagnetic Stations (SFEMSs) are now operating at two deep seafloor sites called the 'WPB' and the 'NWP' in the West Philippine Basin and the Northwest Pacific Basin, respectively. One of the main objectives of the SFEMSs is to detect the geomagnetic secular variations on the deep seafloor where long-term geomagnetic observations have not so far been achieved. SFEMSs can measure the absolute geomagnetic total force as well as the geomagnetic vector field with precise attitude monitoring systems. The vector geomagnetic time-series that was observed for more than 5 years revealed that the westward drift of the equatorial dipole dominates in the geomagnetic secular variation at the NWP.

Keywords: Seafloor geomagnetic observatories, Attitude monitoring, Geomagnetic secular variations, Westward drift, Equatorial dipole

1 INTRODUCTION

It has long been pointed out that a “land-locked” view alone cannot provide the true image of the Earth because the continents occupy only 30% of the Earth’s surface. Disciplines in solid Earth geophysics such as seismology strongly require an “ocean-locked” view of the Earth as well as the “land-locked” view in order to know the true internal structures of our planet. Some disciplines such as geodesy or geomagnetism may circumvent this difficulty because remote sensing of potential fields by low-Earth-orbit satellites (e.g., Gaya-Piqué et al., 2005) is possible in those disciplines. The “ocean-locked” view, however, is indispensable even for disciplines in which Earth-observing satellites play dominant roles in providing the bulk of the data, especially when temporal variations of geophysical phenomena are of particular interest.

A considerable amount of effort has been made to develop ocean bottom geophysical observatories. For example, pilot deployments of a multi-disciplinary seafloor observatory have been repeated in the Mediterranean Sea (Beranzoli et al., 1998; 2003). In North America, a broadband ocean bottom seismic observatory was installed in the Monterey Bay, which was firstly uncabled (Romanowicz et al., 2006) and then recently realized real-time connection through a submarine cable (<http://www.mbari.org/mars/>). However, it should be noted here that the seafloor observatories are mostly coastal rather than deployed in open oceans, and the coastal observatories have been maintained at better instrument servicing and data recovery rates.

Toh et al. (1998) developed a prototype geomagnetic observatory for use in remote open oceans. The instrument, the SeaFloor ElectroMagnetic Station (SFEMS), was designed to continuously measure not only the geomagnetic but also the geoelectric field for more than one year by one-minute sampling. In the course of its development, it was found that attitude monitoring is crucial to realize the absolute observation of the geomagnetic vector field (Toh et

al., 2004), culminating in installation of accurate tiltmeters and a fibre optical gyro for orientation detection, in addition to the original electromagnetic (EM) sensors, such as an absolute scalar Overhauser-type (1953) proton precession magnetometer and a vector fluxgate magnetometer. The final version of SFEMS is now operating at two sites in the northwest Pacific, i.e., at the NWP (41°06'08"N, 159°57'47"E, -5580 m) since 2001 and at the WPB (19°19'18"N, 135°06'41"E, -5690m) since 2006 (Toh et al., 2006).

The intent of this paper is to outline the long-term geomagnetic observation at the seafloor being conducted by the two SFEMSs in the western Pacific, with special attention to possible detection of the secular variation in the vector geomagnetic field. In the following paper, (1) instrumentation of the geomagnetic observatories on the deep seafloor, (2) deployment/recovery procedures of the SFEMSs at the time of recent sea experiments, (3) description of obtained EM time-series, and (4) results of analysis of the geomagnetic secular variations found in the observed vector geomagnetic data will be illustrated. Finally, the results and perspectives for the future will be discussed and concluded.

2 INSTRUMENTS

Figure 1 shows the outer and schematic views of an SFEMS. The SFEMSs are pop-up type, self-contained and unmanned systems capable of monitoring the geomagnetic and geoelectric field together with auxiliary measurements of environmental parameters at a preset sampling rate. The environmental parameters include temperature, horizontal tilts, and the orientation of the SFEMSs on the seafloor. The instruments' attitude data, i.e., the tilt variations and the azimuthal measurements with respect to true north, turned out to be essential especially for detection of geomagnetic secular variations. The azimuthal measurements alone were conducted intermittently on the seafloor, viz., once every few months, due partly to limitation of power supply and to magnetic noises that were produced by a fibre optical gyro (Gyro) at the time of the azimuthal measurements. The measuring frame of the instruments' attitude was carefully aligned to that of the EM measurements prior to the SFEMSs' deployments at sea.

The geomagnetic field was continuously monitored by an Overhauser-type absolute scalar proton precession magnetometer (indicated by 'OHM' in the right of Figure 1) and a fluxgate-type vector magnetometer (Ocean Bottom ElectroMagnetometer; OBEM). The geoelectric field sensed by the mutually orthogonal electrode dipoles shown in Figure 1 was also stored in the OBEM. Silver-silver chloride electrodes (Perrier et al., 1997) were used as sensing electrodes for the geopotential variations. The dipole length was normally set to around 5 m. All the EM data and the environmental parameters were recorded not only by each client sensor such as OHM, OBEM, and Gyro, but also by an interface circuit (I/F) that was equipped with a master clock with sub-ppm precision and large digital storage.

Recovery of the SFEMSs was enabled by acoustic release. Each SFEMS was equipped with an acoustic transponder with a unique release code for this purpose. The SFEMSs were designed to be submersible to 6700 m depth for more than three years in terms of the acoustic release. However, the lifetime of the SFEMSs is now determined by the capacity of the power supply from lithium primary cells (Batt) attached to each SFEMS rather than that of the acoustic transponder. Energy saving schemes built into the electronics made it possible to elongate the SFEMSs' actual lifetime on the seafloor for more than two years even with a battery capacity of several hundred Ah.

Although the SFEMSs weigh approximately 400 kg in air at the time of installation, their weights in water are only around 50 kg. After releasing their non-magnetic lead weights, they weigh less than 300 kg in air at recovery. They are also equipped with a pair of a VLF radio transmitters and a flashing light for easier spotting of the instruments at the sea surface.

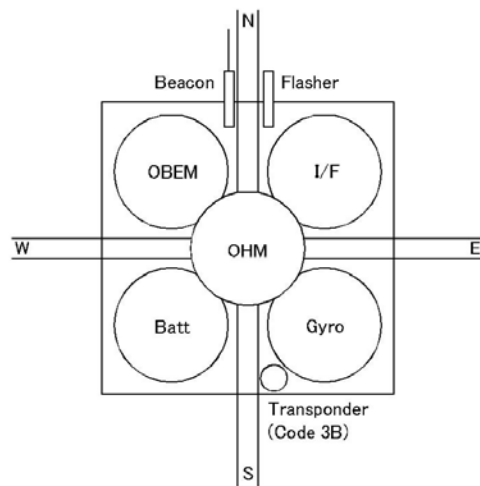
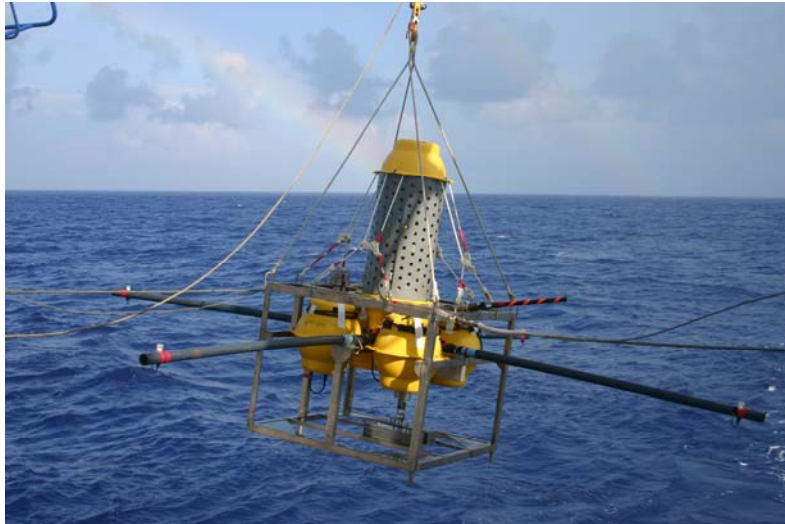


Figure 1. The SFEMS at the time of deployment to the WPB (top) and its schematic top view (bottom). The mutually orthogonal electrode dipoles are as long as 5 m. The five yellow glass spheres contain the parts of the SFEMS depicted in the bottom. The length of each side of the large square in the bottom diagram is 1.2 m, which is also equal to the height difference between the OBEM and OHM spheres. A double rainbow is seen in far back in the top diagram (photo: courtesy by JAMSTEC). See text for details.

3 SEA EXPERIMENTS

Since preliminary reports of earlier sea experiments have already been published elsewhere (e.g., Toh et al., 1998; 2004; 2006), we will focus on three recent sea experiments in this section. All of the three cruises were conducted by a combination of R/V Kairei and ROV Kaiko 7000II. They are KR05-08, KR06-06, and KR07-08 research cruises, in which KR06-06 alone was organized to deploy an SFEMS for the first time to the WPB. Establishment of another long-term EM observation site on the seafloor in the middle of the Philippine Sea plate enables monitoring of the dynamics in the Earth's outer core at a regional scale. This may contribute to detection of turbulent flows in the liquid core by observing the difference in the geomagnetic secular variations between the WPB and NWP. Prior to those three sea experiments, EM data were available only at the NWP although the total length of the obtained EM time-series was more than 1300 days. A pair of KR05-08 and KR07-08 cruises at the NWP has added another 21-month long EM time-series, yielding the total length at the NWP to be slightly fewer than 2000 days. In 2005, however, the EM data had a gap for approximately five months from February through July due to an unsuccessful request for a proposal of a research cruise in 2004 (we were not able to do any sea experiments between KR03-08

and KR07-08). Figure 2 shows a site map depicting the relative position of the two long-term seafloor EM sites and two photos illustrating the procedure of the SFEMS replacement. By making use of a submersible, it is now possible to install a new SFEMS to a seafloor position very close to the old SFEMS, say within 20 m, and conduct side-by-side simultaneous EM measurements for at least one whole day during one replacement cruise before recovery of the former SFEMS.

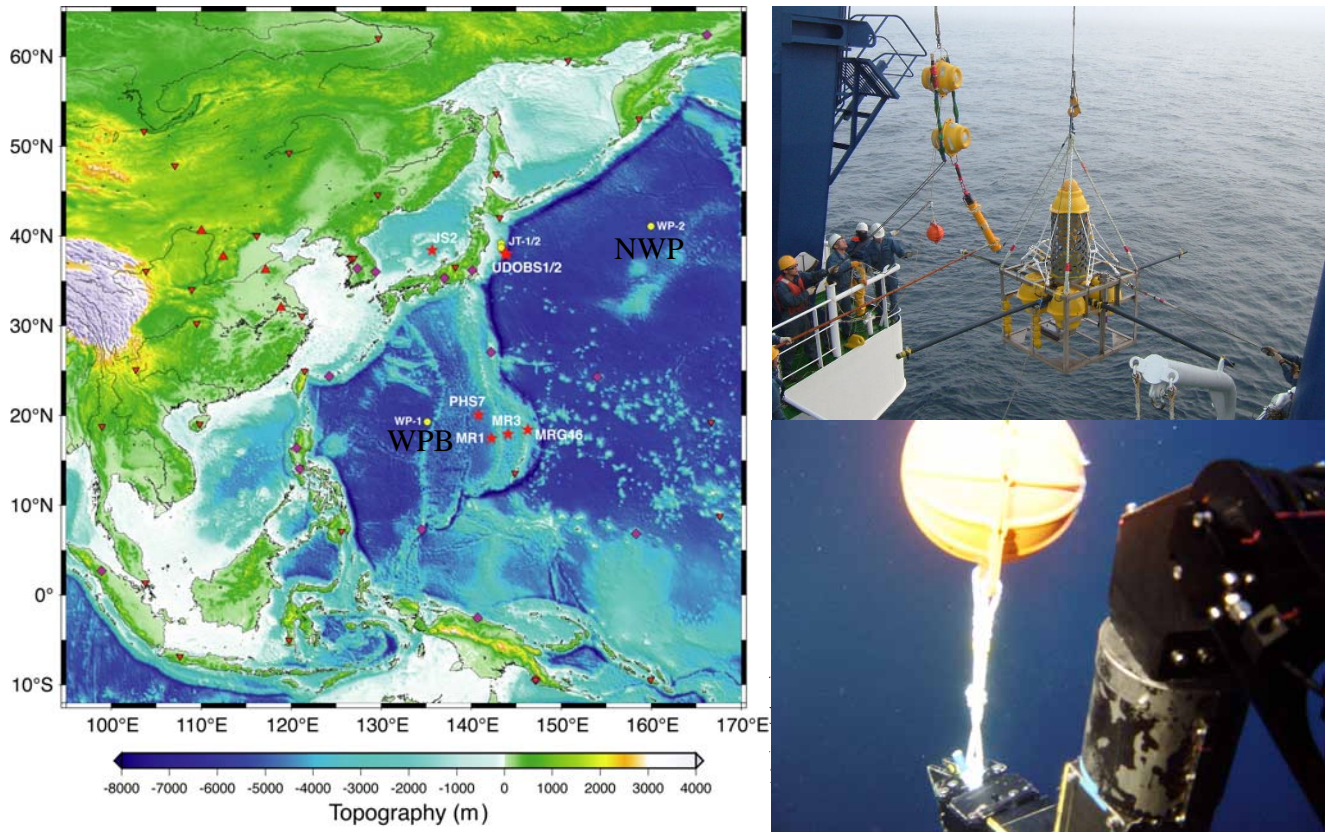


Figure 2. The site map (left), the SFEMS just before launch at the NWP (upper right), and a photo taken by the submersible ROV Kaiko 7000II at the time of the sea experiment by the research cruise KR07-08 of R/V Kairei (lower right). The two long-term EM observation sites, the WPB and the NWP, are collocated with the borehole seismometers, WP-1 (Salisbury et al., 2006) and WP-2 (Suyehiro et al., 2004), respectively. Other colored symbols denote seismic stations in the western Pacific. Additional buoyancy (the two large yellow glass spheres with a small orange one in a line: upper right) was given to the SFEMS at the time of installation in the KR07-08 cruise in order to carry the seafloor instrument to the desired pin-point position, i.e., next to the already installed SFEMS by the submersible. The transportation was realized by grasping the tip of the whole seafloor system with the submersible's manipulator (lower right).

4 DATA

It was a good surprise for us that the synthetic geomagnetic total force using the geomagnetic three components of the SFEMs coincided well with the absolute geomagnetic total force measured by the Overhauser magnetometer (Toh et al., 2006). This fact motivated us to focus on a study of the vector geomagnetic secular variations, leaving the geoelectric data for a subsequent investigation. However, it was also found that correction for observed tilt variations is crucial for the seafloor geomagnetic data to recover the true vector geomagnetic secular variations. Sample plots of the recovered vector secular variations are shown in Figure 3 together with the geomagnetic secular variations of the vertical component observed at land stations in the western Pacific.

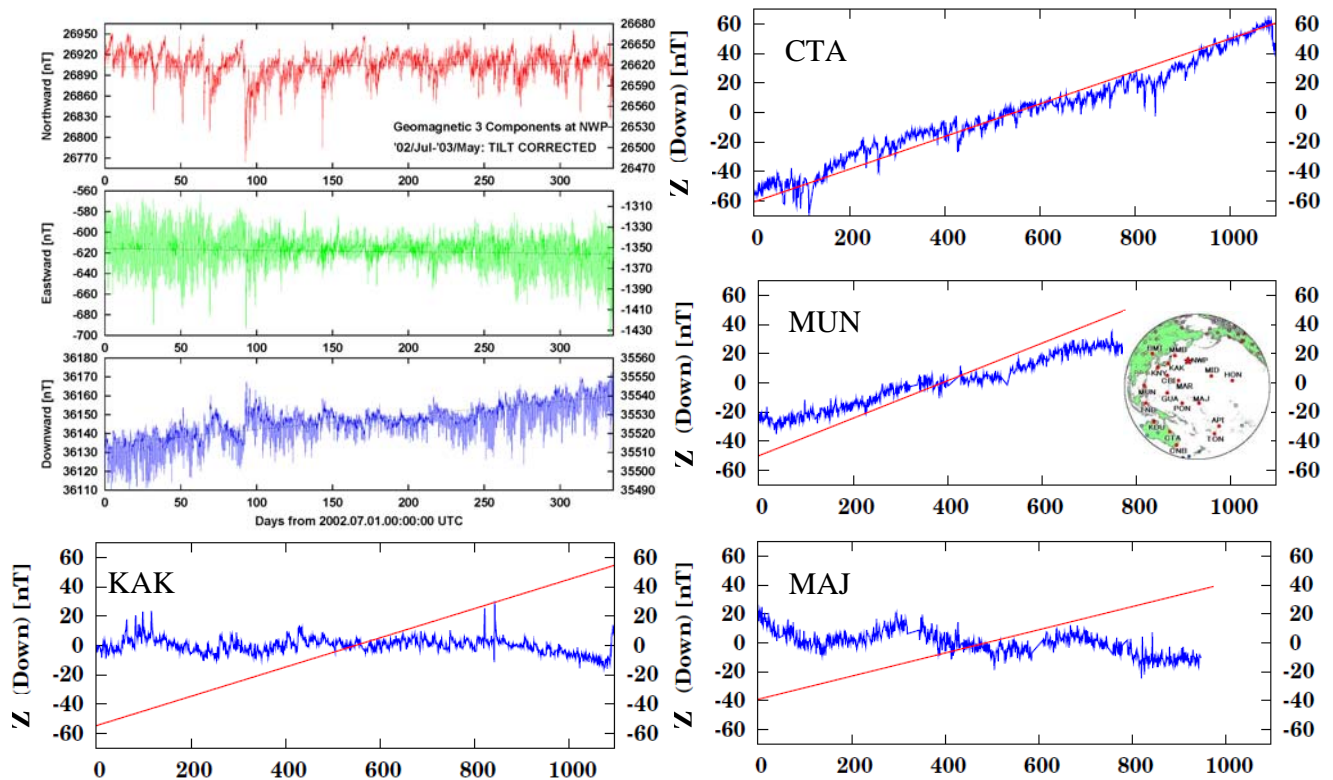


Figure 3. Vector geomagnetic time-series observed in the western Pacific. The geomagnetic three components at the NWP (upper left) that show a good agreement with the geomagnetic secular variations predicted by a global geomagnetic reference field model (Olsen, 2002; the thin dotted line). As for the remaining four sites (KAK, CTA, MUN, and MAJ), those of the vertical geomagnetic component Z alone are shown. Biases of the vertical components on land have been subtracted to give them null means. The abscissae for the land station are also in days with the origin at 00:00:00 UTC on August 1, 2001. Locations of each site are depicted in the inset together with other station/observatory locations. The red solid lines are the predicted secular variations of equatorial dipole origin (see text for more details).

The recovered vector geomagnetic secular variations are in good agreement with prediction by a global geomagnetic field model based mainly on magnetic satellite data (Olsen, 2002). As will be shown in the next section, contribution of the equatorial dipole is dominant in the secular variations of the vertical geomagnetic component at the NWP.

However, not all the geomagnetic stations in the Pacific show this tendency. For instance, the stations in the Philippines (e.g., Muntinlupa: MUN) and along the northeast coast of Australia (e.g., Charters Towers: CTA) obey this rule of thumb, while Japanese stations such as Kakioka (KAK) and the stations in the central Pacific such as Majuro (MAJ) are not dominated by the equatorial dipole contribution alone.

Non-dipole contribution to not only the spatial distribution but also the geomagnetic secular variations is known to be very small over the Pacific Ocean (Toh et al., 2007). This phenomenon is coined as ‘Pacific Dipole Window (or Pacific Non-dipole Low’ (McElhinny et al., 1996). It, therefore, is natural if the secular variations caused by the westward drift of the equatorial dipole dominate in the western Pacific. A problem arising here is why there are regions with less prominent dipole contributions. To address this question, we will show results of a detailed mapping of the geomagnetic secular variations of the vertical component because the component is believed to be the only component that is continuous across the core-mantle boundary (CMB) and thus directly relevant to core dynamics of the Earth (Bloxham & Jackson, 1991).

5 RESULTS

A closer look at the vector geomagnetic secular variations observed at the NWP revealed that they coincide well with not only prediction by the global geomagnetic field model (Olsen, 2002) but also the low-degree secular variations caused by the westward drift of the equatorial dipole. Figure 4 illustrates the situation. The geomagnetic secular variations of horizontal components are not considered here since they are not guaranteed to be continuous across the CMB due to the very high electrical conductivity ($\sim 10^5$ S/m) of the Earth’s outer core. On the other hand, those of the vertical component are definitely continuous across the CMB, conveying the information relevant to flows in the outer core all the way to the surface through the mantle. Figure 4(a) for the vertical component shows the modeled secular variations at the NWP for a year from July, 2002 through June, 2003. Interestingly, almost all the observed variations can be explained solely by those of the equatorial dipole terms (\dot{g}_1^1 and \dot{h}_1^1). In other words, the secular variations by the axial dipole and by the remaining non-dipole contribution seem to cancel each other out at this specific seafloor site.

To confirm the tendency over the Pacific, we mapped out a model prediction of the geomagnetic secular variations in the rest of the three plots in Figure 4. We used the 10th generation of the International Geomagnetic Reference Field (IGRF-10; IAGA WG-VMOD, 2005) in order to calculate the predicted secular variations at each numerical grid on the Earth’s surface because IGRF-10 can give more constraints on the geomagnetic secular variation than the global model by Olsen (2002) in the time period from 2000 through 2005.

Non-dipole secular variations in the vertical geomagnetic component were found to be negative around Japan and the central Pacific (Figure 4(d)), while some areas such as the northeast coast of the Australian continent, the island arcs of both Indonesia and the Philippines, and a narrow but significant path between Japan and the central Pacific were found to have negligible non-dipole contribution in their geomagnetic secular variations.

As for the equatorial dipole, its S-pole obviously exists on the equator in the western Pacific (see Figure 4(c)). This is the very reason why we see the equatorial dipole contribution alone at sites NWP, CTA, and MUN (cf. Figure 3). Because the non-dipole components are negligible at those sites, the long wavelength component, viz., the equatorial dipole component, in the background becomes dominant at those sites. If we add both contributions, we end up with Figure 4(b), which is not necessarily dominated by the equatorial dipole alone. Rather, it looks similar to the non-dipole distribution in Figure 4(d).

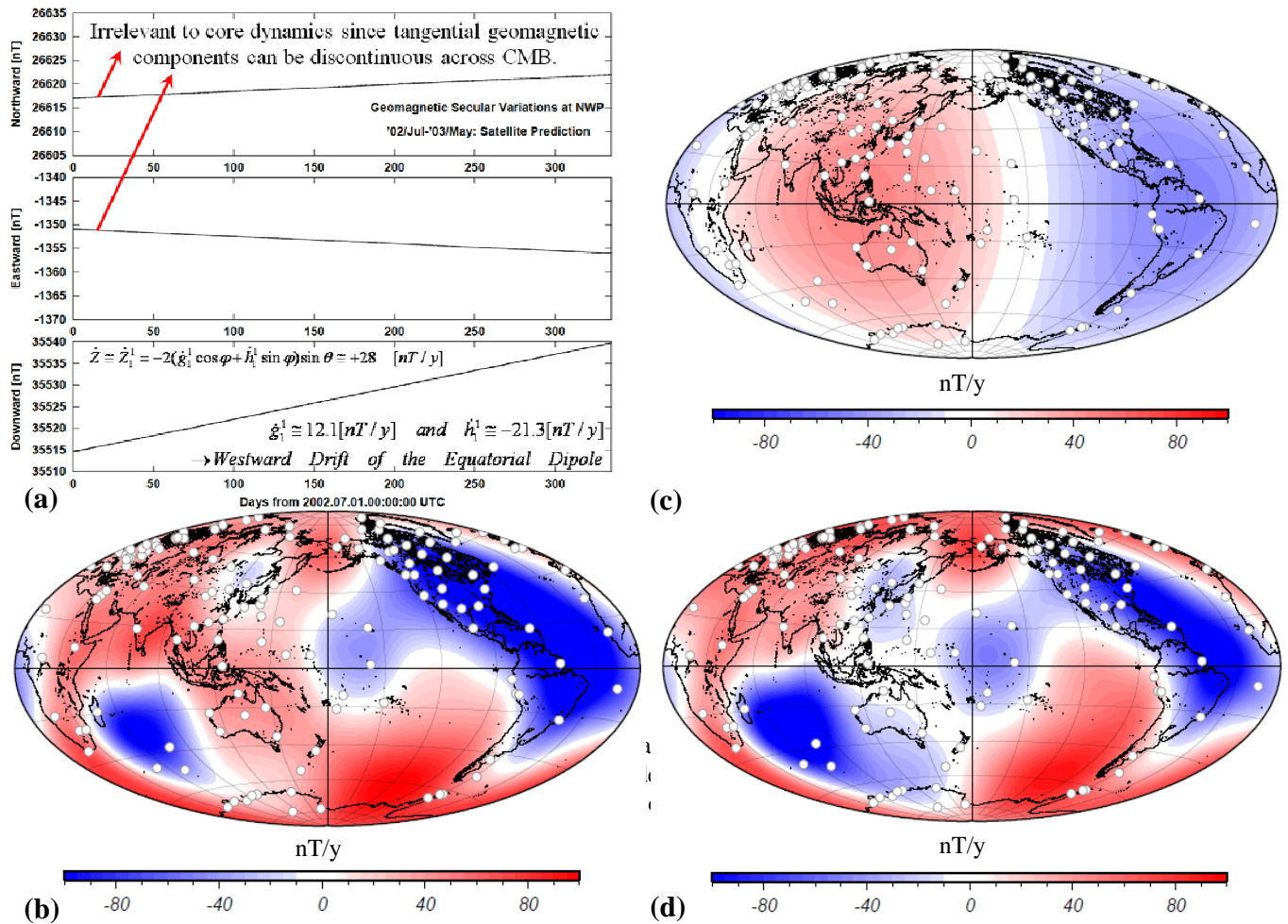


Figure 4. (a) Interpretation of the vector geomagnetic secular variations observed at the NWP by the westward drift of the equatorial dipole. (b) Global distribution of the geomagnetic secular variations for the vertical component including all the spherical harmonic degrees up to 8. (c) That of the equatorial dipole components alone (\dot{g}_1^1 and \dot{h}_1^1) and (d) non-dipole components alone (degree>1). Open circles indicate locations of geomagnetic observatories.

6 DISCUSSION

It is curious that most of the null non-dipole regions in Figure 4(d) seem to collocate with the preferred paths of the virtual geomagnetic poles (VGP) at the time of geomagnetic reversals (Laj et al., 1991). Runcorn (1992) advocated that a high conductive zone at the base of the mantle beneath the Pacific Ocean can produce such preferred paths by a repulsive force between eddy currents in the high conductive zone and the travelling geomagnetic poles. However, these arguments still remain speculative without reliable evidence based on solid observation. It is also worth noting that the distribution of the null non-dipole paths resembles that of the high conductivity anomalies beneath the Circum-Pacific Belt (Kelbert et al., 2008). However, the origin and/or mechanism of these anomalies and the preferred paths can be totally different because many of the anomalies were found at a depth of 660 km seismic discontinuity except beneath the Andes. If the 660 km anomalies are relevant to so-called stagnant slabs (Fukao et al., 2009), it is natural that the anomalies are absent beneath the Andes where the subducted plates are penetrating into the lower mantle without stagnation at the 660 km discontinuity. Furthermore, it may not be strange that we find

a spatial correlation between the conductivity anomalies and the preferred paths if the stagnant slabs and the high conductive zone at the bottom of the mantle are related through dynamics in the lower mantle. What is evident here is that the spatial distribution of the null non-dipole paths found in the western boundary of the Pacific Ocean cannot be explained by just one cause.

Results using the observed geoelectric data have not been included in this study. However, the long enough geoelectric time-series at the NWP together with the simultaneous vector geomagnetic data can resolve the electrical conductivity structure of the mantle deeper than 660 km by applying magnetotellurics. To what extent the mantle is wet is an important issue because the water content in the mantle can govern its viscosity, seismic velocity, and electrical conductivity. Recently, there has been a hot debate over how effectively water can enhance the electrical conductivity of mantle minerals. Experimental results with realistic mantle conditions have provided opposing views in terms of the effect of water on the major mantle minerals, such as olivine (Yoshino et al., 2006; Wang et al., 2006), wadsleyite, and ringwoodite (Yoshino et al., 2008; Huang et al., 2005). While Yoshino and others reported less effect from water in both the upper mantle and the mantle transition zone depths, Karato and coworkers claimed a larger effect of water. It will thus be very crucial to determine the reliable electrical conductivity profile in the mantle by field works in order to estimate the actual water content in the oceanic mantle. Because the mantle minerals in the transition zone (i.e., wadsleyite and ringwoodite) are known to have high potential to contain as much as ~3 wt% water (e.g., Inoue et al., 1995), the actual water content in the mantle transition zone is the key parameter to test the Bercovici and Karato's (2003) water filter hypothesis that is strongly dependent on of the order of magnitude difference in the potential for water storage of each mantle mineral in the transition zone and the upper mantle. Magnetotelluric sounding at the NWP and/or WPB will have high priority in our future study, in the sense that the two sites can sample different parts of the oceanic mantle, one (WPB) under the influence of a significant amount of possible water release from the stagnant slabs and the other (NWP) free from the effect of the stagnant slabs.

Even though the present version of the SFEMSs is satisfactory in terms of long-term EM data acquisition in remote regions with significant logistical difficulties, it still needs additional improvements. Reinforcement of their acoustic capability is one of the urgent tasks to be accomplished. Presently, replacement of the SFEMSs is carried out by installing a new SFEMS close to the former one with the aid of submersibles. This inevitably results in undesired changes in the position of the seafloor observation site. In addition, the present procedure needs in-situ calibration of the two SFEMSs using the simultaneous records on the seafloor. It, therefore, is desirable to establish an acoustic and power supply port deployed a few tens of meters away from each SFEMS. The submersibles will access the port alone at the time of maintenance when battery packs are replaced by the submersibles, leaving the SFEMSs untouched. The in-situ calibration will also be conducted at the same time using the acoustic modems attached to the maintenance ports at the seafloor and their counterparts brought down by the submersibles. Real-time connection to the submersibles' tender ship is made possible by wiring the output from the acoustic modems to the submersibles' serial ports.

7 CONCLUSIONS

Vector geomagnetic secular variations can now be observed even on the deep seafloor. The long-term geomagnetic observation by the SFEMS in the Northwest Pacific Basin has revealed that the secular variations of the vertical geomagnetic component are dominated by the westward drift of the equatorial dipole. This is because the non-dipole contribution to the geomagnetic secular variations is almost nil there. The relation of the non-dipole low to the electrical conductivity anomalies at 660 km discontinuity beneath the Circum-Pacific Belt and at the base of the mantle beneath the Pacific Ocean was argued. A combination of the SFEMSs at the NWP and at the WPB may reveal regional-scale dynamics in the Earth's liquid core although the cause and mechanism of the non-dipole low and its relation to the proposed conductivity anomalies are still not understood well.

The electrical conductivity profile beneath each SFEMS, an important research topic, requires thorough future study. The profile will be able to address the on going arguments among experimentalists in mineral physics on the water content in the mantle. Bercovici and Karato's (2003) water filter is the only available hypothesis that can solve the long-lasting contradiction of the geochemically layered but geophysically mixed view of the whole mantle. This hypothesis needs to be tested by direct and long-term observations on the deep seafloor. Here, the combination of the SFEMSs at the NWP and WPB is also essential in studying the effect of the stagnant slabs. Comparison of the

EM data from the stagnant slab-free site (i.e., NWP) and that from the WPB may elucidate the effect of water on the mantle electrical conductivity released from the stagnant slabs.

Further instrumental improvements are still required for the present version of the SFEMSs. Addition of an acoustic and power port for each SFEMS makes it semi-permanently fixed to the same position on the seafloor. This enables the in-situ calibration of the SFEMSs as well. The advent of unmanned submersibles capable of elaborate tasks on the seafloor makes the improvement now quite feasible.

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