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Magnetic anomaly caused by soil excavation and its long-term stability: Case study of a magnetic anomaly in the absolute observation house at Kanoya Magnetic Observatory

by

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Abstract

A newly designed absolute observation house was built in 1995 at the Kanoya Magnetic Observatory. In June 1995, two months after completion, we conducted a magnetic survey inside the house with a proton precession magnetometer. We found a relatively high-amplitude magnetic anomaly of about 20 nT at 1. 5 m above floor level, spread over the entire house. Because there was no such magnetic anomaly before construction, the magnetic anomaly was evidently caused by the construction of the absolute observation house.

We assumed that the magnetic anomaly resulted from the excavation and backfilling of soil necessary for installing pillars to support measurement instruments. To confirm this assumption, we used a model based on the shape of the excavated section of ground to calculate the magnetic anomaly that would arise upper the area of excavated ground. The results of the calculation based on this model agreed well with the observed anomaly. We also used the model to estimate the distributions of three components of the magnetic anomaly inside the absolute observation house.

Almost 10 years after the first survey, in August 2004 and March 2005, we conducted second and third surveys to check the magnetic anomaly inside the absolute observation house. The profiles of the magnetic anomaly found during those surveys was almost the same as that found in the first survey. This fact suggests that the magnetization of the excavated and backfilled soil has remained stable for almost 10 years, and we expect that the magnetic anomaly caused by the excavated soil will pose no serious problems for secular magnetic observation.

1. Introduction

In order to maintain the accuracy of geomagnetic observations, it is essential to keep the quality of the electromagnetic environment permanently around the observation site. Artificial noise from DC-powered electric railcars and automobiles pose significant threats to geomagnetic observatories. Natural noise, which is caused by changes in topography or soil magnetization in the vicinity of an observatory, also interferes with observation.

Topographic change near an observation site often makes a noise, especially in volcanic regions which are often observed on slopes. An overseas observatory once reported that their observations were affected by rats digging underneath the floor of the absolute observation house. This is another example of noise generated by a topographic change. With respect to changes in soil magnetization, anomalous change due to lightning strikes has been reported (Utada and Koyama 1982; Yamazaki et al. 2003). When lightning strikes the ground, the soil acquires isothermal remanent magnetization (IRM) through the effect of the momentary strong magnetic field which is created by the heavy current from the bolt of lightning; IRM then results in stepwise changes in the geomagnetic field in the surrounding area. Because the acquired IRM is not so stable over time, it is known to have the troublesome characteristic of causing anomalous fluctuations in the sense of the stepwise changes dissipating over several years. There have also been reports that geomagnetic field changes with the thermal fluctuations at normal temperatures, and seasonal temperature changes result in the demagnetization or magnetization of soil and which, although small, causes annual variations in the geomagnetic field (Ojima et al., 1996; Utada et al., 2000). Although there has been little discussion from the point of view of rock magnetism, there also appears to be geomagnetic variations due to the alteration of magnetic minerals or changes in the unstable IRM or viscous remanent magnetization (VRM) over time.

We have experienced several times unexplainable fluctuations of several nT in the differences of total magnetic intensity between observation points. Similar fluctuations in the differences between observation points have been reported recently by the Yatsugatake Geoelectromagnetic Observatory (Ogawa and Koyama 2007, 2009). This may be a fairly common occurrence at geomagnetic observatories, although rarely reported. Even though the causes of such fluctuations in the differences between observation points are often left unaddressed, one of them may be caused by changes in unstable soil magnetization.

Anomalous fluctuations occurring in the differences between observation points in an absolute observation house, which is designed to carry out accurate observation of secular variations in Earth's magnetic fields, will be a significant obstacle to quality of the observation. In order to prevent it, an absolute observation point is designed to have an elevated floor which keeps the magnetometer as far as possible from the ground, and it is constructed at a point where the magnetic profile is as even as possible. The ground, however, needs to be excavated to a certain depth in order to install stable pillars for the instruments, and the excavation work itself generates a magnetic anomaly. Absolute geomagnetic observations are carried out on the assumption that the magnetic anomaly created by the excavation of the ground will remain unchanged over time. In fact, however, we have yet to understand whether or not the remanent magnetization of the backfill soil will remain so over a long period of time. In order to address this issue, Yamazaki (1997) and Yamazaki et al. (2008) surveyed the magnetic profile inside the absolute observation house at the Kanoya Magnetic Observatory in order to investigate the magnetic anomaly created by the soil excavation and its secular change. In this report, we supplement the findings of Yamazaki et al. (2008) and explain the phenomenon in more detail.

2. Magnetic anomaly due to soil excavation

Fig. 1 is a schematic diagram of the magnetic anomaly caused by soil excavation and backfill. In general, soil has magnetism because of the magnetic minerals in it. This magnetism usually aligns with the direction of Earth's magnetic field. If the ground is flat and uniformly magnetized, as illustrated in Fig. 1, the magnetic field is uniformly distributed on the surface. When the ground is excavated, however, a magnetic anomaly occurs. When the excavated ground is backfilled with the original soil, the direction of the remanent magnetization in the backfilled soil becomes randomized, and the soil becomes demagnetized overall. Accordingly, the magnetic anomaly, which is caused by remanent magnetization, is not eliminated by backfilling. With respect to induced magnetization, on the other hand, backfilling generally restores the original magnetization, and the magnetic anomaly created by the induced magnetization is

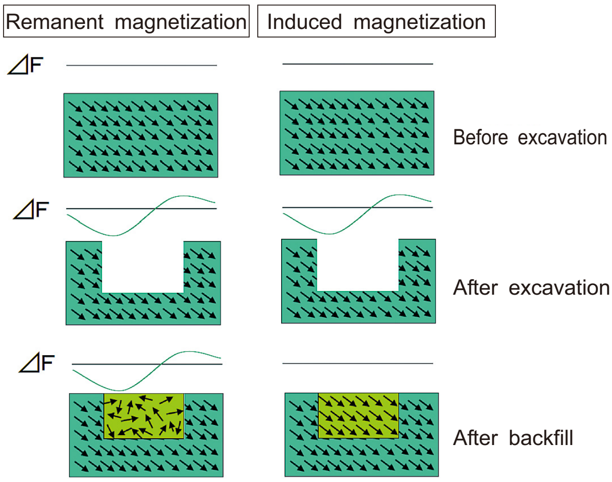


Fig. 1 Schematic diagram of the formation of magnetic anomaly due to excavation and backfill of soil.
Left: Remanent magnetization;
Right: Induced magnetization.
ΔF: Visualization of anomalous total magnetic intensity observed immediately above the excavation area.

Fig. 2 (a) Exterior of the absolute observation house at Kanoya Magnetic Observatory
(b) Interior of the absolute observation house
Looking east from the west side of the house. The instrument pillar at the center is the absolute observation point equipped with an FT-type magnetometer to measure the declination and inclination. Sensors for the proton precession magnetometer are installed on the east and west pillars. The sensor on the west side (94B) is used to measure total magnetic intensity for the absolute observation.

believed to be eliminated as a result.

What is important to geomagnetic observation is whether or not the remanent magnetization of the soil demagnetized by backfilling will remain stable over time. If the backfilled soil directly beneath the absolute observation house is slowly magnetized in the direction of the earth's magnetic field, the observation of secular magnetic variations will be adversely affected.

3. Profile of total magnetic intensity inside and around the absolute observation house at Kanoya

The new absolute observation house at the Kanoya Magnetic Observatory was built in 1995. The structure is constructed of wood with copper sheet roofing. Three pillars for the instruments installed at the center of the house are made of non-magnetic granite, with the center pillar acting as the absolute observation to measure the declination and inclination using a fluxgate theodolite magnetometer. The east and west pillars mount sensors for a proton precession magnetometer, with the one on the west side used to measure the total magnetic intensity for the absolute observation (Fig. 2).

In June 1995, two months after completion of the absolute observation house, we surveyed the total magnetic intensity profile inside the house with a portable proton precession magnetometer. The measurements were taken at grid points spaced 1-m apart at 1.5 m and 2.2 m above floor height (2.5 m and 3.2 m above the ground) (Fig. 3). The reference point for the survey was the total magnetic intensity continuous observation point (80F) located 110 m northwest of the absolute observation house. The results of the survey indicated the presence of a relatively large magnetic anomaly over the entire house. The profile indicated that the total magnetic intensity in the absolute observation house increased in the northerly direction, and the gradient was the steepest at the center of the house. The difference between the north and south ends of the house was about 20 nT measured at 1.5 m above the floor. Since the magnetic anomaly measured at 2.2 m above the floor was about 30% less overall compared with the results obtained at 1.5 m above the floor, the source of the anomaly was indicated to be in the ground underneath the absolute observation house.

Fig. 4 shows the results of the total magnetic intensity survey around the absolute observation house carried out before and after construction. The measurements were taken at grid points spaced 5 m apart, with the sensor positioned 2.5 m above the ground surface (Ookawa et al., 1996). The reference point for the total magnetic intensity in that survey was also 80F. As seen from the total magnetic intensity profile of the site before construction of the absolute observation house (Fig. 4a), the gradient of the total magnetic intensity was around 0.5 nT/m (at 2.5 m above

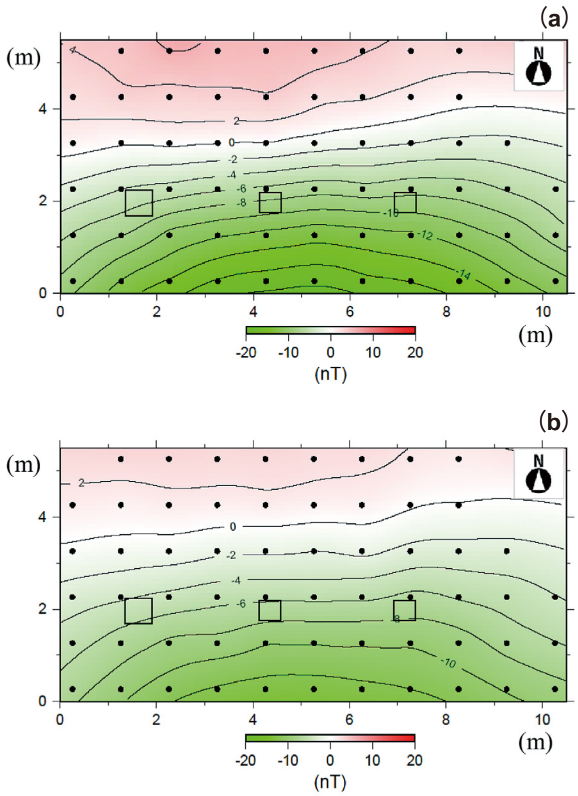


Fig. 3 Profile of the total magnetic intensity in the absolute observation house at Kanoya.
The total magnetic intensity continuous observation point at Kanoya (80F) was used as a reference point. Black dots indicate magnetic survey points on a grid spaced at 1 m. The three squares in the center of the diagram represent the pillars for the instruments. The contour interval is 2 nT.
Panel (a): Measurements taken at 1.5 m above the floor (2.5 m above the ground surface); Panel (b): Measurements taken at 2.2 m above the floor (3.2 m above the ground surface).

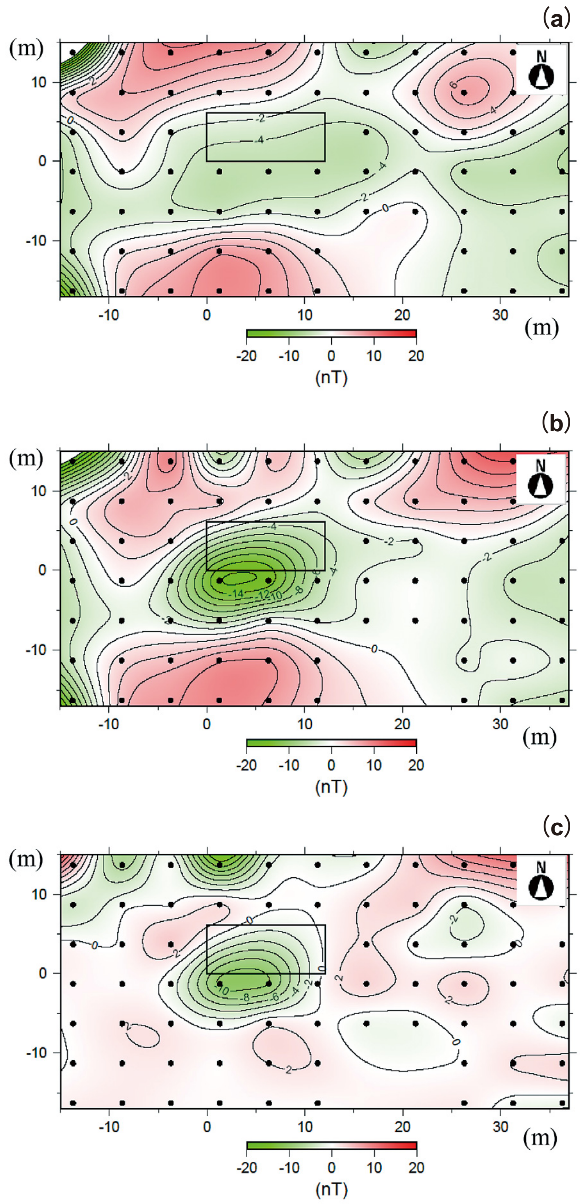


Fig. 4 Profiles of the total magnetic intensity around the absolute observation house (Ookawa et al., 1996).
Black dots indicate magnetic survey points on a grid spaced at 5 m. The area marked by the rectangle in the center represents the location of the absolute observation house. Measurements were taken 2.5 m above the ground surface. The contour interval is 2 nT.
Panel (a): Before construction of the absolute observation house; Panel (b) After construction; Panel (c): Difference in total magnetic intensity before and after the construction (post-construction-pre-construction).

the ground surface), gradually increasing in the northward direction. The definite formation of a negative anomaly in the total magnetic intensity after completion of the absolute observation house clearly points to the effect of construction.

The profile of total magnetic intensity in the absolute observation house (Fig. 3) is a result of the overlap between the post-construction magnetic anomaly and the original magnetic profile. Removing the original magnetic profile will more accurately reflect the magnetic profile inside the absolute observation house created by its construction. The total magnetic intensity profile in Fig. 4 is the result of measurements taken at 2.5 m above the ground surface, which is convenient because it corresponds with the height of the profile in Fig. 3a which was measured at 1.5 m above the floor (i.e. 2.5 m above the ground surface). The correction was made by determining a correction value for each of the measurement points in Fig. 3a by applying an appropriate curved surface to the magnetic profile in Fig. 4a. The magnetic profile at 1.5 m above the floor inside the absolute observation house after the correction by this method is presented in Fig. 5. Although there is not a great difference compared to Fig. 3a, it can be seen that the gradient of the total magnetic intensity is not as steep on the north side of the absolute observation house.

4. Excavated area and magnetic anomaly caused by the excavation

As stated in the previous section, we found that a magnetic anomaly was present in the absolute observation house at Kanoya Magnetic Observatory and that it was created by the construction of the absolute observation house. Since the absolute observation house is basically constructed of non-magnetic materials, this magnetic anomaly is believed to have been caused by the excavation of soil to install the pillars for the instruments. In order to confirm this, we analyzed the magnetic anomaly caused by the soil excavation and compared the results with those of the observation.

During construction of the absolute observation house, for installation of the three pillars, the ground was excavated over an area 2 m wide north-to-south and 10 m long east-to-west to a depth of 2 m (Fig. 6). After the pillars were installed, the area was backfilled with soil dug out

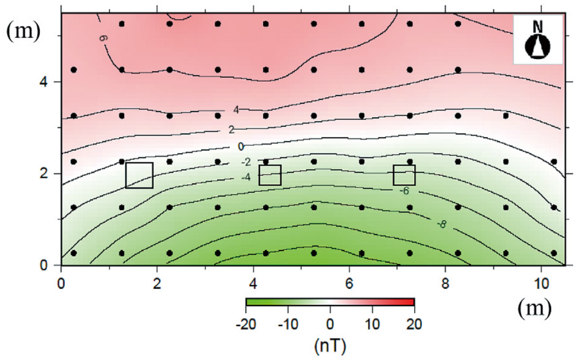
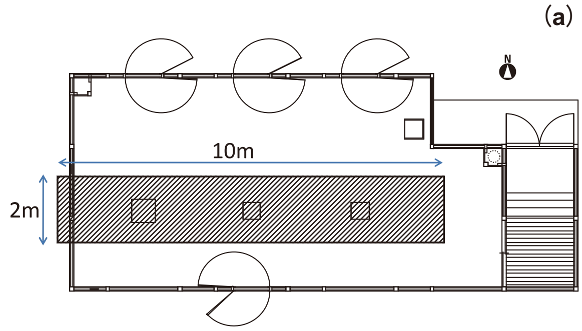


Fig. 5 Profile of the total magnetic intensity in the absolute observation house at 1.5 m above the floor after subtracting the pre-construction profile.

(a)



(b)

Fig. 6 (a) Area of ground excavated for installation of pillars of the absolute observation house (shaded area). Excavated to a depth of 2.0 m. (b) Photo: Installation of the pillars; Looking west from the east end.

during excavation. Assuming that the magnetic anomaly detected inside the absolute observation house was caused by the dissipation of the remanent magnetization in the excavated soil, we calculated the magnetic anomaly that would occur according to the shape of the excavated area. We calculated the magnetic anomaly by using an analytic solution of the magnetic field formed by a rectangular prism (Nakatsuka 1998). The direction of dissipated remanent magnetization was assumed to be the same as that of the current magnetic field of the earth. The magnitude of the remanent magnetization used, 0.23 A/m, was estimated to most closely match that of the observed value. Although the corrected total magnetic intensity profile (Fig. 5) was used as the observed value, the use of 80F as the reference point posed the problem of offsetting the magnetic field in order to compare it with the calculation results. Accordingly, taking into consideration the fact that the magnetic anomaly was caused by the excavation of soil underneath the central part of the absolute observation house, the offset was made by subtracting the average total magnetic intensity over the entire absolute observation house. The zero line of the total magnetic intensity profile for the observed value and the calculated value agreed, which validated the subtraction of this average value. The profile of the total magnetic intensity at 1.5 m above the floor produced by the excavation model is shown in Fig. 7a, and the difference from the observed value presented in Fig. 5 is shown in Fig. 7b. The observed value agrees well with the magnetic anomaly produced by the excavation model, proving the cause of the magnetic anomaly inside the absolute observation house to be the excavation of soil.

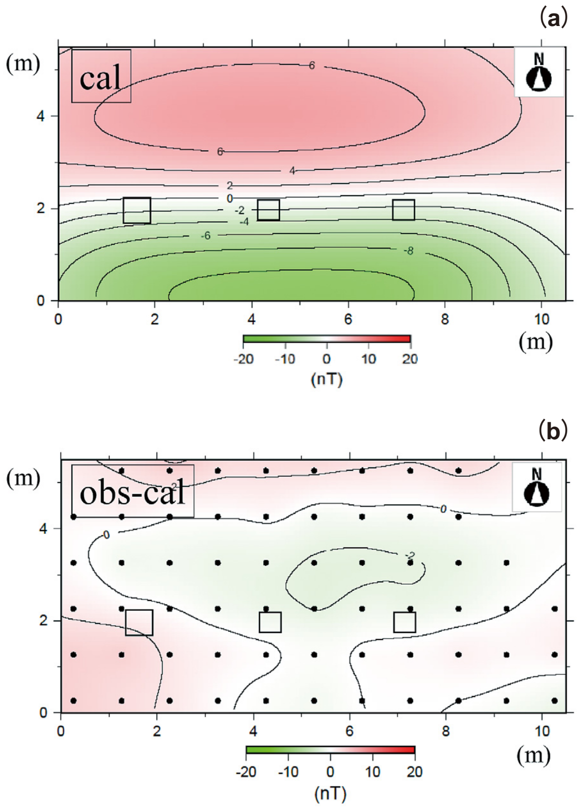


Fig. 7 (a) Total magnetic intensity profile calculated from the shape of the soil excavation area presented in Fig. 6.
Here the height is 1.5 m above floor level. The calculation assumed a magnetization of 0.23 A/m.
(b) Difference between the observed value shown in Fig. 5 and the calculated value (observed value) − (calculated value).

Fig. 8 shows the anomaly in three geomagnetic components as estimated by the excavation model for the height of 1.5 m above floor level. The Y component is set to be positive and facing east. Although it is difficult to measure the profiles of the three geomagnetic components in the absolute observation house, they are assumed to generally represent the magnetic anomaly of the three components in the absolute observation house. Although the effect of the excavation on the value of the total magnetic intensity was not very large (about 2 to 3 nT) at the points immediately above the pillars, the effect was estimated to be as much as 10 nT for the X and Z components.

5. Secular changes in differences between total magnetic intensity observation points

In order to investigate how the total magnetic intensity inside the absolute observation house changes over time relative to nearby observation points, we examined the secular changes in the differences in total magnetic intensity. The total magnetic intensity data from the Kanoya premises (80F in Fig. 9) and the data from the remote comparative observation point at Haraigawa (HRG), located 4 km northwest of Kanoya, were used in our investigation. Fig. 10 represents monthly averages of the differences in total magnetic intensity from 1995 to 2004. The data marked 94B and 94A in the Figure are from the proton precession magnetometer installed on the western and eastern pillars (respectively) of the absolute observation house (see Fig. 2b). It should be noted that data was collected at 94B only until 2000.

An examination of the differences in total magnetic intensity from the HRG observation point indicates that the difference between 94A and the HRG decreased by around 2nT over eight years. As a similar trend is obvious between 94B and the HRG, similar secular changes are likely to have occurred at 94A and 94B inside the absolute observation house. With respect to the differences from 80F, a stepwise increase of around +2 nT was noticeable in 1999 and again in 2001 as a result of the construction of a Japan Agriculture Co-

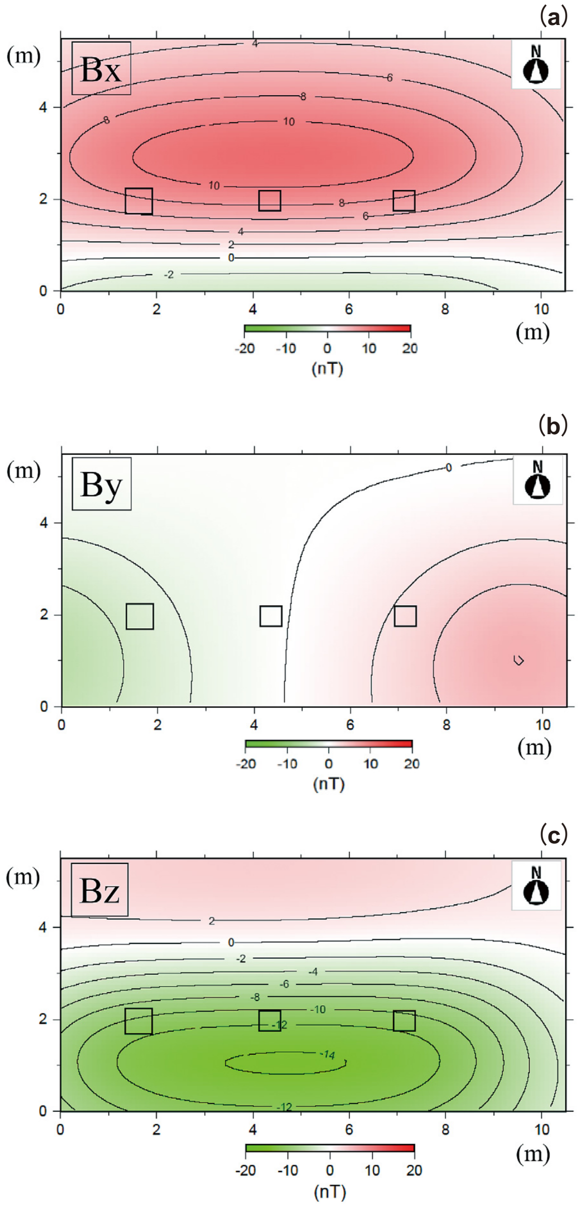


Fig. 8 Profiles of three components of magnetic field in the absolute observation house at 1.5 m above the floor as estimated by the excavation model
The contour interval is 2 nT. Panel (a): X component; Panel (b): Y component (facing east, positive); Panel (c): Z component.

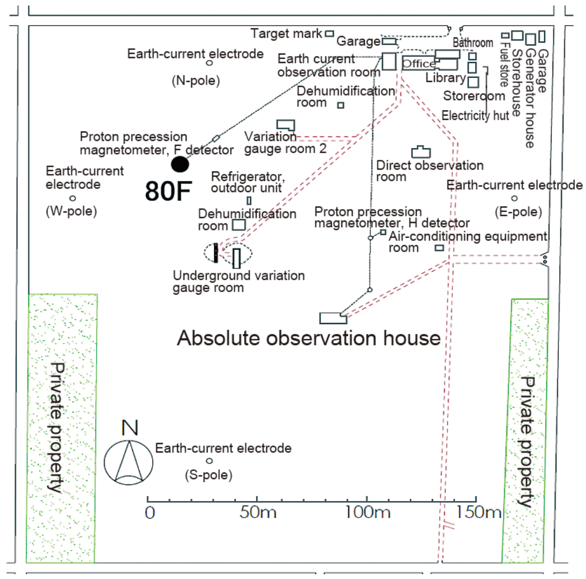


Fig. 9 Site plan of Kanoya Magnetic Observatory
The point marked 80F is the total magnetic intensity continuous observation point at Kanoya.

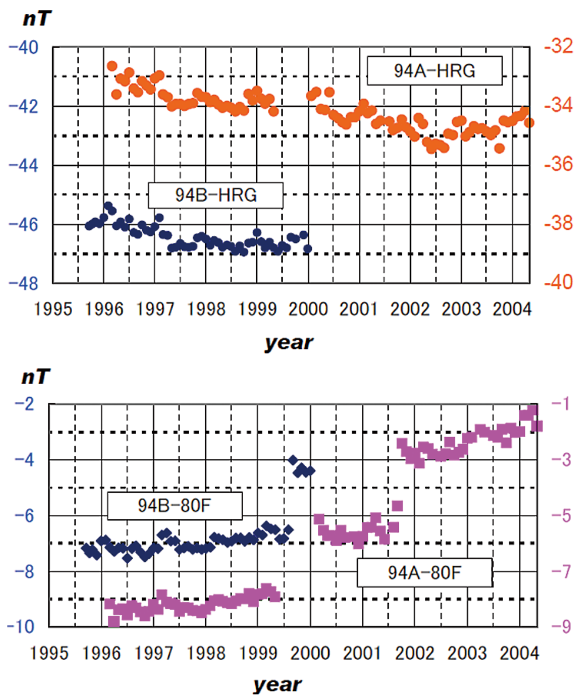


Fig.10 Changes over time in differences between the total magnetic intensity observation points 94A and 94B (in the absolute observation house), 80F and HRG.
The remote comparative observatory at Haraigawa (HRG) is located 4 km northwest of Kanoya Magnetic Observatory.

operative (JA) facility adjacent to the west side of the Kanoya premises affecting 80F. If this effect is removed, the difference between 94A and 80F increased by 2 nT over eight years, indicating a reverse sense of the 94A-HRG difference. Although the cause of these fluctuations in the differences in total magnetic intensity between observation points is yet to be fully understood, it is possible that secular changes in the total magnetic intensity at the HRG observation point follow a somewhat different pattern from those at Kanoya located 4 km away. On the other hand, it is also possible that the 80F observation point is still being slowly affected by the JA facility even after removal of the stepwise changes. Although we may conclude that the secular change in the magnetic field in the absolute observation house has stabilized to within around 2 nT over eight years, we cannot discuss the stability beyond this point from the data of the differences of the total magnetic intensity.

6. Re-survey of the total magnetic intensity profile in the absolute observation house

As we learned of the presence of the magnetic anomaly in the absolute observation house caused by the excavation of soil, we needed to check the stability of this anomaly over time. If the anomaly remains stable over a period of time, it will not interfere with the observation of secular variations. If, however, the backfilled soil becomes magnetized over time in the direction of the earth's magnetic field, the anomaly in the absolute observation house will gradually diminish, which will prevent accurate observation of secular geomagnetic variations.

Consequently, we decided to carry out a re-survey in August 2004, nine years after construction, in order to detect any changes in the magnetic anomaly in the absolute observation house. The reproduction of the original survey points was considered accurate because the grid points had been marked on the floor. The magnetic gradient on the survey plane inside the absolute observation house was around 5 nT/m at maximum for both the horizontal and perpendicular directions. Accordingly, even if there is a 1-cm shift in the survey points, the effect of such a shift will be 0.05 nT at most, and the overall accuracy of the re-survey is likely to be within the range of 0.2 to 0.3 nT after taking into consideration the position of the survey points and the peculiar differences between the proton precession magnetometers.

As a result of the re-survey, we confirmed that the profile of the magnetic anomaly had remained nearly unchanged and the remanent magnetization of the backfill soil had been stable. A closer look, however, indicated that the total magnetic intensity tended to increase on the south side and slightly decrease on the north side of the absolute observation house. As this sense pointed to a general decrease in the anomaly in the absolute observation house, it was possible that the magnetic anomaly was gradually decreasing over time. Subsequently, we carried out a third survey in March 2005 for the purpose of re-confirming this minute change, and found that the results of the third survey were more similar to the first survey than the second survey with no detection of the pattern of the changes which had been found by the second survey.

Fig. 11 shows the position of three north-south survey lines (B, E and H) in the absolute observation house. The total magnetic intensity measured at 1.5 m and 2.2 m above the floor are show in Figs. 12 and 13 respectively. Black, red, and blue lines in the graphs represent the results of the first survey (June 1995), the second survey (August 2004) and the third survey (March 2005), respectively. The observation point 80F was used as the reference point; however, as explained in the previous section, the values were calculated by determining the total intensity referencing 80F

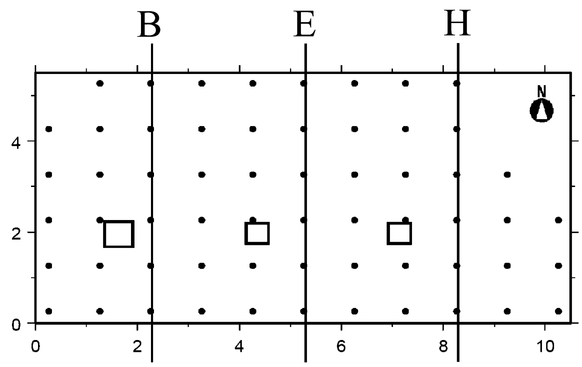


Fig.11 Locations of the three north-south survey lines (B, E, H) in the absolute observation house referred to in Fig. 12 and 13.

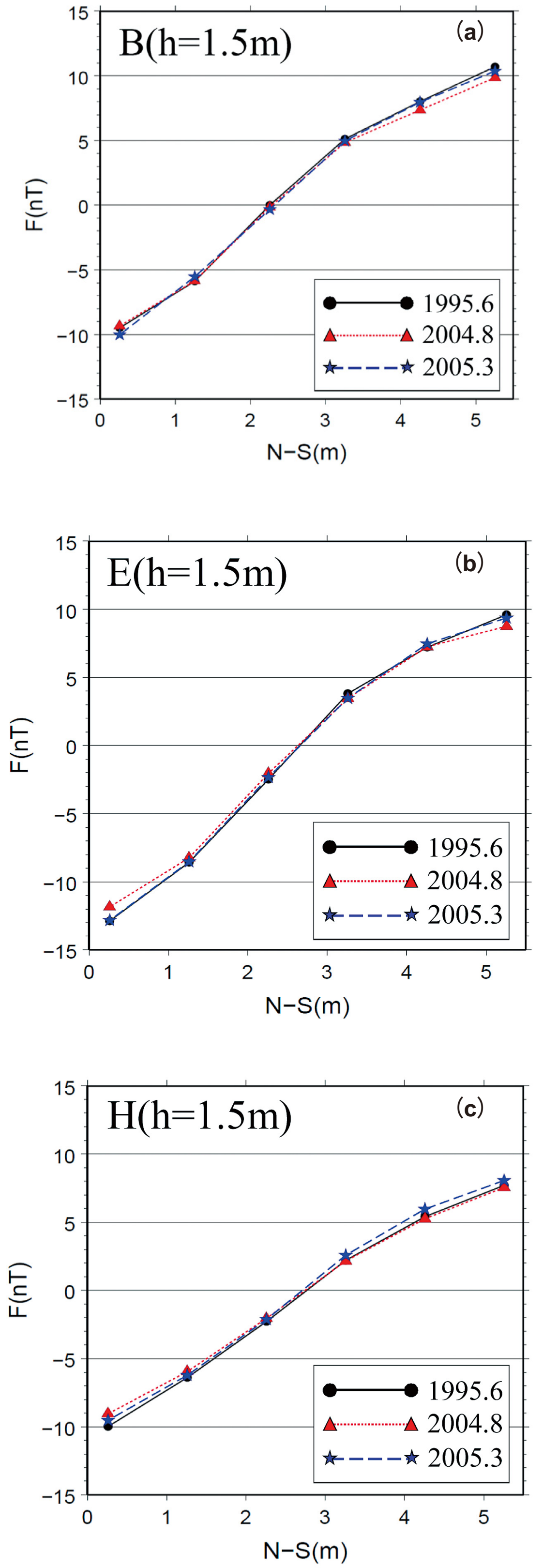


Fig.12 Total magnetic intensity measured in the absolute observation house along the north-south survey lines at 1.5 m above the floor. Black, red, and blue lines represent the first survey (June 1995), the second survey (August 2004), and the third survey (March 2005), respectively. Panels (a), (b), and (c) show measurements along survey lines B, E, and H, respectively.

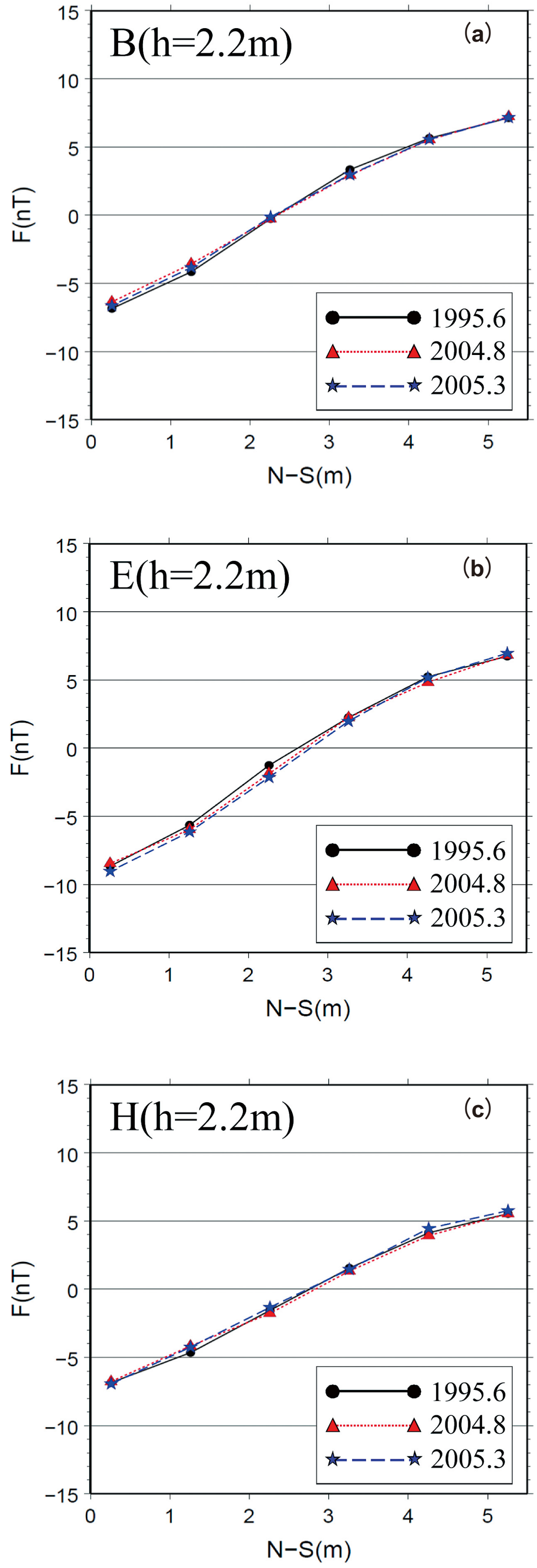


Fig.13 Total magnetic intensity measured in the absolute observation house along the north-south survey lines at 2. 2 m above the floor. Black, red, and blue lines represent the first survey (June 1995), the second survey (August 2004), and the third survey (March 2005), respectively. Panels (a), (b), and (c) show measurements along survey lines B, E and H, respectively.

first and then subtracting from the result the average of the total intensity profile in the absolute observation house so as to eliminate the effects of secular changes at both 80F and the absolute observation house. The graphs indicate that the results of the first and third surveys are similar to each other but the second survey results show a certain trend in which the total magnetic intensity measured increased slightly on the south side and decreased slightly on the north side of the absolute observation house on all survey lines. Since this trend was clear in the measurement taken at 1.5 m above the floor but less so in those take at 2.2 m, the source of the fluctuations was believed to exist below the ground surface.

Next, the time change distribution of the differences in total magnetic intensity in the absolute observation house indicated by the first and the second surveys is presented in Fig. 14 and the first and the third surveys in Fig. 15. Figs. 14 and 15 show prominent changes in the east end and the northeast section of the absolute observation house, which are due to the effect of the relocation of nearby magnetized observation instruments. As explained earlier, the results of the second survey generally indicated an increase in the total magnetic intensity on the south side and a decrease on the north side of the absolute observation house in contrast to the results of the first survey. This trend is more obvious at 1.5 m above the floor. On the other hand, the results of the third survey indicated that the differences in the total magnetic intensity compared with the first survey results were generally small at less than 0.5 nT. In addition, there was no north-south bias.

7. Summary and discussion

In this study we investigated the magnetic anomaly and its stability over time in the absolute observation house at the Kanoya Magnetic Obser-

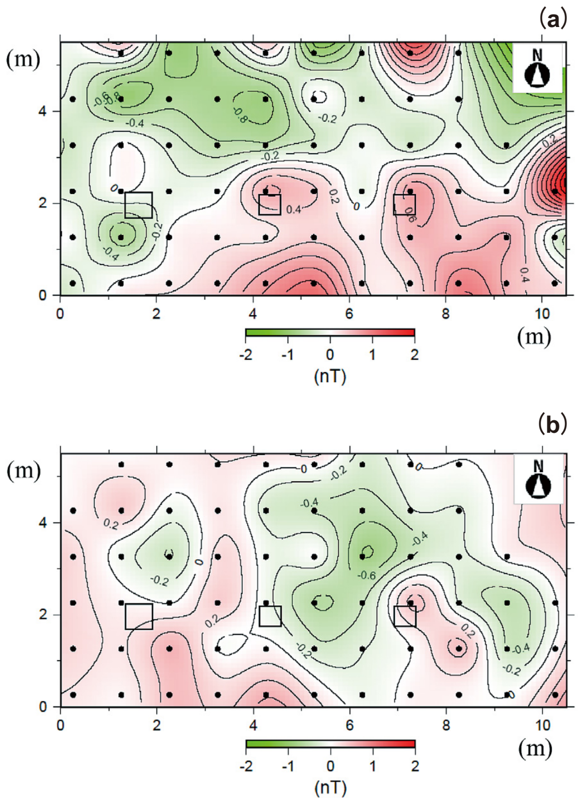


Fig.14 Profile of the differences in the total magnetic intensity in the absolute observation house measured in the first and second surveys (calculated as the second survey results - the first survey results). The contour interval is 0. 2 nT.
Panel (a): Results at 1. 5 m above the floor; Panel (b): Results at 2. 2 m above the floor.

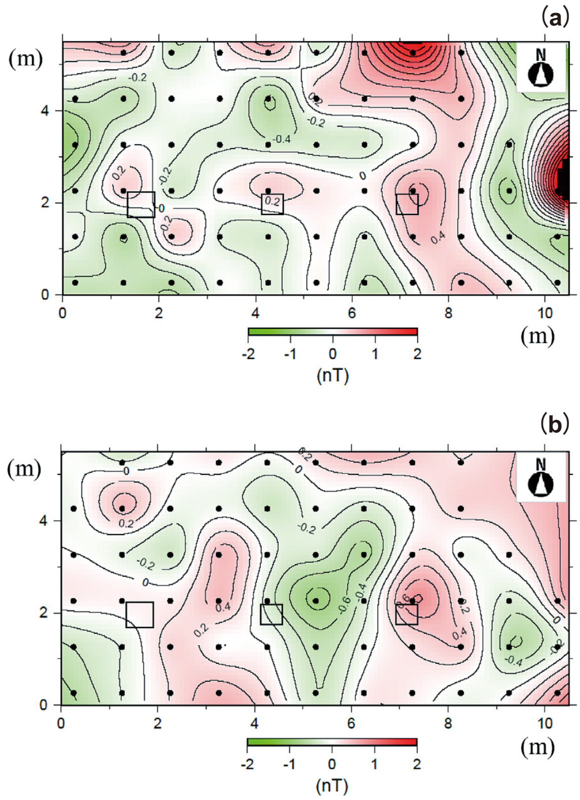


Fig.15 Profile of the differences in the total magnetic intensity in the absolute observation house measured in the first and third surveys (calculated as the third survey results - the first survey results). The contour interval is 0. 2 nT.
Panel (a): Results at 1. 5 m above the floor; Panel (b): Results at 2. 2 m above the floor.

vatory. A survey of the total magnetic intensity inside the absolute observation house after its construction showed a magnetic anomaly of about 20 nT in amplitude over the entire house. Since a survey of the site prior to construction showed no such magnetic anomaly, it was suggested that the magnetic anomaly occurred as a result of the construction of the absolute observation house. Assuming that the magnetic anomaly was caused by the excavation of soil for the installation of the pillars for the instruments, we calculated the anomaly using an excavation model which explained the observation results well, and confirmed that the anomaly was indeed caused by the soil excavation. We also used the excavation model to estimate the magnetic profile of three geomagnetic components inside the absolute observation house.

The second problem was whether the magnetic anomaly created by the soil excavation would remain stable over time. Based on comparisons between the total magnetic intensity inside the absolute observation house and the total magnetic intensity at a continuous observation point on the Kanoya premises as well as at a remote comparative observation point at Haraigawa, we confirmed that during the period from 1995 to 2004 the total magnetic intensity in the absolute observation house had been stable within about 2 nT. Furthermore, we confirmed on the basis of re-surveys in 2004 and 2005 that the magnetic anomaly in the absolute observation house had remained largely unchanged over a period of about 10 years. These findings signified that the soil magnetization which was demagnetized by the excavation and backfill had been stable over time and posed no impediment to the absolute observation activities.

However, we also discovered from the results of the re-surveys that the magnetic profile in the absolute observation house was undergoing subtle changes, although the range of fluctuation was generally within 1 nT. The second survey in particular showed a pattern of changes which increased to the south side and decreased to the north side of the absolute observation house. The results of the third survey, however, did not produce the same results; they were similar to those of the first survey. In other words, the magnetic profile in the absolute observation house was not necessarily changing in the same direction over time; rather it was undergoing subtle changes under the effects of temperature and other factors.

Utada et al. (2000) studied the annual variations frequently detected in the observation of geomagnetic fields at volcanic region and identified temperature changes as a cause of the changes in soil magnetization. The changes in soil magnetization occur because changes in temperature in a near normal range cause slight changes in remanent and induced magnetization in rocks on the ground surface. As a result, seasonal variations in temperature cause annual variations of several nT in amplitude in magnetic fields detected near the surface. Although the magnetic anomaly that occurred in the absolute observation house at the Kanoya Magnetic Observatory was caused by excavation work, the anomaly was brought about by the magnetization of the soil outside the excavated area. It is believed that the anomaly inside the absolute observation house tends to decrease when a slight demagnetization occurs in the surrounding soil with rising temperatures. Since the second survey was carried out in the summer in August, the diminishing of changes in the magnetic anomaly inside the absolute observation house can be explained by assuming that the soil around the absolute observation house was slightly demagnetized at that time. However, due to the insufficiency of the latest survey data to discuss the minute temporal variation in the magnetic anomaly in detail, we can only suggest this possibility.

Our study found that the magnetic anomaly occurring at Kanoya after the excavation and backfill of soil had remained stable over a temporal scale of about 10 years. Nevertheless, the stability of the magnetic field in the absolute observation house is critical to our observations, and the total magnetic intensity in the absolute observation house should be surveyed at least once every several years to detect any changes in the magnetic profile. Furthermore, we are yet to find out whether the stability of the magnetic anomaly caused by soil excavation, as seen in the case of the Kanoya Magnetic Observatory, is applicable to every soil type. At any rate, it is important to take note of the presence of a soil magnetization problem such as this.

Acknowledgements

We would like to express our gratitude to the people who were involved in the construction of the absolute observation house. We also would like to express our appreciation of the tireless work by the people of the Kanoya Magnetic Observatory during the magnetic survey inside as well as the vicinity of the observation house in 1995. We acknowledge that we used the GMT (Wessel and Smith 1995) in the mapping of magnetic profiles.

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