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Recent Advancement of High-Resolution Aeromagnetic Surveys at the Geological Survey of Japan

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Abstract: The high-resolution aeromagnetic survey (HRAM) has made a great progress at the Geological Survey of Japan (GSJ) during the last decade. A research and development project on the HRAM was conducted in the first half of the 1990's at the GSJ. Several case studies in the project and related technical developments including new interpretation methods have made the HRAM a practical tool for understanding subsurface structures. In the second half of 1990's, the HRAM has been applied mainly to geo-hazard mitigation purposes such as earthquake and volcanic hazard mitigation by the GSJ. Those surveys successfully revealed many new findings as follows:

(1) Extensions of the Kisakata debris avalanche deposits in the Yurihara Area.
(2) A very conspicuous distribution of magnetization intensities with a four quadrangle pattern related to left-lateral strike-slip Tanna and Ukihashi faults.
(3) As for Asama volcano, subsurface extensions of volcanic rocks, especially andesite — dacite lavas and weakly magnetized areas probably demagnetized by hydrothermal alteration and/or heat of the conduit.
(4) A magnetization intensity map shows the subsurface distribution of older volcanoes such as Okata, Fudeshima, and Gyojanoiwaya on Izu-Oshima Island. An apparent magnetization low area was found on the west coast of the island and may be related to the hydrothermal alteration of volcanics or the demagnetization by the heat of the magma chamber or conduits.
(5) A broad magnetic high area occupies the western half of the Fukui plain, with a sharp NNW-SSE trending boundary to the east, corresponding well to the predicted location of the concealed Fukui Earthquake Fault.

Based on domestic and foreign related studies, we have begun a new study on slope stability estimation of active volcanoes by airborne geophysics. We have already conducted HRAMs and airborne EM surveys (AEM) over Usu and Iwate-san volcanoes to better understand their slope stability as well as to assess their volcanic activity.

1. Introduction

High-resolution aeromagnetic surveys have been widely adopted at the Geological Survey of Japan (GSJ) to better understand detailed subsurface structures in the last decade. A special research and development (R&D) program on the high-resolution aeromagnetic survey (HRAM) was conducted in the early 1990's at the GSJ. Its usefulness for revealing subsurface structures has been confirmed by subsequent case studies. In the late 1990's, the HRAM has been recognized as a practical tool for geophysical surveys for geo-hazard mitigations and applied to investigations on structures of concealed active faults and volcanoes in Japan.

The case study results on the R&D and recent applications of the technology at the GSJ will be summarized and discussed in this paper. A new study on evaluation of slope stability of active volcanoes by airborne geophysics will be also outlined in this paper.

2. R&D on High-Resolution Aeromagnetic Surveys at the GSJ

2.1 Case Studies

A special R&D study on the HRAM was conducted from 1990 to 1994 by the GSJ (Fig. 1). During the project, several case studies were applied to different fields.

Yurihara Area

In 1990, the first HRAM by the GSJ was flown in the Yurihara area, northeast Japan. The area is located north of Chokai volcano, a Quaternary active

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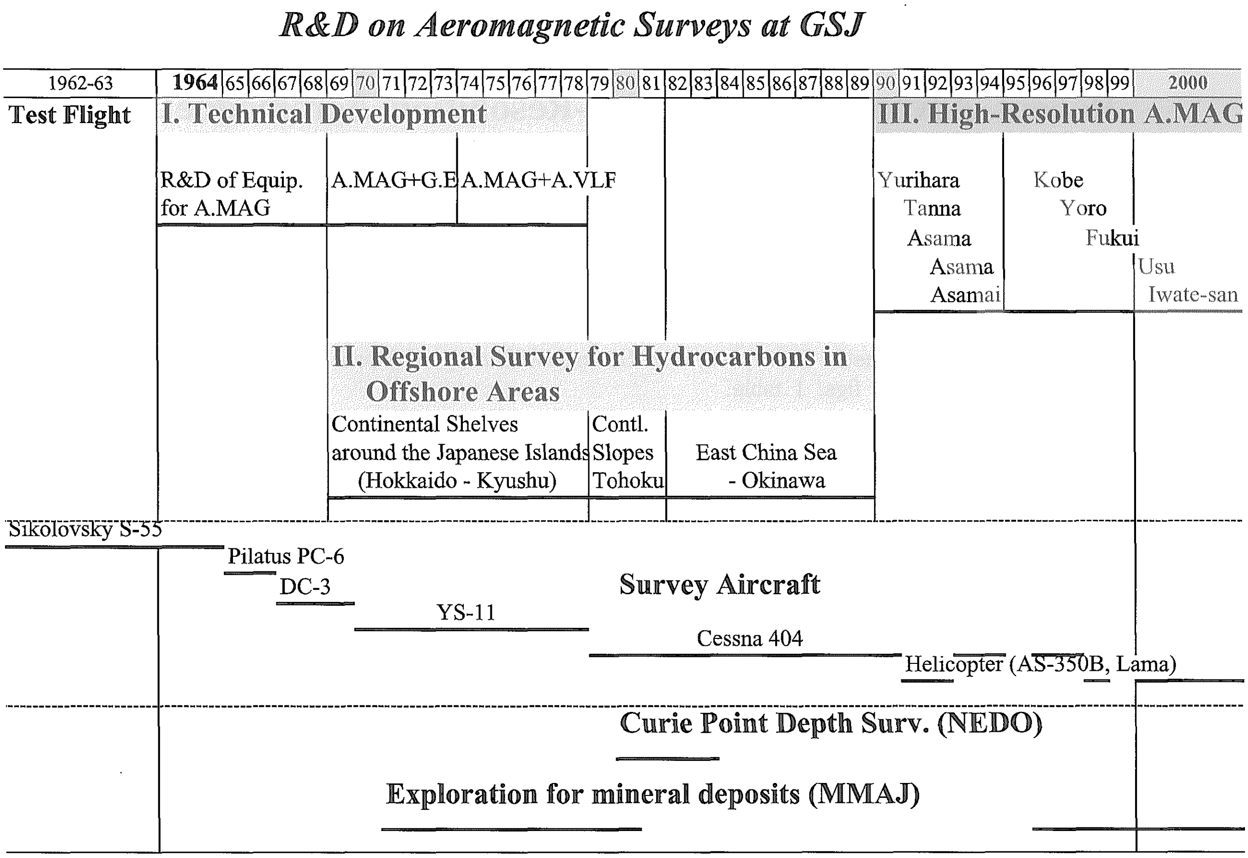


Fig. 1 Research and development on aeromagnetic surveys at the Geological Survey of Japan.

volcano, and occupies the Yurihara plateau. The Yurihara area is covered widely and thinly by dated and undated debris avalanche deposits (Fig. 2). The main purpose of the survey was to reveal the deep-seated structure of Tertiary volcanic layers, which intercalate oil and gas deposits. Besides longer-wavelength magnetic anomalies related to the deep structure, high-frequency magnetic anomalies were observed mainly over the valleys of the survey area (Fig. 3(a)). These magnetic anomalies were found to be caused by thin layer models and horizontal polygons (Fig. 3(b)). It was interpreted to be associated with the Kisakata debris avalanche deposits (KDAD), which came down originally from Chokai volcano by a debris avalanche. This occurred around 3,000 years ago. A subsequent rock magnetic study (Okuma *et al.*, 1998; Okuma *et al.*, in preparation) confirmed that the KDAD have strong natural remanent magnetizations (NRM) as well as strong magnetic susceptibilities compared to non-magnetic Quaternary sediments, which underlie the deposits. However, the NRM directions of rock samples from the KDAD differ at each place and no concentration was observed (Fig. 4). This result implies that the corresponding magnetic anomalies are caused mainly by magnetic susceptibilities of the KDAD. A further northern extension of the magnetic highs suggests that the KDAD or older debris avalanche deposits underlie in that area.

Tanna Fault Area

In 1991, a helicopter-borne magnetic survey with a bird system was conducted in the Tanna fault area, central Japan (Nakatsuka, 1995). Apparent magnetization intensity mapping was applied to the magnetic anomalies of the area. The result shows a very conspicuous distribution of magnetization intensities with a four-quadrangle pattern. It is related to the left-lateral strike-slip Tanna and Ukihashi faults, which were displaced considerably during the 1930 Kita-Izu earthquake. A similar four-quadrangle pattern of gravity anomalies was also recognized in the area by a gravity survey (Okubo, 1992). Lower magnetization intensities appeared west of the southern part and east of the northern part of the Tanna fault, and in a narrow zone between the Ukihashi central and west faults. The magnetization distribution pattern was thought to originate from the effect of the compressional stress field caused by strike-slip faulting.

Asama Volcano

In 1992, a helicopter-borne magnetic survey with a bird system was also conducted over Asama volcano, central Japan (Makino *et al.*, 1993b, 1994; Fig. 5). The survey was flown with a vertical gradiometer

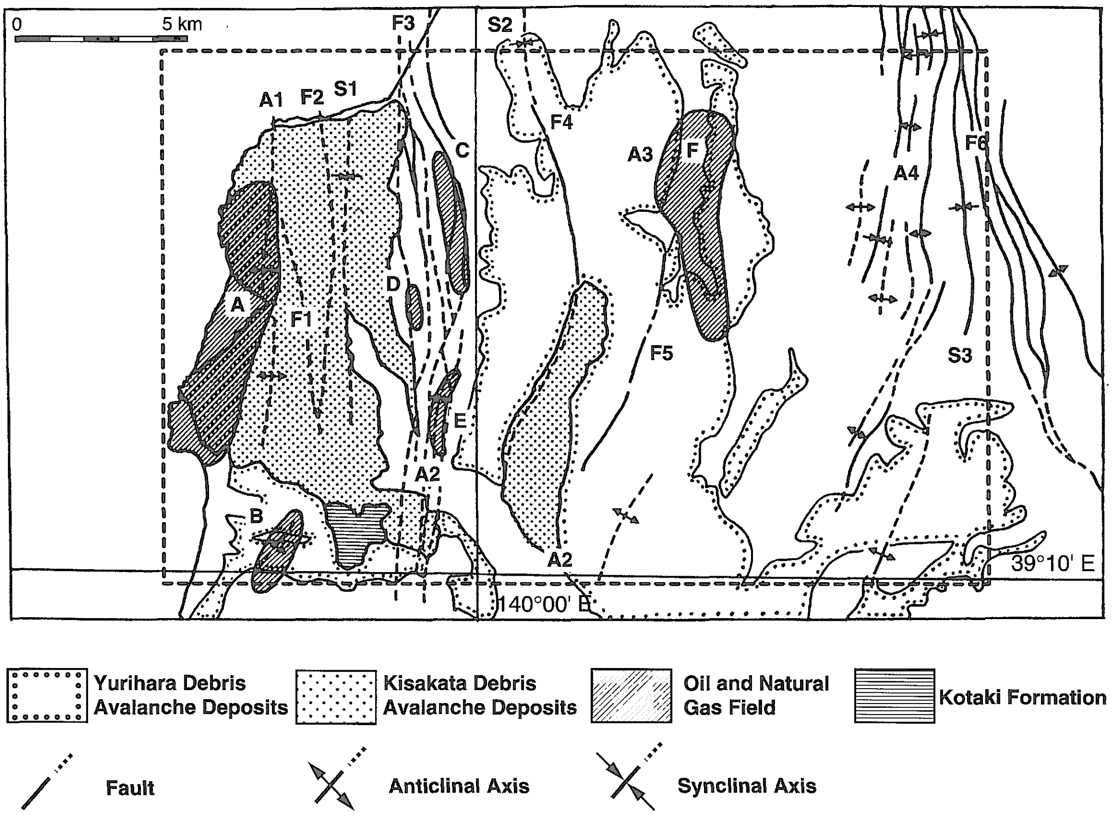


Fig. 2 Geologic map of the Yurihara area, northeast Japan.
A rectangle area bound of broken lines shows the study area.
A: Kisakata Oil Field, B: Kotaki and Kamihama Oil Field, C: Innai Oil Field, D: Nishi-Oguni Gas Field, E: Katsurazaka Oil Field, F: Yurihara Oil and Gas Field, A1: Kisakata Anticline, A2: Nikaho Anticlines, A3: Yurihara Anticline, A4: Yashima Anticlinorium, S1: Shirayuki River Syncline, S2: Nishime Syncline, S3: Shinjyo Syncline, F1: Active fault west of Otake, F2: Kotaki Reverse Fault, F3: Nikaho Thrust Faults, F4: Kamaga-dai Fault, F5: Oyachi Fault, F6: Toritame Faults.

configuration of two proton magnetometers and a single-channel GPS receiver along east-west flight lines at an altitude of 150 m above terrain and spaced 150 m apart. The observed data has been reprocessed and total intensity anomalies have been compiled on a smoothed observed surface. The reduction to the pole anomalies (Fig. 6) have been also calculated from the total intensity on the surface.

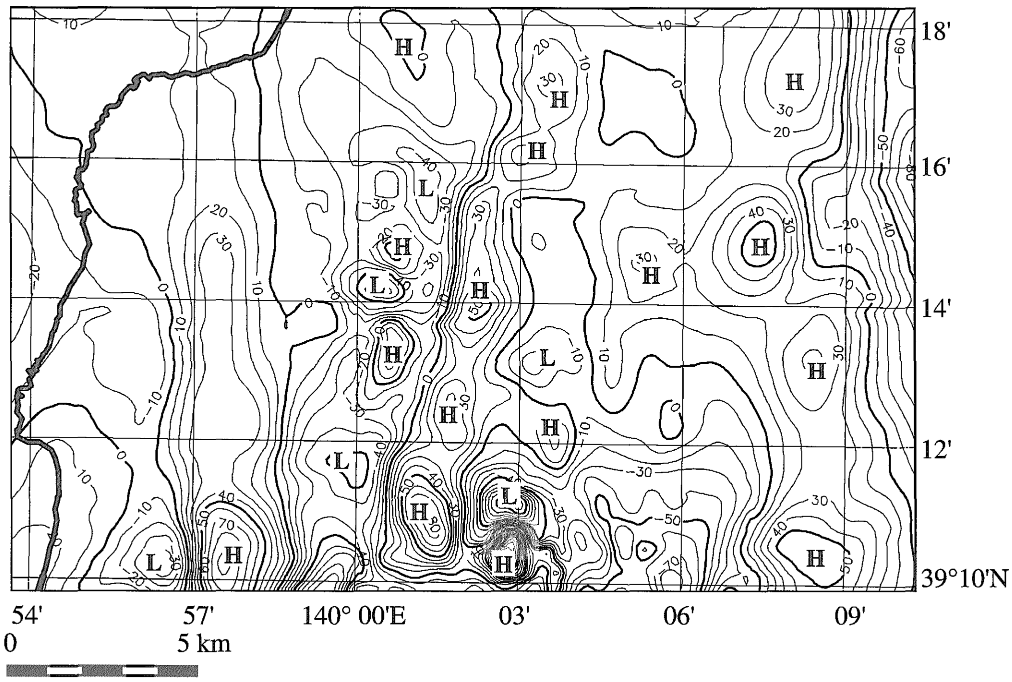
Asama volcano is an active Quaternary volcano and has three major volcanic activities through Holocene (Aramaki, 1993). The magnetic survey revealed the subsurface extension of volcanic rocks, especially andesite — dacite lavas and weakly magnetized areas probably demagnetized by hydrothermal alteration and/or heat of the conduit.

According to the reduction to the pole anomaly map (Fig. 6), the characteristics of the magnetic anomalies over the volcano are summarized as follows:

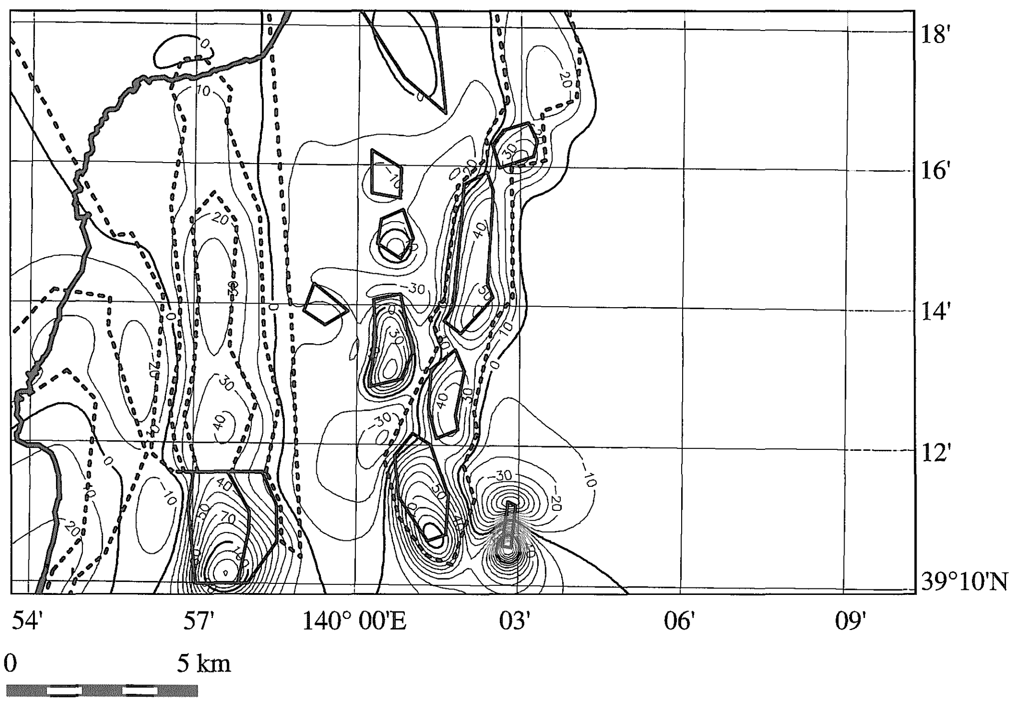
In the western part of Asama volcano, magnetic highs lie on Kurofu-yama and Kenga-mine comprised mainly of lava flows and pyroclastic rocks of augite-hypersthene andesite. These peaks are the remanents of the oldest member of Asama volcano that was destroyed by a large-scale collapse about 20,000 years ago. In the southern part of Asama volcano, a magnetic high is distributed over the Sekison-zan lava dome comprised of andesites. In the southeastern part of Asama volcano, magnetic highs are distributed over some outcrops of Hotokeiwa lavas comprised of silicic dacite implying iron-rich parts and/or thicker lava flows.

Apparent magnetic highs lie over Maekake-yama, a stratocone atop the volcano, and northern flank of the volcano. Some of the highs correspond to the outcrops of the Maekake-yama lavas implying a subsurface extension of the lavas under younger volcanic rocks such as Oni-oshidashi lavas. Magnetic highs are also distributed over the Oni-oshidashi lavas, a 1873 eruption product, but their amplitude is smaller than that of the Maekake-yama lavas.

A magnetic low is observed over the summit caldera of Kama-yama, suggesting that the caldera is composed of less magnetic volcanic rocks and/or is thermally demagnetized by the magma heat. Magnetic lows are distributed over Yunotaira and Jabori river, thought to have been a center of an older volcano,



(a)



(b)

Fig. 3 Magnetic modeling of the Yurihara area, northeast Japan (Okuma *et al.*, 1995).
(a) Observed total intensity magnetic anomalies of the Yurihara area, northeast Japan.
(b) Synthetic magnetic anomalies which best fit the observed (a).
The areas bound of solid and broken lines indicate thin layer models and horizontal polygons, respectively.

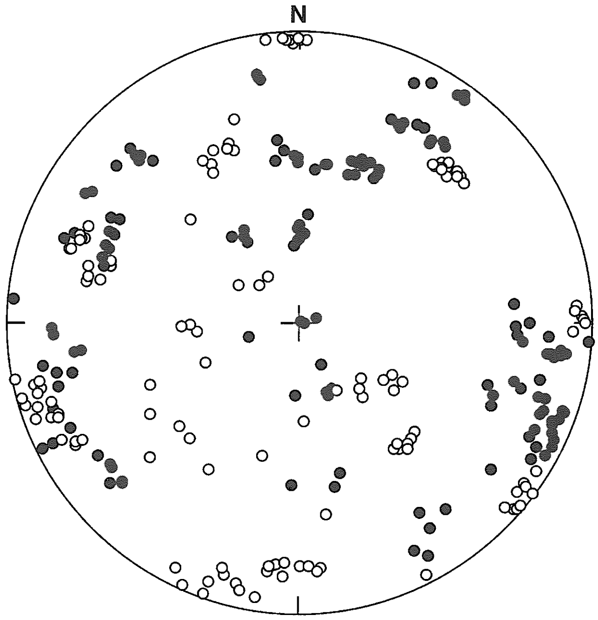


Fig. 4 Equal area projection of NRM of rock samples from the Kisakata debris avalanche deposits (KDAD) (Okuma *et al.*, 1998).
Solid and open dots indicate projections to the lower and upper hemispheres, respectively.

Kurofu-yama. Intense alteration areas are seen there. Magnetic lows lie between Maekake-yama and Sekison-zan on the southern slope of Asama volcano, although small-amplitude magnetic highs are distributed from the Maekake-yama to the upper parts of the southern flank. This implies that the magnetic low area seems to lack magnetic rocks and comprise mainly of pyroclastic rocks. A quarter fan shape magnetic low area ranges from west of Sennin-dake, a peak northeast of Kurofu-yama, to the northern flank suggesting a demagnetization by hydrothermal activity. Actually, the hydrothermal area, called Shirozore, exists in the northern part of the crater wall of Kurofu-yama just beneath the southern edge of the lows.

Izu-Oshima Volcano

Okuma *et al.* (1994) showed that a magnetization intensity map of Izu-Oshima volcano generally indicates a good correlation with the surface geology (Fig. 7). To give a few exambles, magnetization highs coincide with the exposure of spatter ramparts at Yuba and volcanics of Fudeshima volcano, in addition to the distribution of the post-caldera lava flows.

Magnetization lows, which correspond to the distribution of the main stratovolcano's older edifice at the pre-caldera stage and volcanics of Gyojanoiwaya volcano, predominate on the northeastern coast.

However, some areas of the island lack geologic information in spite of the presence of characteristic distribution of magnetization intensity. For instance, a low intensity area of magnetization ranges from Motomachi to Nomashi on the western side of the island, where no relevant surface geologic features are known. This low intensity area of magnetization may be related to the hydrothermal alteration of volcanics by hot groundwater or the demagnetization by the heat of the magma chamber or conduits, in addition to the inferred distribution of the main stratovolcano's older edifice at the pre-caldera stage and a complex of altered volcanics.

Table 1 Important items for high-resolution aeromagnetic surveys.

Data Acquisition	(1) Low Flying Altitude, Narrow Spacing of Survey Lines, Dense Spacing of Sampling Points, High-Sensitivity Measurements
Data Processing & Reduction	(1) Reduction to a Smoothed Surface (2) Evaluation and Reduction of Artificial Noise
Data Analysis & Interpretation	(1) Evaluation of Shallow Structure by Apparent Magnetization Mapping (2) Rock Magnetic Measurements

2.2 State of the Art of the HRAM and Interpretations of Data

Through those case studies on the HRAM, several important things are summarized as follows (Table 1):

In data acquisition, a recent development of Differential Global Positioning System (DGPS) has enabled us to conduct practical high-sensitivity magnetic measurements. Recently, a survey helicopter can be flown at an altitude of 150 m above the terrain with a sampling interval of 0.1 second by an optical-pumping magnetometer. In this case, a drape flight is common especially over the mountainous region in Japan. Magnetic data are measured on a three-dimensional surface not on a plane and the data must be reduced onto a smoothed surface for subsequent analyses and interpretations. Some methods have been proposed for such a reduction. Cordell (1992) proposed scattered equivalent-source methods for interpolation and gridding of potential-field data in three dimensions. For such problems, Makino *et al.* (1993a) introduced a distribution of equivalent anomalies below the observed surface, which best fits the observed anomalies.

The observed magnetic data are sometimes contaminated by cultural noises caused by artificial structures and electrical currents from railroads especially in urban areas of Japan. The evaluation and reduction of artificial noises are crucial problems in such areas to analyze the magnetic data correctly. Nakatsuka *et al.* (1997) showed the results of HRAM over Kobe-Kyoto area, central Japan, where the 1995 Kobe Earthquake hit. An evaluation of cultural noise was made by both subsequent ground observations and a synthetic calcu-

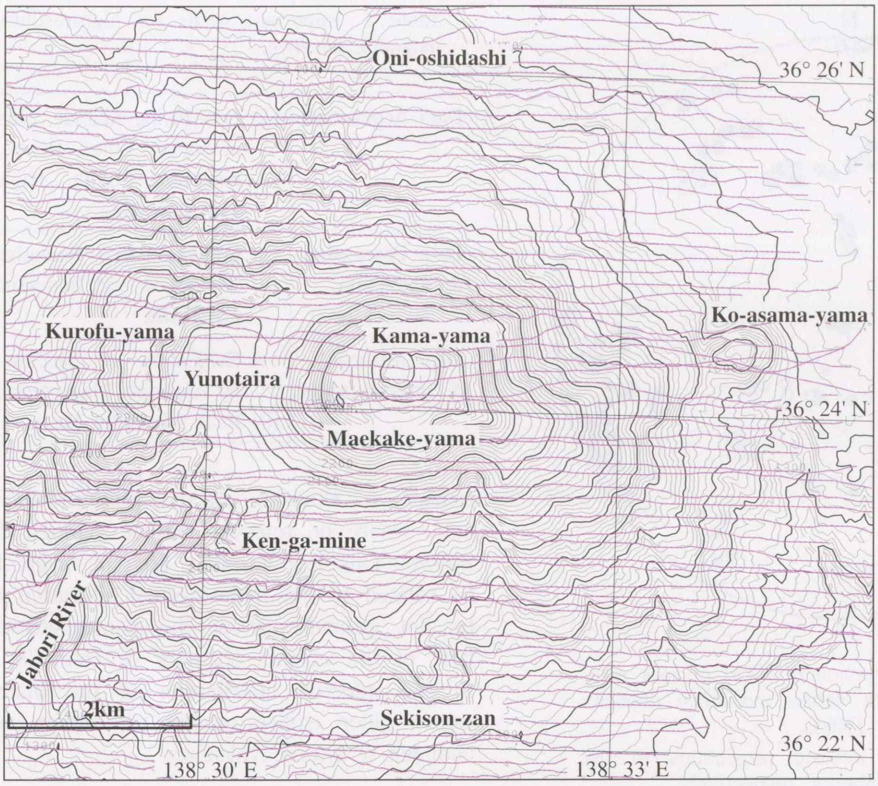


Fig. 5 Flight lines of a high-resolution aeromagnetic survey over Asama volcano, central Japan, superimposed on a topographic map created from the DEM data with a 50 m grid by the Geographical Survey Institute (GSI). Thin solid lines show the flight lines of the GSJ survey. The survey was flown at an altitude of 150 m.

Fig. 6 Reduction to the pole anomaly map of Asama volcano with a topographic shading.
The data was reduced onto the smoothed observed surface. Contour interval is 50 nT. The area bound of broken lines shows the extension of Hotoke-iwa Lavas (Aramaki, 1963).

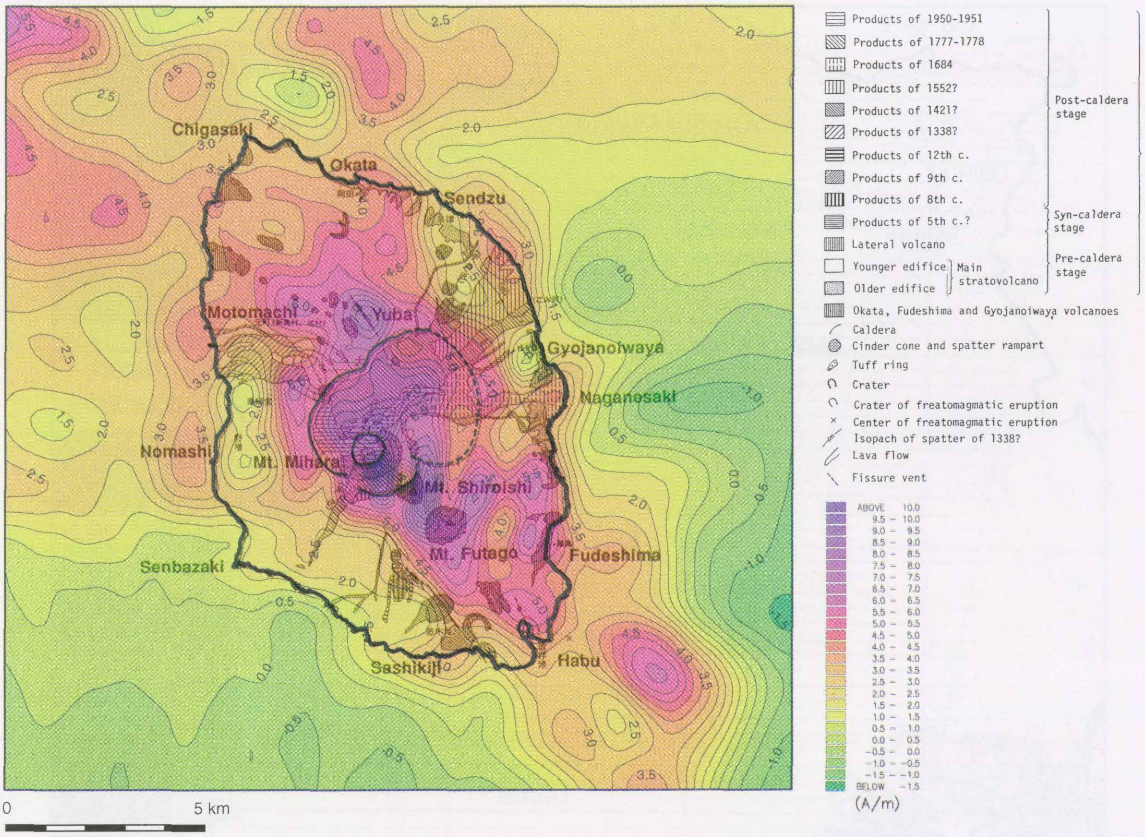


Fig. 7 Apparent magnetization intensity map of Izu-Oshima volcano, Japan, superimposed on a geologic map of the volcano before the 1986 eruption (Sakaguchi *et al.*, 1988).
Contour interval is 0.5 A/m.

lation of magnetic anomalies caused by electric currents of a railroad loop.

The HRAM can reveal high-frequency and short-wavelength anomalies, which can not be measured by conventional constant high-altitude survey flights. These anomalies sometimes include important geophysical and geological information. A case study in the Yurihara area has been already explained in the previous section. Okuma *et al.* (1994) and Nakatsuka (1995) developed apparent magnetization intensity mapping methods that convert observed magnetic anomalies to a horizontal magnetization distribution of an assumed causative body by a steepest descent method and a conjugate gradient method, respectively. The methods are useful to analyze magnetic anomalies as a tool of geologic interpretation. If you know the shape of a causative body, it is easy to analyze and interpret the anomalies by these methods. For instance, the methods can be applied to interpret magnetic anomalies in Quaternary volcanic areas because the magnetic structure can be assumed to be a so-called terrain model with the top depth corresponding to terrain surface. The results of the mapping can indicate subsurface dyke intrusions, lava flows overlain by recent pyroclastic flows, hydrothermally altered areas, and thermally demagnetized areas by the heat of magma that are important for volcanic hazard mitigation as well as realizing subsurface structures of active volcanoes.

3. High-Resolution Aeromagnetic Surveys for Geo-hazard Mitigation

Based on the R&D at the GSJ, the HRAM is now being applied to geo-hazard mitigation. As some surveys applied to volcanic hazard problems have already been described in other sections, we will show here a result of the HRAM for revealing subsurface active faults.

The GSJ has conducted a helicopter-borne high-resolution aeromagnetic survey over the Fukui Plain, central Japan, to better understand concealed faults associated with the 1948 Fukui Earthquake (June 28, 1948, M=7.3) that caused tremendous damage to this area (Okuma *et al.*, 1999). The survey was flown with a Cesium vapour magnetometer and differential GPS along east-west flight lines at an altitude of 150 m above terrain and spaced 300 m apart (Fig. 8). The reduction to the pole anomaly map (Fig. 9) was compiled from the total intensity map of IGRF residuals and shows interesting magnetic features as follows:

(1) A broad magnetic high area occupies the west-

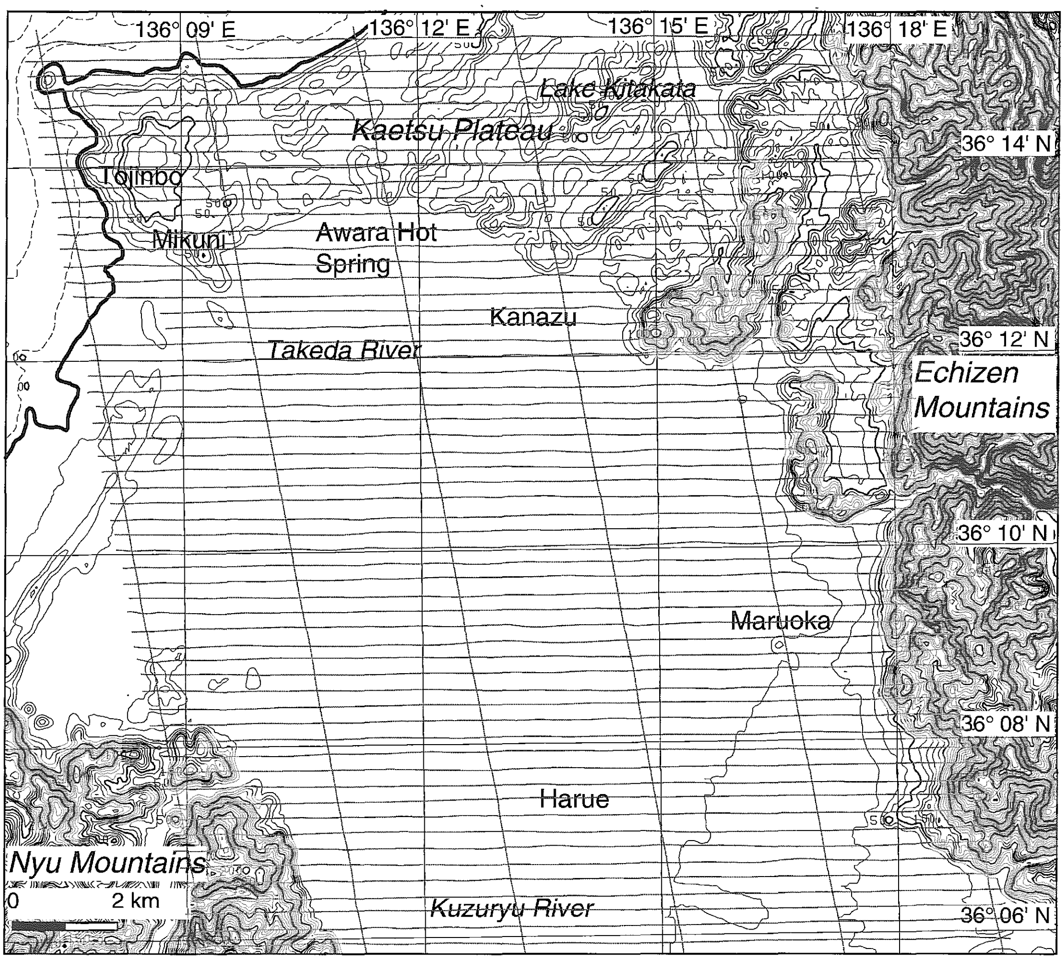


Fig. 8 Flight lines of a high-resolution aeromagnetic survey over the Fukui plain, central Japan, superimposed on a topographic map created from the DEM data with a 50 m grid by the Geographical Survey Institute (GSI). Thin solid lines show the flight lines of the GSJ survey.

ern half of the plain, consisting of several large-amplitude magnetic anomalies and small-amplitude regional magnetic highs.

(2) A small-amplitude magnetic high extends from eastern Harue to downtown Maruoka in a SW-NE direction, implying the existence of a local uplift of the basement.

(3) Generally, known fault systems correspond well to the local discontinuation of magnetic highs. A sharp NNW-SSE trending boundary to the east of the broad magnetic high area corresponds well to the predicted location of the concealed Fukui Earthquake Fault. A low-amplitude magnetic high extends from the south along the predicted location of the Fukui Eastern Earthquake Fault.

(4) One of the distinctive magnetic anomalies in the broad magnetic high area lies at the western part of the Awara Hot Spring, implying the existence of intrusions associated with the hot spring.

(5) Magnetic lows are dominant along the coast line of the Sea of Japan and in its offshore areas, suggesting the existence of reversely magnetized volcanic rocks which lie offshore and may outcrop along the coast line.

Rock samples have been collected from outcrops around the plain to better interpret magnetic anomalies. We will incorporate the results of rock magnetic measurements with the high-resolution magnetic anomalies and promote further studies for revealing the origin of the anomalies associated with fault displacements.

4. New Study on the Estimation of Slope Stability of Active Volcanoes by Airborne Geophysics

Corruptions of volcanic edifices and subsequent debris avalanches are one of major volcanic disasters. A corruption of volcanic edifice happens not only by eruptions but also by big structural earthquakes. If a corruption happens, a resultant debris avalanche runs down the slope of volcano rapidly and reaches far away from the original site, causing tremendous dam-

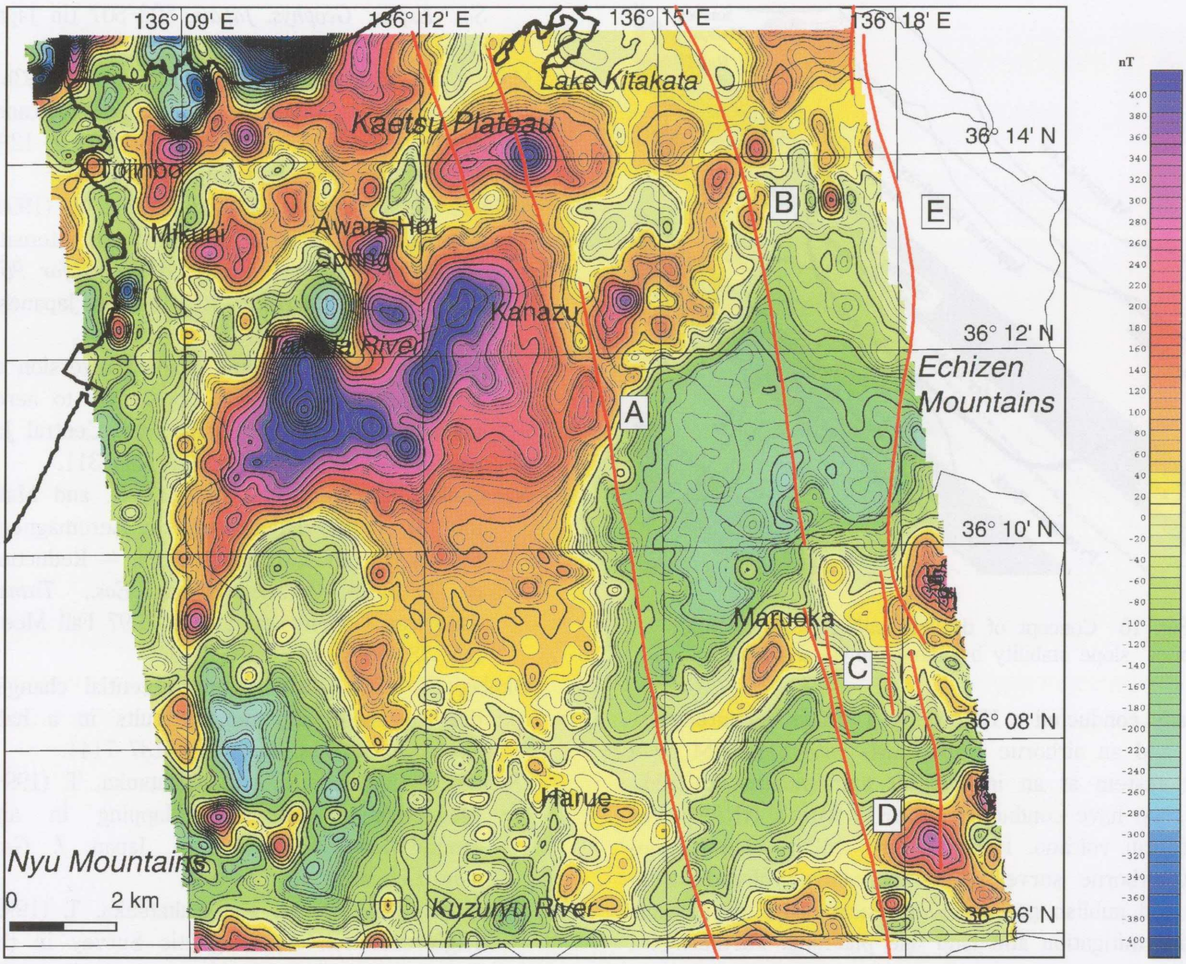


Fig. 9 Reduction to the pole anomaly map of the Fukui plain.
Contour interval is 10 nT. Red solid lines indicate fault lines. The survey was flown at an altitude of 150 m, spaced 300 m apart. A: Fukui Earthquake Fault, B: Hosorogi Fault, C: Shinooka Fault, D: Fukui Eastern Earthquake Fault, E: Kengatake Fault (after the Research Group for Active Faults of Japan (1991)).

age on the way. Thus, an evaluation of slope stability of volcano is a very important mitigation procedure against the disaster. Airborne geophysics is a promising technique for surveying these volcanic areas with rugged terrain, where access on foot is very difficult.

Mt. Rainier is treated as a decade volcano in the U.S. and extensive studies have been conducted so far. The volcano is covered partly with a glacier and geological mapping is very difficult on the ground. Airborne EM and magnetic surveys were conducted by the USGS and altered areas were estimated successfully by calculating correlation coefficients between the apparent resistivity and magnetic anomalies (Finn *et al.*, 1998).

Based on the pioneering study by the USGS, we have just started a new study on the estimation of the slope stability of active volcanoes by airborne geophysics (Fig. 10). We will incorporate the results of the surveys with other data such as topography and geology, and estimate the slope stability of active volcanoes in Japan. As for the first survey for this purpose, we have completed an airborne EM survey with HRAM over Iwate-san volcano, northeast Japan.

5. Conclusions

During the last decade, high-resolution aeromagnetic survey (HRAM) has made a great progress. At the GSJ, a R&D program was conducted with several case studies, which were applied to various geological backgrounds. We believe the HRAM incorporated with other aerogeophysics will be applicable especially to geo-environmental problems in the 21st century. We have just started conducting airborne geophysics for detecting unstable steep slope areas of Japanese volcanoes.

In 2000, three Japanese volcanoes erupted: Usu, Hokkaido-Koma-gatake and Miyake volcanoes. Volcanic tremors have been observed at Asama and Aizu-Bandai-san volcanoes as well as Iwate-san volcano, where volcanic activities started three years ago. To monitor the volcanic activity of Usu volcano, we have

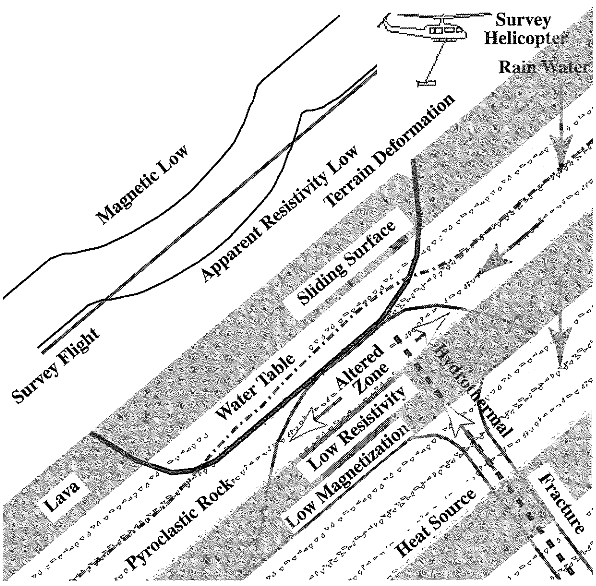


Fig. 10 Concept of the evaluation of active volcanoes' slope stability by aerogeophysical surveys.

already conducted a HRAM by a stinger-mounted system and an airborne EM (AEM) with a HRAM by a bird system at an interval of four months. In addition, we have conducted an AEM with a HRAM over Iwate-san volcano. Hopefully, we will be able to conduct airborne surveys for each active volcano in Japan and publish precise geophysical maps for volcanic hazard mitigation and land use planning. Furthermore, we hope to promote airborne geophysics over world volcanoes, in collaboration with other domestic and foreign institutes, to better understand the subsurface structures of them and assess the volcanic activities by repeat measurements if applicable.

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地質調査所における空中磁気探査の最近の進歩

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要　旨

最近10年間で地質調査所における高分解能空中磁気探査（HRAM）は大きく進歩した．地質調査所においては1990年代前半にHRAMに関する技術開発研究を実施し，様々なフィールドへの適用を検討するとともに解析技術等の技術開発を行い，その結果HRAMが地下構造を調査するのに有効であることを検証した．1990年代後半になって，地質調査所ではHRAMは主に地震や火山災害軽減のための調査に用いられるようになった．これらの調査により以下が明らかとなった．

(1) 秋田県由利原地域における象潟岩屑なだれ堆積物の広範な分布

(2) 丹那断層と浮橋断層とに関連する4象限パターンの磁化強度分布

(3) 浅間火山での安山岩－石英安山岩等の強磁性火山岩の伏在範囲や熱水活動や火道の熱による低磁化強度域の分布

(4) 伊豆大島での岡田，筆島および行者ノ窟火山等の古い火山体の伏在範囲，同島西海岸地域での顕著な低磁化強度域の存在と熱水変質，マグマ溜まりおよび火道の熱等との関係

(5) 福井平野西部を中心とした高磁気異常域の存在とその東端と福井地震断層との関係

以上の研究や国際共同研究等により，地質調査所では新たに空中物理探査による火山の山体安定性評価手法の開発に関する研究に着手した．既に当該研究や緊急研究により，山体安定性評価や活動度評価のために，有珠火山地域での高分解能空中磁気探査および空中電磁・磁気探査，岩手山での空中電磁・磁気探査を実施している．