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## Evaluation of a High-resolution Aeromagnetic Survey in a Volcanic Region

### —The Case of Yurihara Area, Northeast Japan

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#### ABSTRACT

Recently high-resolution aeromagnetic surveys have been attracting attention from airborne geophysicists. High-quality aeromagnetic anomaly maps can reveal buried structures such as faults, folds and intrusions along with mineral deposits. To evaluate the ability of a high-resolution aeromagnetic survey for revealing the subsurface structure in a volcanic region we carried out a high-resolution aeromagnetic survey in the Yurihara Plateau, Northeast Japan.

The plateau is widely but thinly covered with magnetic Quaternary debris avalanche deposits from Chokai Volcano south of the plateau. Drilling has shown the existence of Miocene mafic volcanics, named the Aosawa Formation overlain by Miocene sediments such as sand and silt beneath the debris avalanche deposits. The Aosawa Formation can cause apparent magnetic anomalies because of its strong magnetic susceptibility.

A compiled high-resolution aeromagnetic anomaly map shows that magnetic highs correspond to the distribution of the Kisakata Debris Avalanche Deposits (KDAD) in a valley of the southern plateau. A further continuation of the magnetic highs and magnetic models imply the subsurface extension of the KDAD in the plateau. This result shows that a reconstruction of geologic maps is recommended for debris avalanche deposits to assess volcanic hazard in this area. A three-dimensional two-layer model inversion was applied to the residual magnetic anomalies after removing the effect of estimated distribution of magnetic debris avalanche deposits. In general, the resultant lateral distribution of depths to the magnetic basement corresponds well to that of the upper boundary of the Aosawa Formation. The shallow magnetic basement lies around the Yurihara Oil and Gas Field, where a local uplift of the Aosawa Formation exists. However the magnetic basement is much shallower in the western part of the study area than the presumed upper boundary of the formation in a geologic cross-section. The depth differences between the magnetic basement and the presumed upper boundary of the Aosawa Formation might be caused by lateral variations of the magnetic susceptibility or thickness of the Aosawa Formation.

Consequently, our high-resolution aeromagnetic survey reveals that this type of survey is useful for revealing deep subsurface structures as well as shallow magnetic structures, especially when the information on magnetic properties of the causative rocks is available. The new estimates for the extent of Quaternary debris avalanches can be used for determining the volcanic hazards of the region.

Key words: High-resolution Aeromagnetic Survey

#### 1. Introduction

Recently high-resolution aeromagnetic surveys have been attracting attention from airborne geophysicists (HOOD and TESKEY, 1989; HILDEN-BRAND and RAINES, 1990; HOOD, 1990). The developments of both high-resolution magnetometers such as an optical pumping magnetometer

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and high-resolution positioning systems such as a differential Global Positioning System have enabled us to conduct high-resolution aeromagnetic surveys. High-resolution aeromagnetic anomalies are considered to be affected relatively by shallow subsurface structures, because high-resolution aeromagnetic surveys are usually flown at a lower altitude than those of other regional surveys. Besides, those anomalies are considered to contain more detailed information on the subsurface structure because of denser spacing of flight lines.

The Geological Survey of Japan (GSJ) conducted a research project on high-resolution aeromagnetic surveys. There are two objectives in this project. The first objective is to develop highresolution aeromagnetic survey systems that employ an airplane or a helicopter. In the case of a helicopter, a vertical gradiometer survey would be done. The second objective is to develop interpretation techniques suitable for analyzing highresolution aeromagnetic anomalies. We have already performed four aeromagnetic surveys using an airplane and two helicopter-borne surveys.

In 1990, we conducted a high-resolution aeromagnetic survey in the Yurihara Plateau, Northeast Japan (Figure 1). The purpose of this survey is to evaluate the ability of a high-resolution aeromagnetic survey for revealing the subsurface structure in a volcanic region. In addition to intensive geologic surveys, many wells for oil and gas exploration have been drilled in the Yurihara Plateau, so that geologic maps have been compiled. These maps enable us to compare results of magnetic interpretations with the fine geology of this area. Because of this point of view, the Yurihara Plateau was selected as the survey area. After an estimation of positioning errors, we compiled a high-resolution aeromagnetic anomaly map of the Yurihara Plateau and its surroundings (Morijiri et al., 1992). Rock magnetic measurements of samples from the study area were also made to support analyses of the magnetic anomalies.

In this paper, we describe important characteristics of the magnetic anomalies in the study area, with a reference to geologic maps. Then we analyze the magnetic anomalies to make a model of a shallow magnetic structure that corresponds to Quaternary debris avalanche deposits thinly but widely covering the area, and also to make a model of a deep magnetic structure, correspond-



Fig. 1 Topographic map of the Yurihara Plateau and its adjoining areas A rectangle bounded by thick solid line shows the area of aeromagnetic survey conducted by the GSJ in 1990. Contour interval is 100 m. Black dots, A1–A9, C1 and C2, denote sampling sites for rock magnetic measurements. Stars, MRS–1 and MRS–2, represent two slave stations of Microwave Ranging System (MRS).

ing to Miocene volcanics and intrusions underlying Tertiary sediments.

On the basis of the above results, we discuss magnetic properties of the debris avalanche deposits, in particular the relation between magnetic models and geologic structures. Then a high-resolution aeromagnetic survey in a volcanic region will be evaluated.

#### 2. Yurihara Plateau

The Yurihara Plateau is situated 10–20 km north of Chokai Volcano (Figure 1). It is bounded by the north-south trending Nikaho Hill to the west and the Koyoshi River lowland to the east. Chokai Volcano faces the Sea of Japan to the west, and its latest eruption occurred in 1974. The part enclosed with solid lines in Figure 1 shows the area of 1990 aeromagnetic survey. Our aeromagnetic survey covers the Yurihara Plateau and adjoining areas, including offshore areas.

The Yurihara Plateau is widely but thinly covered with the Quaternary Yurihara Debris Avalanche Deposits (YDAD) (OZAWA *et al.*, 1982;



Fig. 2 Simplified regional geologic map of the aeromagnetic survey area and Chokai Volcano, modified from MORIJIRI *et al.*, (1992) (originally from OZAWA *et al.* (1987)). A rectangle bounded by broken lines shows the surbey area.

OZAWA *et al.*, 1987; OZAWA *et al.*, 1988) (Figure 2). Younger Kisakata Debris Avalanche Deposits (KDAD) are distributed in the southern half of the Yurihara Plateau and Kisakata area west of the Nikaho Hill. These debris avalanche deposits comprise chiefly of andesite blocks and volcanic ash and sand. Radiocarbon dating data (OZAWA *et al.*, 1982) show that the latter debris avalanche deposits were formed about 3,000 years ago.

The drilling for hydrocarbon exploration has shown the existence of Miocene mafic volcanics, the Aosawa Formation, overlain by Miocene sediments such as sand and silt beneath the debris avalanche deposits. The Aosawa Formation consists mainly of basalt lava and its pyroclastic rocks, intercalating mudstone and felsic pyroclastic rocks (OZAWA *et al.*, 1988). Recently the first oil and gas deposit was found in the Aosawa Formation. Successive oil exploration is being conducted now. Therefore it is important to know the subsurface distribution of the Aosawa Formation in this area.

#### 3. Aeromagnetic Survey

# 3.1 Previous Regional Aeromagnetic Surveys

In this region, the GSJ and the New Energy and Industrial Technology Development Organization (NEDO) conducted regional aeromagnetic surveys. The GSJ carried out regional aeromagnetic surveys (GSJ, 1972; GSJ, 1978) for hydrocarbon exploration but the surveys were limited mainly to offshore areas. The NEDO conducted a wider aeromagnetic survey for a geothermal assessment in Japan. The latter survey was flown along east-trending flight line spaced approximately 3 km apart at an altitude of 1,370 m (4,500 ft) above sea level (ASL) except for the higher mountainous areas (NEDO, 1982). The observed data were continued upward to 2,440 m (8,000 ft) ASL (Figure 3). Generally, longwavelength magnetic anomalies predominate. A broad magnetic high ranges from the coastline of the Japan Sea to offshore. Another regional ma-



Fig. 3 Total intensity aeromagnetic anomalies (IGRF residuals) surveyed and compiled by the NEDO. The altitude of datum plane is 2,440 m (8,000 ft) ASL. The survey was mostly flown at an altitude of 1,370 m (4,500 ft) ASL with E-W flight lines spaced approximately 2-3 km apart. Contour interval is 10 nT.



Fig. 4 High-resolution total intensity aeromagnetic anomalies (IGRF residuals) surveyed and compiled by the GSJ. Flight altitude was 920 m (3,000 ft) ASL. Contour interval is 10 nT. A rectangle bounded by thick solid line denotes the range of quantitative analysis corresponding to Figs. 9-14. Spined lines indicate survey lines.

### Total Intensity (altitude=2,440 m ASL)



Fig. 5 High-resolution total intensity aeromagnetic anomalies (Fig. 4) on a bird's-eye view map of the topography of study area. Contour interval is 10 nT. The area is 18 km long by 32 km wide.Veritical exaggeration is 5: 1.

getic high lies on the northeastern part of the survey area. A broad magnetic low is centered in the Yurihara Plateau.

#### 3.2 High-resolution Aeromagnetic Survey

In 1990, the GSJ conducted a high-resolution aeromagnetic survey in the Yurihara Plateau, Northeast Japan, employing Cessna 404. The survey was flown with Microwave Ranging System (MRS) navigation along east-west flight lines at an altitude of 920 m (3,000 ft) ASL and spaced approximately 300 m apart (MORIJIRI et al., 1992) (Table 1). We employed the navigation system for positioning with a nominal accuracy of less than  $\pm 1.5$  m within the range of 40 km of the distances from the aircraft to slave stations on the ground. The accuracy of the MRS positioning in this survey was inferred to be around 20 m. We compiled a high-resolution aeromagnetic anomaly map (Figure 4) from the survey data. As compared with magnetic anomalies shown in Figure 3, high-frequency anomalies are obvious in our map shown in Figure 4. Most of them correspond to geologic characteristics of the area, which will be described in detail later in this paper.

Next, we compare the magnetic anomalies with the topography in the survey area. In Figure 5, magnetic anomalies are plotted on a bird's-eye view map of the topography. This map demonstrates relationships between two data sets. Positive magnetic anomalies are distributed above valleys, instead of above ridges, and along the coast and above the area east of the Yurihara Plateau.

Generally, almost all the chracteristics are explained by a geologic map (Figure 6) of the study area. The KDAD are distributed in a valley of the southern part of the Yurihara Plateau, and Kisakata area west of the Nikaho Hill, and correspond to magnetic highs in those areas. In the eastern part, the Yashima Anticlinorium exists in a north-south direction, bounded by the Toritame Faults to the east (Figure 6). Magnetic highs apparently correspond to each anticlinal axis of the Yashima Anticlinorium.

Regional magnetic lows, corresponding to the topographic effect of Chokai Volcano, are distributed at the southern edge of the survey area (Figures 4 and 5). We do not take account of this effect in this paper, because the effect is limited within an area close to the edge and it is also difficult to estimate the amount of the effect at this stage.

(WORIJIRI et al., 1992)				
Period	: July 24–August 2, 1990			
Area	: Yurihara, Akita Prefecture			
Aircraft	: Cessna 404, JA5267			
Line Length	: 1,490 km tatal			
Line Direction	: E-W (traverse line)			
Air Base	: Akita Airport			
Flight Altitude	: 920 m (3,000 ft) ASL			
Navigation	: Visual flight supported by Doppler radar			
Positioning	: Microwave Ranging System (MRS) and video camera			
Magnetic Base Station	: 39°10′02″N, 140°08′03″E			
MRS Remote Stations	: No. 1 39°15′50.5″N, 140°12′18.2″E			
	No. 2 39°21′39.8″N, 140°10′02.3″E			
Equipment On-board	: Proton precession magnetometer, EG & G GeoMetrics G813			
	Data acquisition system, Marubun 821000, 831000, 832000			
	MRS, DECCA DDMU520, SENAR SNCS- 21			
	Doppler radar, SINGER SKK-1000, SKQ-601			
	Barometric altimeter, Marubun 833000			
	Vertical video recording system, Nakanihon Air Service BPV–002, etc.			
On the ground	: Proton precession magnetometer, EG & G GeoMetrics G856A			

# Table 1Specifications of the aeromagnetic survey<br/>in the Yurihara Area, in July 1990<br/>(MORIJIRI et al., 1992)

#### 4. Rock Magnetic Measurement

We collected twenty rock samples from eleven outcrops (Figure 1) by hand. Those samples are from basalt dikes of the Aosawa Formation, Tertiary dolerites that were emplaced in the Aosawa Formation, and Quaternary andesite lavas from Chokai Volcano. Unfortunately, sampling sites were limited to outside the survey area, because no Tertiary volcanic rocks are exposed within it.

Magnetic susceptibility and natural remanent magnetization (NRM) of the specimens were measured using a susceptibility meter (Bison Instruments Model 3101) and a spinner magnetometer (Natsuhara Giken SMM-85), respectively. A mean value of rock magnetism for each sample was calculated from the values of its three specimens. We did not perform any magnetic cleaning, because the main object of this study is to analyze magnetic anomalies in this region.

Table 2 shows the result of the measurements. The direction of NRM for each sample except the andesite lavas from Chokai Volcano is plotted in an equal area net (Figure 7). More than half of all data concentrates within a broken circle in Figure 7. Rock samples whose directions are plotted outside the circle were collected from the areas (A3, A4 and A8 in Figure 1) where the outcrops of the Aosawa Formation and dolerites are bounded sharply by the Aosawa Faults (Figure 2) to the west. The Aosawa Faults are composed of several north-south trending reverse faults (TSUCHIYA, 1989). Thus there is a large possibility that these areas have been rotated, causing a variety of directions of NRM of the rock samples. Because of this, we consider only the eleven data points within the circle. The magnetic susceptibility ranges  $2.0-4.0 \times 10^{-3} \times 4\pi$ (SI) regardless of rock types. On the other hand, NRM intensity is classified into two groups, a lower group of 0.1-0.6 (A/m) and a higher group of 0.9-2.0 (A/m). The lower one corresponds to the basalt dikes, while the higher to the dolerites.

The mean magnetic susceptibility of the samples of the Aosawa Formation and dolerites is  $3.49 \times 10^{-3} \times 4\pi$  (SI). The mean intensity, inclination and declination of NRM of the samples are 0.62 (A/m), 70.0° N and 1.5° W, respectively. The intensity, inclination and declination of the present Earth's magnetic field in the study area are 47,500 nT, 53.0° N and 7.5° W, respectively. Königsberger ratio (Qn ratio) ranges from 0.10 to 0.83 and the mean value is 0.39. This result suggests that remanent magnetization is negligible compared to induced magnetization. The Aosawa Formation is also composed of less magnetic rocks such as both mafic and felsic pyroclastic rocks, and mudstone. This implies that an average magnetic susceptibility of the Aosawa Formation and the dolerites is reduced by those less magnetic rocks.

The mean magnetic susceptibility of the samples of the andesite lavas is  $3.23 \times 10^{-3} \times 4\pi$  (SI). The mean intensity of NRM of the samples is 3.67 (A/m). The inclination and declination of NRM of sample C1–1 are 58.6° N and 11.8° W, respectively. This result shows that the C1–1 is magnetized roughly parallel to the present



Fig. 6 Geologic map of the study area after OZAWA et al. (1982, 1987 and 1988)

Earth's magnetic field. The mean Qn ratio of the samples is 2.49. These results show that we have to take account of the remanent magnetization in addition to the induced magnetization when we analyze magnetic anomalies caused directly by this rock in this area.

#### 5. Magnetic Modeling

We assume that the magnetic structure can be classified into two parts in this area; namely shallow and deep structures (Figure 8).

We employ a combination of surface thin-layer model and shallow horizontal polygon model for shallow structures (Figure 8). In this study, the thin-layer model represents debris avalanche deposits which thinly but widely cover the Yurihara Plateau. The thin-layer model is a synthesis of fine three-dimensional prisms with constant thicknesses and variable top elevations coincident with the ground surface. Magnetic anomalies of this model are synthesized from anomalies caused by each prism (BHATTACHARYYA, 1964). On the other hand, the horizontal polygon model corresponds to the highly magnetic part of those debris avalanche deposits. In this case, magnetic



Fig. 7 Equal area projection of NRM directions of rock samples from the Yurihara Plateau and its adjoining areas

Table 2Rock magnetic measurements of samples from the Yurihara Plateau and its adjoining areaPreceding two digits of sample name correspond to sampling sites shown in Fig. 1.

				1	······		· · · · · · · · · · · · · · · · · · ·
No.	Sample Name	Rock Type	Suscentibility	Natural			
			$\times 10^{-3} \times 4\pi$ (SI)	$\begin{array}{c} Intensity \\ (A/m) \end{array}$	Inclination (degrees)	Declination (degrees)	On Ratio
1	Al-1	Dolerite	3.50	0.96	62.4	22.4	0.58
2	A2-1	Dolerite	3.28	1.29	61.2	6.2	0.83
3	A2-2	Dolerite	3.43	1.29	58.4	-11.4	0.79
4	A3-1	Dolerite	4.59	1.02	-31.1	-70.9	0.47
5	A3-2	Dolerite	4.91	0.24	-30.9	-105.4	0.10
6	A4-1	Dolerite	2.77	0.68	-6.1	-134.7	0.52
7	A4-2	Dolerite	2.73	0.68	-7.7	-153.1	0.52
8	A5-1	Dolerite	2.07	0.46	70.5	-37.8	0.47
9	A5-2	Dolerite	2.49	0.40	73.1	-73.1	0.33
10	A6-1	Basalt Dike	4.81	0.45	59.2	2.2	0.20
11	A6-2	Basalt Dike	4.92	0.42	64.2	-9.3	0.18
12	A7-1	Basalt Dike	4.71	0.48	65.0	14.3	0.22
13	A7-2	Basalt Dike	4.62	0.52	62.2	15.4	0.23
14	A8-2	Basalt Dike	0.988	2.08	18.9	-165.5	4.43
15	A8-3	Basalt Dike	1.02	2.08	19.7	-161.8	4.29
16	A9-1	Basalt Dike	2.31	0.28	89.0	41.2	0.25
17	A9–2	Basalt Dike	2.28	0.27	83.8	43.8	0.25
18	C1-1	Andesite Lava	3.87	2.60	58.6	-11.8	1.41
19	C2–1	Andesite Lava	2.82	4.18	no data	no data	3.12
20	C2–3	Andesite Lava	3.01	4.22	no data	no data	2.95

anomalies are calculated using the formulation presented by TALWANI (1965). Furthermore, a two-layer model inversion (GERARD and DE-BEGLIA, 1975; OKUMA *et al.*, 1989) is applied for analyzing low-pass filtered magnetic anomalies assumed to be caused by the deeply buried Aosawa Formation.

First, we analyzed magnetic anomalies caused by shallow structures. Before the analysis, a second-order polynomial surface was removed from the observed total intensity anomalies to isolate the effect of shallow sources (Figure 9). Next, an apparent magnetization intensity map (Figure 10) was created from the residuals by employing an iterative convergence method (OKU-MA *et al.*, 1994). In this analysis, the magnetic model was assumed to be a thin layer with a thick-

#### **Magnetic Models**



Fig. 8 Schematic configuration of magnetic interpretation models employed in this study



Fig. 9 High-pass filtered aeromagnetic anomalies of the detailed study area
 A second-order polynomial surface was removed from the observed field (Fig. 4). Contour interval is 10 nT. H and L represent high and low magnetic anomalies, respectively.



Fig. 10 Apparent magnetization intensity map of the detailed study area Contour interval is 0.5 A/m. The assumed thickness of the magnetic source is 100 m. The standard deviation of the differences between the high-pass filtered magnetic anomalies (Fig. 9) and the synthetic anomalies is 1.70 (nT). See also the caption of Fig. 9.



Fig. 11 Synthetic magnetic anomalies caused by the surface thin-layer models (L1-L6) and the shallow horizontal polygons (P1-P12)

Parameters used in these models are summarized in Table 3. The areas bounded by broken lines show thin-layer models, while the areas bounded by thick solid lines show horizontal polygons.



Fig. 12 Differences between the high-pass filtered aeromagnetic anomalies (Fig. 9) and the synthetic magnetic anomalies (Fig. 11)
 See also the caption of Fig. 11.

The six polygons enclosed by broken lines in Figure 11 show surface thin-layer models, and those polygons bounded by thick solid lines show horizontal polygon models. The differences between the high-pass filtered aeromagnetic anomalies (Figure 9) and the synthetic magnetic anomalies (Figure 11) are shown in Figure 12. These optimum models were created by trial and error. We employed a common thickness of 100 m for all thin-layer models, because the KDAD, corresponding to the shallow magnetic structure, are inferred to have a maximum thickness of about 100 m (OZAWA *et al.*, 1982).

In the half of the all horizontal polygon models which we employed here, the thickness is 100 m and the magnetic susceptibility contrast is  $3.0-4.0 \times 10^{-3} \times 4\pi$  (SI) (Table 3).

Thin-layer models L3 and L6 correspond to the distribution of the KDAD and their inferred extensions. Thin-layer models L1 and L2 represent the relatively magnetic parts of the KDAD and some volcanics probably from Chokai Volcano. Thin-layer models L4 and L5 and horizontal polygon models P8–P11 represent more magnetic parts of the KDAD. Horizontal polygons P1 and P2 correspond to the KDAD and andesite lavas that underlie the Kotaki Formation in and around a dried lake. Horizontal polygons P3–P7 represent the local magnetic parts of the YDAD. The polygon P12 represents a dike that intruded into the Tertiary sediments.

According to our rock magnetic measurements, the andesite lavas from Chokai Volcano have high NRM. However the remanent magnetization of the andesite blocks does not apparently contribute to magnetic anomalies, because their directions are inferred to be almost random in the debris avalanche deposits. Therefore, we assumed that high-pass filtered magnetic anomalies are caused mainly by magnetic susceptibility of andesite blocks within the Quaternary YDAD and KDAD. However, actual magnetic susceptibilities of some thin-layer models and horizontal polygon models are much larger than the average value of the andesite lava. For example, L5 is  $7.50 \times 10^{-3} \times 4\pi$  (SI) and P11 is  $8.00 \times 10^{-3} \times 4\pi$  (SI) in magnetic susceptibility. We will discuss this problem later in this paper.

Next these synthetic magnetic anomalies, which are inferred to be caused by shallow structures, were removed from the observed total intensity anomalies. Before the next analysis, the residual field was continued 1,000 m upward to 1,920 m ASL to reduce high-frequency noises, and a first-order regional field was also removed.

A three-dimensional two-layer model inversion (GERARD and DEBEGLIA, 1975; OKUMA et al., 1989), in use of pseudogravity and reduction to the pole anomalies, was applied to the residual field. The thickness of the Aosawa Formation is not well known, because only one drill hole cut through the lower boundary of the formation at the eastern edge of the Yurihara Plateau. According to the result of drilling and a geologic interpretation of the area, the formation thickness is thought to be at least 1,500 m in the plateau (OZA-WA et al., 1982.) Therefore, we thought it possible to estimate the depth to the Aosawa Formation, employing a two-layer model inversion. Table 4 shows parameters used for this inversion. As we took account of the effect by less magnetic rocks included in the Aosawa Formation, we employed a magnetic susceptibility of  $2.10 \times 10^{-3}$  $\times 4\pi$  (SI) for the magnetic basement. Figure 13 shows a topographic contour map of the study area. Figure 14 shows a resultant magnetic basement map when the average of absolute differences between the observed and synthetic reduction to the pole anomalies is 2.57 nT. A mean depth of the magnetic basement, 3.54 km (-1.62 km ASL), was calculated from the slope of the radially averaged power spectrum of the reduction to the pole field. Generally, the depth to the magnetic basement fluctuates laterally along an east-west direction. The magnetic basement is shallow at both eastern and western edges of the study area, whereas, it is deep in the most area of the Yurihara Plateau.

Sometimes a cross section map makes it much easier to oversee general features of data than a contour map. Figures 15 and 16 show north-south and east-west cross sections, respectively. Lateral variations of the magnetic basement highly correlate with the general geology of the study area; namely magnetic basement highs correspond to anticlines and an anticlinorium, while magnetic basement lows correspond to syn-

	Induced Magnetization			Rem	anent Magne			
Model No.	Susceptibility contrast	Inclination	Declination	Intensity contrast	Inclination	Declination	Top Depth <sup>*3</sup> (km)	Bottom Depth <sup>*3</sup> (km)
	$\times 10^{-3} \times 4\pi$ (SI)	(degrees)	(degrees)	( <b>A</b> /m)	(degrees)	(degrees)		
L1*1	2.00	53.0	-7.5				*4	*5
L2	2.00	53.0	-7.5				*4	*5
L3	2.00	53.0	-7.5				*4	*5
L4	2.50	53.0	-7.5				*4	*5
L5	3.00	53.0	-7.5				*4	*5
L6	3.00	53.0	-7.5				*4	*5
P1*2	3.00	53.0	-7.5				0.770	0.970
P2	3.00	53.0	-7.5				0.770	0.970
P3	4.00	53.0	-7.5				0.820	0.920
P4	2.00	53.0	-7.5				0.820	0.870
P5	3.00	53.0	-7.5				0.620	0.670
P6	3.00	53.0	-7.5				0.570	0.670
P7	3.00	53.0	-7.5	1.0	90.0	-7.5	0.520	0.620
P8	3.00	53.0	-7.5				0.820	0.920
P9	4.00	53.0	-7.5				0.720	0.820
P10	4.00	53.0	-7.5				0.670	0.770
P11	5.00	53.0	-7.5				0.620	0.720
P12	4.00	53.0	-7.5	2.0	0.0	10.0	0.570	3.570

Table 3 Parameters of surface thin layer models and shallow horizontal polygons used for analyzing high-passed magnetic anomalies

\*<sup>1</sup>: L denotes a thin layer model, \*<sup>2</sup>: P denotes a horizontal polygon, \*<sup>3</sup>: depths from a plane at 1,920 m ASL, \*<sup>4</sup>: ground surface, \*<sup>5</sup>: 100 m below the ground surface

clines (Figure 6).

#### 6. Discussion

# 6.1 Magnetic properies of the KDAD and the YDAD

We made magnetic models that represent shallow debris avalanche deposits, referring to an apparent magnetization intensity map (Figure 10) and detailed geeologic maps (Figure 6). In this case, we considered only magnetic susceptibilities of andesite blocks in the deposits without remanent magnetizations, assuming that remanent magnetizations of the rocks are directed almost randomly in the debris avalanche deposits. However, the actual magnetic susceptibilities for the models exceed the average of 
 Table 4
 Parameters used for a two-layer model inversion

Data level: 1,920 m ASL			
Data number: $241 \times 156(E-W \times N-S)$			
Grid interval: 100 m			
Magnetic susceptibility: $2.10 \times 10^{-3} \times 4\pi$ (SI)			
Intensity of the Earth's magnetic field: 47,500 nT			
Inclination of the Earth's magnetic field: 53.0°N			
Declination of the Earth's magnetic field: 7.5°W			

rock magnetic measurements. Two explanations are possible. First, remanent magnetizations of andesite blocks might be directed almost parallel to the present Earth's magnetic field in the debris



Fig. 13 Topography of the detailed study area Contour interval is 50 m. Lines (A–B) and (C–D) show the locations of N–S and E–W cross sections revealed in Figs. 15 and 16. The area bounded by a thick solid line indicates the Yurihara Oil and Gas Field. See also the caption of Fig. 9.

avalanche deposits and might contribute to magnetic anomalies in addition to magnetic susceptibilities. In fact, rock magnetic measurements show that andesite blocks, within pyroclastic flows in the southern flank of Chokai Volcano, indicate remanent magnetizations parallel to the present Earth's magnetic field (UI, 1972). The similar phenomena might be expected also in the debris avalanche deposits.

Andesite lava at a fall (Naso Fall) from a dried dammed lake corresponds to that from Chokai Volcano (HAYASHI, 1984). Hence, the same lava is inferred to be overlain by the KDAD or the Kotaki Formation in the dried dammed lake and to cause magnetic anomalies in addition to the debris avalanche deposits. Further rock magnetic studies are necessary to solve this problem.

# 6.2 Relation between magnetic models and geologic structures

High-resolution magnetic anomalies and their derived models have a close relation with geologic structures in the study area (Figures 4 and 6).

The models of thin-layers and horizontal polygons apparently show a distribution of magnetic parts of the KDAD and the YDAD in the central and western parts of the area. The boundaries of these models clearly correspond to faults. Some of these faults are presumed to be still active (OZAWA et al., 1982). With a reference to the topography and faults, the distribution of magnetic parts of the KDAD and the YDAD are inferred to have been controlled by them; namely, the debris avalanche deposits came down from Chokai Volcano mainly along valleys. On the way, they filled depressions such as lakes and flooded over depressions and ridges associated with faults. Our shallow magnetic models, such as P1 and P2, might show thicker parts of those deposits, though we assumed a common thickness of 100 m for most magnetic models.

In our aeromagnetic anomaly map (Figure 4), the Nikaho Thrust Faults range on a northsouth trending slope zone of magnetic anomalies. Magnetic anomalies are not apparent over the faults except the one represented by P3.



Fig. 14 Magnetic basement depths of the detailed study area Contour interval is 250 m. The average of absolute differences between the observed and synthetic reduction to the pole anomalies is 2.57 (nT). See also the caption of Fig. 13.



Fig. 15 N-S cross section of the magnetic basement (Fig. 14) A broken line shows the presumed upper boundary of the Aosawa Formation from geologic studies (Ozawa et al., 1988)



Fig. 16 E-W cross section of the magnetic basement (Fig. 14)
 Broken lines show both the presumed upper and lower boundaries of the Aosawa Formation (OZAWA et al., 1988). A1: Kisakata Anticlines, A2: Nikaho Anticlines, A3: Yurihara Anticline, A4 Yashima Anticlinorium; S1: Shirayuki River Syncline, S2: Nishime Syncline, S3: Shinjyo Syncline

However, a low-amplitude magnetic high 2.5 km wide in the north-south direction, is distributed only in the northern half of the faults system in the study area. The southern boundary of this magnetic high apparently corresponds to a bend of one of anticlinal axes in the faults. Volcanic detritus from Chokai Volcano are thinly distributed in the area of a magnetic high (OZAWA et al., 1982) but does not seem to cause apparent magnetic anomalies. Therefore, we analyzed the magnetic anomalies with the assumption that this magnetic high is caused by a deep structure. There is a depth difference of the magnetic basement between in the northern and southern parts of this area along the Nikaho Thrust Faults. A magnetic basement high lies only in the northern part. This implies a difference of the subsurface distribution of the Aosawa Formation, though we have no other information that supports this idea.

In the eastern part, magnetic highs apparently correspond to each anticlinal axis of the Yashima anticlinorium (Figures 4 and 6). The magnetic basement was found to be shallow up to 500 m below sea level (BSL) in this area (Figures 14 and 16). These magnetic basement highs clearly correspond to uplifts of the Aosawa Formation. A magnetic basement high exists locally in a vicinity of the Yurihara Oil and Gas Field in the center of the study area. In this area, hydrocarbon deposits are expected to lie near uplifts of the Aosawa Formation. However, other magnetic basement highs do not lie apparently in the Yurihara Plateau.

As we mentioned above, the lateral distribution of the magnetic basement in general shows a good agreement with the presumed boundary of the Aosawa Formation in the cross-sections. However, magnetic basement depth is much shallower than the presumed upper boundary of the Aosawa Formation west of the Nikaho Hill. Although the thickness of the Aosawa Formation exceeds 1.500 m at least in the western half of the Yurihara Plateau, it is inferred to be around 750 m at the eastern edge of the plateau (OZAWA et al., 1988). The depth differences between the magnetic basement and the presumed upper boundary of the Aosawa Formation might be caused by lateral variations of the magnetic susceptibility and/or thickness of the Aosawa Formation. At any rate, there is a limitation of a two-layer model inversion with an assumption of uniform magnetization of the bottomless model. Other methods with more flexible model parameters are necessary for more detailed analyses.

#### 7. Conclusion

We conducted a high-resolution aeromagnetic survey over the Yurihara Plateau to evaluate such a survey in a volcanic region. A rock magnetic study was also conducted to support magnetic modeling. A compiled high-resolution aeromagnetic anomaly map reveals especially low-amplitude magnetic highs, which were not observed by a higher altitude survey. These magnetic highs correspond well to the distribution of the KDAD in a valley of the southern plateau. The subsurface extension of the KDAD in the plateau is inferred by a further continuation of the magnetic highs and analyzed magnetic models. This result shows that a reconstruction of geologic maps is recommended for debris avalanche deposits to assess volcanic hazard in this area.

A three-dimensional two-layer model inversion was applied to the residual magnetic anomalies after removing the effect of estimated distribution of magnetic debris avalanche deposits. In general, the resultant lateral distribution of depths to the magnetic basement corresponds to that of the upper boundary of the Aosawa Formation. The shallow magnetic basement lies around the Yurihara Oil and Gas Field, where a local uplift of the Aosawa Formation exists. However the magnetic basement is much shallower in the western part of the study area than the presumed upper boundary of the formation in a geologic cross-section. The depth differences between the magnetic basement and the presumed upper boundary of the Aosawa Formation might be caused by lateral variations of the magnetic susceptibility and/or thicknesses of the Aosawa Formation. More flexible methods are necessary to obtain further accurate estimations of the depth, in addition to intensive rock magnetic studies of the debris avalanche deposits and the core samples of the Aosawa Formation.

Our high-resolution aeromagnetic survey shows that this type of survey is useful for revealing deep subsurface structures as well as shallow magnetic structures, especially when the information on magnetic properties of the causative rocks is available. The new estimates for the extent of Quaternary debris avalanches can be used for assessment of the volcanic hazards of the region.

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### 火山地域における高分解能空中磁気探査の評価 一秋田県由利原地域の例

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#### 要旨

高分解能空中磁気探査は、金属鉱床等や地下に伏在する断層、褶曲および貫入岩体等の存在を明らか にすることが期待されている。地質調査所は火山地域における地下構造調査を目的とした高分解能空中 磁気探査を評価するため、秋田県由利原台地地域において空中磁気探査を行った。

由利原台地は、その南方に位置する第四紀火山、鳥海山からの薄い岩屑なだれ堆積物に広く覆われて いる。岩屑なだれ堆積物に含まれる鳥海山からの安山岩は、強い磁気的性質を示す。当該地域では、掘 削された坑井データより岩屑なだれ堆積物の下位に砂やシルトからなる中新世の堆積層があり、さらに この下位に中新世の苦鉄質火山岩からなる「青沢層」が伏在することが分かっている。そして、この青 沢層もまた磁気異常の原因となりうる強い磁気的性質を有している。

編集した高分解能空中異常図と地質図とを比較すると、由利原台地南部の谷筋にある高磁気異常が 「象潟岩屑なだれ堆積物」によく対応することが分かる。この高磁気異常はさらに北に向かって続き、 また解析結果の磁気的構造モデルからも「象潟岩屑なだれ堆積物」がさらに伏在して北方に延長するこ とが推定される。当該地域の火山災害を見積もるため、岩屑なだれ堆積物について地質図を見直す必要 があると思われる。

次に,3次元2層構造インバージョンを岩屑なだれ堆積物に対応する短波長の磁気異常を除去した残 差磁気異常に対して行った。大局的に,磁気基盤深度の水平方向の変化は青沢層の上面深度のそれによ く対応する。由利原石油・ガス田周辺では青沢層の局所的な隆起が認められるが,これに対応して磁気 基盤深度も浅くなる。しかし,調査地域の西部においては磁気基盤深度が地質断面図において想定され る青沢層上面深度よりもかなり浅く解析される。この差は青沢層の磁気的性質の水平方向の変化あるい は層厚の変化によって説明されるかもしれない。

最終的に、今回の高分解能空中磁気探査は、この種の調査が磁気異常源となる岩石の磁気的性質に関 するデータが得られた場合、浅部の磁気的構造と並んで深部構造を明らかにできる可能性を持っている ことを示している。また本手法は第四紀の岩屑なだれ堆積物のマッピッグに有効なため、当該地域の火 山災害の軽減、防止に貢献することが期待される。