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Use of magnetic surveying in landslide analysis at the boundary between the granite region and the green tuff region in southwestern Toyama Prefecture

Toshihide Sugimoto*
Kazuo Kawasaki**
Hideo Sakai**

*MLIT Hokuriku Regional Development Bureau, River Department
**University of Toyama, Division of Earth and Environmental Systems l

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ABSTRACT

A helicopter-borne magnetic survey is conducted at the landslide-prone area of the boundary zone between the Hida belt and the green tuff in southwestern Toyama Prefecture, and the effectiveness of the airborne magnetic survey is considered in relation to its ability to verify the magnetic structure in the slope regions. Analysis using the reduction-to-the-pole (RTP) method is applied to airborne magnetic anomaly data in the survey after diurnal correction and removal of the International Geomagnetic Reference Field (IGRF)-7. In addition, the magnetic properties are measured, and x-ray powder diffraction of boring cores drilled in the region of the Funatsu granite is examined. According to the magnetic anomaly distribution using the RTP method, the area of igneous rock distribution shows high magnetic anomaly, and the hydrothermal alteration zone and colluvial deposit area of landslides show low magnetic anomaly. It has become clear through the study of boring cores that pole magnetic anomaly by airborne magnetic survey reflects the distribution of many magnetization substances in the shallow part. Aeromagnetic surveys are an efficient method of identifying both the distribution of collapsed soil sediments in the Neogene and areas of high landslide potential in Funatsu granitic rock.

Keyword: *Magnetic prospecting, Magnetic anomaly, Susceptibility, Hydrothermal alteration, Landslide, Igneous rock*

1. Introduction

A large number of landslide disasters have occurred in Japan in recent years due to the increasing occurrence of localized heavy rainfall and earthquakes. There is a concern that more frequent landslides and deep-seated landslides will occur in the future due to the high probability of increasing frequency of earthquakes and heavy rainfall. In order to prepare for such landslide disasters, it is necessary to gain an understanding, in advance, of the locations and scales of landslides and deep-seated landslides that can result from earthquakes and heavy rainfall. Therefore, numerous studies on risk evaluation methods for slope failure have been conducted (Khasbaatar et al., 2009; Hayashi et al., 2011; Higaki et al., 2011; Uchida et al., 2011). Landslide and slope failure research is generally performed by conducting topographical and geological reconnaissance and boring on site, taking into consideration the results of synoptic surveys based on bibliographic surveys, aerial photointerpretation, and high-precision topographical information. These are then followed by consideration of ground properties and structural analysis (Japan River Association, 1977; Tamura et al., 2008). However, such investigations take many days to perform, are costly, and require specialized techniques based on experience. Taking into consideration the demand for landslide and slope failure investigations in the future, technologies for efficiently detecting unstable slopes from slopes present over a wide area, as well as investigative techniques for gaining an understanding of the geology of slopes over broad areas, are required. For this reason, new technologies such as light detection and ranging (LIDAR), electromagnetic studies, and remote sensing are now being used to gain information on topographic surfaces and underground structures over broad areas (for instance, Suzuki et al., 2009; Uchida et al., 2010; Shiozaka et al., 2010).

An airborne magnetic survey is a method of investigating geological structures from the air. This survey utilizes an aircraft to measure magnetic fields and is used to investigate geological structures and lithology by scanning the distribution of magnetic bodies in the subsurface. The method can be used to obtain a synopsis of the geology and related factors of slopes over a wide area in a short time and is, therefore, considered effective for detecting the occurrence of primary landslides on slopes that manifest no symptoms of changes in topography or where deep-seated landslides are expected. Recent improvements in the measurement accuracy of magnetic sensors and the global positioning system (GPS) have made it possible to perform detailed surveys at lower altitudes and shorter survey line intervals. What was previously a means to explore iron deposits can now be used as an effective means to unravel underground structures and is, in fact, currently being used to survey underground structures of volcanoes (e.g., Okuma et al., 2001; Tanahashi et al., 1995; Hasegawa, 2010). While airborne electromagnetic surveys, which are ordinarily conducted at the same time as airborne magnetic surveys, are now commonly applied in geological surveys over broad areas (Konishi et al., 2001; Nakazato et al., 2004), there have been no studies to clarify the significance of airborne magnetic surveys for detecting landslides, unstable slopes, or boring magnetism by comparing data between the two types of survey.

Sugimoto et al. (2013) conducted an airborne magnetic survey to determine the unstable sloping landslide area southwest of Toyama Prefecture, where there is a boundary between the Hida belt and the green tuff region. The magnetic anomaly values observed in 2000 (after diurnal correction and removal of the International Geomagnetic Reference Field (IGRF)-7) were compared with geographical features and the site geology and they concluded that the magnetic anomalies were correlated with the areas of landslide.

The shape of a magnetic anomaly depends on several factors, including: a) the shape of the causative body; b) the inclination and the declination of the body's magnetization; c) the inclination and the declination of the local earth's magnetic field; and d) the orientation of the body with respect to the magnetic north (Nabighian et al., 2005). The IGRF correction could only remove the effect of the local earth's magnetic field. Therefore, the magnetic anomaly values after IGRF correction by Sugimoto et al. (2013) are less accurate in presenting local magnetic anomalies. Hence, the reduction-to-the-pole (RTP) method is applied to airborne magnetic anomaly data in Sugimoto et al. (2013) to enhance the anomalies and make the relationship between the magnetic anomalies and the area of landslide clearer. The RTP method has been shown to be an effective method for interpreting corresponding magnetic anomalies (Okuma et al., 1990; Hasegawa et al., 2009). In addition, we used in-laboratory techniques, including the magnetic properties and the x-ray powder diffraction of the boring cores drilled at the study site to support the analyzed data. We then compared the geology with the airborne magnetic anomaly data after transformation with RTP to investigate the hydrothermal alteration and shear zone area of the landslide.

2. TOPOGRAPY AND GEOLOGY OF SURVEYED SITES

2.1 Summary of geology

The surveyed sites are located on a boundary between the Hida belt and the region of the Neogene green tuff layers in the southwestern section of Toyama Prefecture. The green tuff layers form the Toga

Graben, which cuts through the Hida denatured plutonic rocks; it extends northeast to southwest and is bordered by a fault system. The Neogene-Miocene Iwaine formation (andesitic lava and homogeneous ash breccia) of the green tuff layers is distributed on the northern to western side of the survey site. Furthermore, the Nirehara formation (sand stones and conglomerate stones), formed between the end of the Paleogene period and the beginning of the Neogene period, is located between the Funatsu granitic rocks and the Iwaine formation, covering the Funatsu granitic rocks (Nozawa et al., 1981).

2.2 Summary of unstable slopes such as landslides

A geological map and a geological feature diagram prepared based on a geological reconnaissance and existing geological literature, as well as boring survey results, are shown in Figs. 1 and 2. There is a cataclastic section in the Funatsu granitic rock area, believed to have been caused by structural movements that occurred prior to the formation of the Toga Graben. There are solid masses in this section of cataclastic granitic rocks, but there are more significant hair cracks along the fault of the Toga Graben, and there is a stronger tendency for hydrothermal alterations to occur in association with multiple dykes. Funatsu granitic rocks, which have significant cracks, likely cause a regional slope failure by bedrock deterioration due to hydrothermal alteration from deep underground.

There is a distinct, northeastern striking fault on the northwestern slope (near-vertical dipping), at the border between the Funatsu granitic rocks and the Iwaine formation, that comprises the western edge of the Toga Graben. Many white viscous layers have formed in the fault and cracks from hydrothermal alterations and these layers are the cause of landslides. Generally, igneous rocks have higher magnetic susceptibility than sedimentary rocks (5×10^{-6} to 2×10^{-2} SI for igneous rocks); the magnetic susceptibility of andesitic rocks and felsic granitic rocks is 9×10^{-5} to 1×10^{-2} SI and 5×10^{-6} to 5×10^{-3} SI, respectively (Society of Exploration Geophysicists of Japan, 1999). While magnetic susceptibility remains within a certain range for homogeneous rocks, it drops significantly below this range when the magnetic minerals have degraded or altered due to the effects of alteration.

The topographic distribution of the landslides in Figs. 3 and 4 is made based on interpretation from the microtopography of the landslides that specifically comprises the gentle slope of the front and the scarp of the head, side cliff, and end climax, as seen from aerial photographs of 20,000 to 1 scale as well as a geological reconnaissance and existing boring survey results. In the study area, the five major landslide areas of Oshiba, Kita-mametani, Ohmametani, Toga, and Iwabuchi are distributed in a row from the north to the south. It is noted that the distribution of landslides is regulated by the underlying rocks, and most of the landslides are distributed in the region of the Iwaine formation or Nirehara formation (Toyama Prefecture, 1992). Large-scale landslides are scarcely distributed in Funatsu granite rocks, except in the Oshiba district. However, regional surface slope failures are likely to occur in Funatsu granite distribution areas that are degraded by bedrock hydrothermal alteration. Although many large-scale compound slides are distributed on the right-bank side of the Toga River and the southern part, small-scale landslides are only locally distributed on the left-bank side. These large-scale landslides slope down to the west on the dip slope as a whole.

The large-scale landslide areas can be roughly divided into three areas, from a geological perspective, and from the occupying position of their sliding surface.

1) Oshiba district: No obvious scarp is noted. The basement rock consists of Funatsu granite rocks and cataclastic granite rocks penetrated by andesite dykes and has, overall, been subject to hydrothermal alterations. Boring core observations and data from borehole inclinometers indicate that the sliding surface likely occurred along a westward-tilted clay seam formed by regional hydrothermal alteration.

2) Kita-mametani and Ohmametani districts: Obvious scarp is noted, with landslide surface shapes of the bottleneck type. The Nirehara formation is distributed as dip slopes on the higher levels of the Funatsu granite rocks, while the volcanic rocks of the Iwaine formation are distributed in a cap rock shape on the uppermost layer. The surface layer is covered by colluvium from large-scale landslides and collapses in the past. Overall, the Iwaine formation has been altered to a green color and the Nirehara formation, composed of sedimentary rocks of sandstone bed and

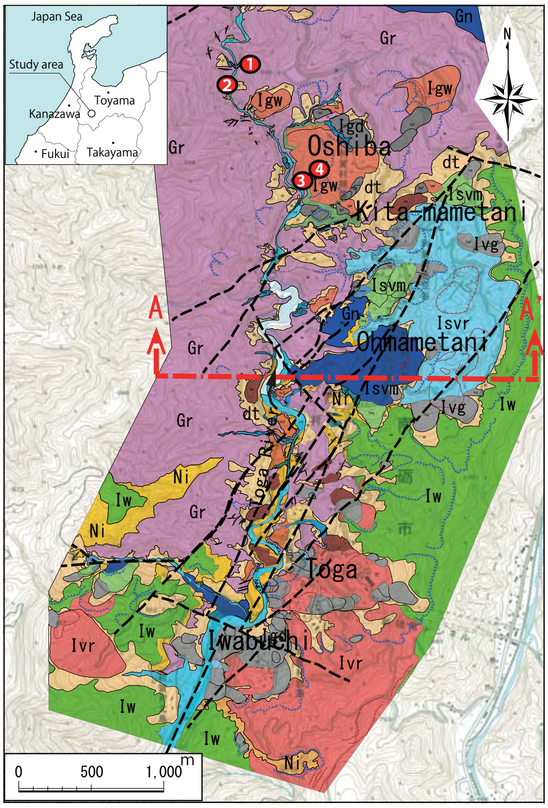


Fig. 1 Geologic map

Geology legend

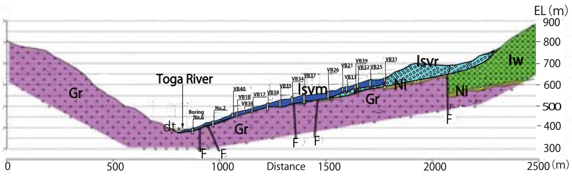
Iw :Iwaine Formation
Ni :Nirehara Formation
Gr :Funatsu granite
dt :detritus

╍╍╍ Fault inferred
Landslide topography
← Landslide direction

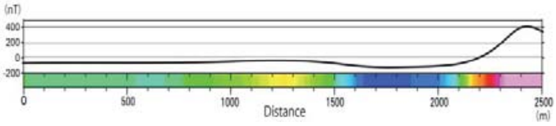
The landslide materials

Ivr :volcanic rock
Ivg :volcanic rock fragments
Isvr:sedimentary-volcanic rock
Isvm:clay mixed gravelly soil
Igd :granular gravelly soil
Igw :weathered granitic rock
A-A' : Cross section position
● Borehole

Legend of Figure 1-4



(a) A – A’ geologic cross section.



(b) A – A’ magnetic intensity.

Fig. 2 Geologic cross section and magnetic intensity

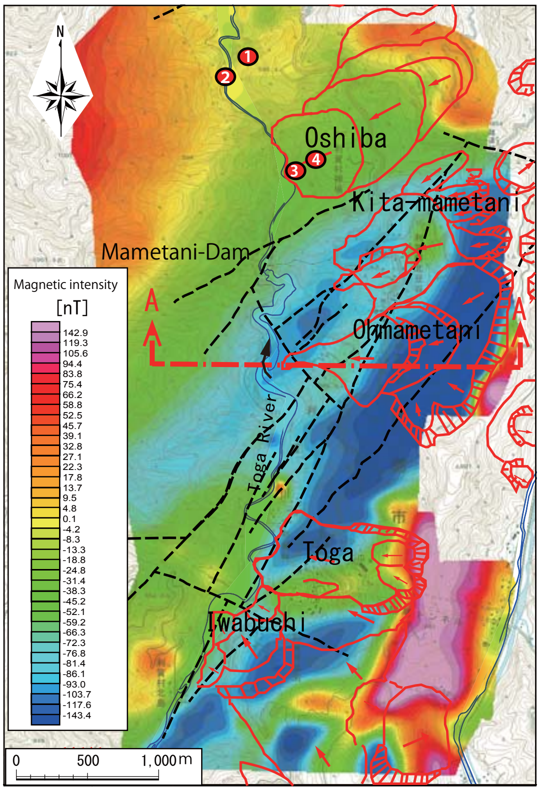


Fig. 3 Regional map showing IGRF residual magnetic anomaly, landslide topography, and landslide. Directions

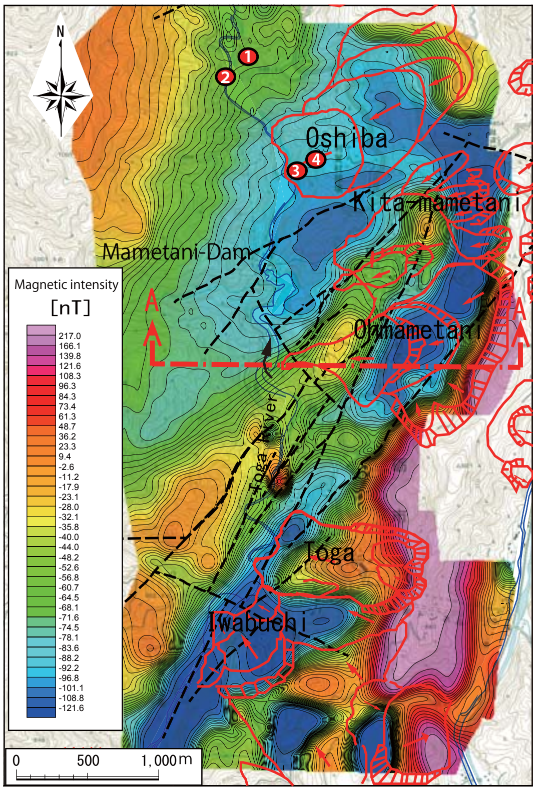
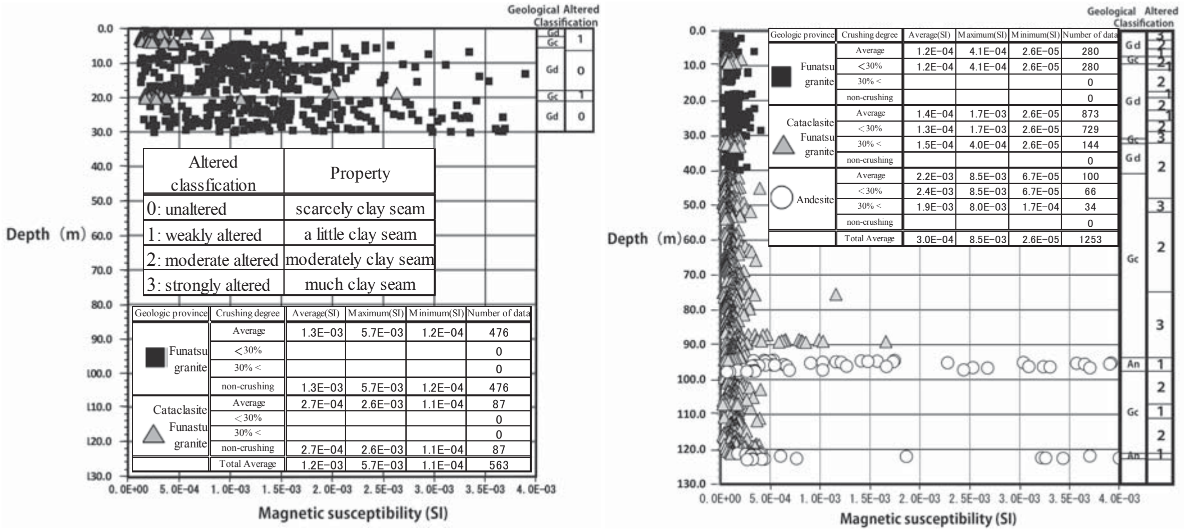


Fig. 4 Regional map showing Magnetic magnetic anomaly after RTP processing, landslide topography, and landslide directions.



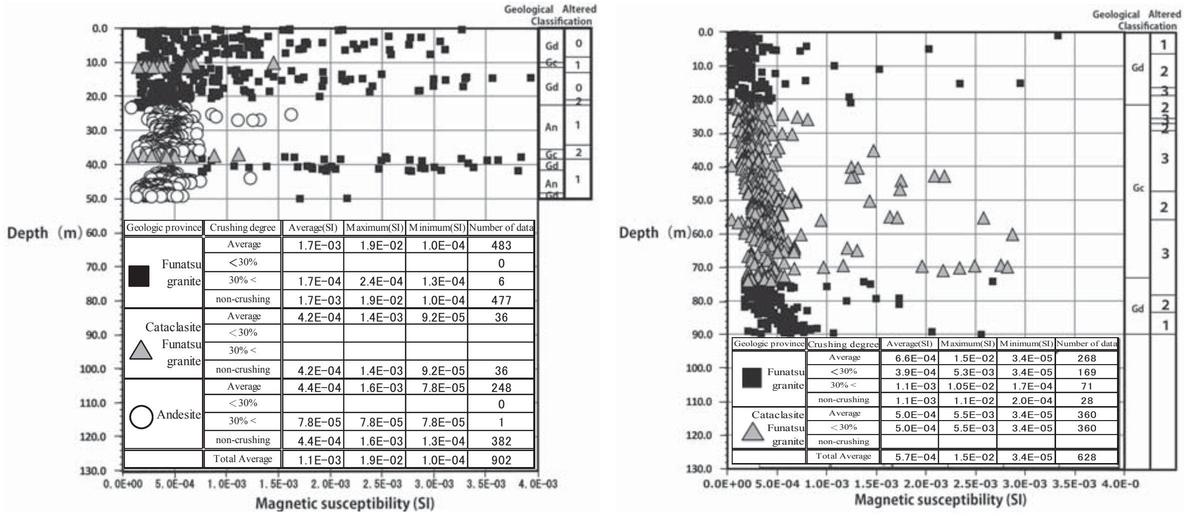
Altered classfication	Property
0: unaltered	scarcely clay seam
1: weakly altered	a little clay seam
2: moderate altered	moderately clay seam
3: strongly altered	much clay seam

Geologic province	Crushing degree	Average(SI)	Maximum(SI)	Minimum(SI)	Number of data
■ Funatsu granite	Average	1.3E−03	5.7E−03	1.2E−04	476
	<30%				0
	30% <				0
	non-crushing	1.3E−03	5.7E−03	1.2E−04	476
▲ Cataclasite Funastu granite	Average	2.7E−04	2.6E−03	1.1E−04	87
	<30%				0
	30% <				0
	non-crushing	2.7E−04	2.6E−03	1.1E−04	87
	Total Average	1.2E−03	5.7E−03	1.1E−04	563

（a）Magnetic susceptibility of No.1 core sample

Geologic province	Crushing degree	Average(SI)	Maximum(SI)	Minimum(SI)	Number of data
■ Funatsu granite	Average	1.2E−04	4.1E−04	2.6E−05	280
	<30%	1.2E−04	4.1E−04	2.6E−05	280
	30% <				0
	non-crushing				0
▲ Cataclasite Funatsu granite	Average	1.4E−04	1.7E−03	2.6E−05	873
	<30%	1.3E−04	1.7E−03	2.6E−05	729
	30% <	1.5E−04	4.0E−04	2.6E−05	144
	non-crushing				0
○ Andesite	Average	2.2E−03	8.5E−03	6.7E−05	100
	<30%	2.4E−03	8.5E−03	6.7E−05	66
	30% <	1.9E−03	8.0E−03	1.7E−04	34
	non-crushing				0
	Total Average	3.0E−04	8.5E−03	2.6E−05	1253

（c）Magnetic susceptibility of No.3 core sample



Geologic province	Crushing degree	Average(SI)	Maximum(SI)	Minimum(SI)	Number of data
■ Funatsu granite	Average	1.7E−03	1.9E−02	1.0E−04	483
	<30%				0
	30% <	1.7E−04	2.4E−04	1.3E−04	6
	non-crushing	1.7E−03	1.9E−02	1.0E−04	477
▲ Cataclasite Funatsu granite	Average	4.2E−04	1.4E−03	9.2E−05	36
	<30%				
	30% <				
	non-crushing	4.2E−04	1.4E−03	9.2E−05	36
○ Andesite	Average	4.4E−04	1.6E−03	7.8E−05	248
	<30%				0
	30% <	7.8E−05	7.8E−05	7.8E−05	1
	non-crushing	4.4E−04	1.6E−03	1.3E−04	382
	Total Average	1.1E−03	1.9E−02	1.0E−04	902

（b）Magnetic susceptibility of No.2 core sample

Geologic province	Crushing degree	Average(SI)	Maximum(SI)	Minimum(SI)	Number of data
■ Funatsu granite	Average	6.6E−04	1.5E−02	3.4E−05	268
	<30%	3.9E−04	5.3E−03	3.4E−05	169
	30% <	1.1E−03	1.05E−02	1.7E−04	71
	non-crushing	1.1E−03	1.1E−02	2.0E−04	28
▲ Cataclasite Funatsu granite	Average	5.0E−04	5.5E−03	3.4E−05	360
	<30%	5.0E−04	5.5E−03	3.4E−05	360
	non-crushing				
	Total Average	5.7E−04	1.5E−02	3.4E−05	628

（d）Magnetic susceptibility of No.4 core sample

Fig. 5 Magnetic susceptibility of the boring cores.

similar material, has also been altered. The sliding surfaces were formed primarily within the Nirehara formation, with the andesitic rocks of the Iwaine formation comprising the majority of the landslide moving bed. The geological profile is shown in Fig. 2 (a).

3) Toga and Iwabuchi districts: The landslide structure is of the cap lock type, with the Iwaine formation distributed with the Nirehara formation, and is partially trapped on the top level of the Funatsu granite rocks. Many andesite dykes penetrate the Funatsu granite rocks, with clay zones due to hydrothermal alterations often confirmed in the vicinity of the boundary with the Iwaine formation. Landslide moving clumps are thickly distributed in the lower section of slopes. Sliding surfaces are formed in the vicinity of the boundary between the Funatsu granite rocks and the Iwaine formation.

3. RESEARCH METHODS

3.1 Airborne magnetic survey

An airborne magnetic survey was conducted using a Scintrex CS2, a cesium magnetometer with a sensor towed by a helicopter. This CS2 magnetometer, with a sensitivity of 0.01 nT, was held at a height of 30 m above the ground during the flight survey. The survey lines were planned mainly in an east-west direction and arranged at intervals of 100 m. The length of each survey line was less than 3.5 km and the total length was approximately 186.6 km. At each survey line, the magnetic force was measured every 1.75 m. Data that could be clearly identified to represent steel towers, buildings, and related structures were deleted from the raw data. Furthermore, no altimetrical compensations were performed, since implementing altimetrical compensations in the research zone in the mountainous area smoothens the localized magnetic alterations at shallow levels resulting in magnetic abnormalities with unclear underground structures. Several corrections, such as diurnal correction and removal of the IGRF-7, were made to the observed data of the airborne magnetic survey. Sugimoto et al. (2013) used the data after correcting the effect of the earth's magnetic field by IGRF data. However, the residual magnetic anomalies that are used to determine the underground magnetic structure are sometimes difficult to determine using this method. The RTP method was considered to be an effective method for solving this problem (e.g., Bhattacharyya, 1965; Makino, 1993). Details of the RTP method are provided by Baranov (1957) and Baranov and Naudy (1964). In the RTP method, an observed magnetic anomaly is transformed into a magnetic anomaly that wouldresult had the area been surveyed at the magnetic pole (Nabighian et al., 2005). In this study, the RTP method has been applied to residual magnetic anomaly data after IGRF correction to study the relationship between the analyzed magnetic anomalies and the geology and/or geographical features in relation to the landslide. Before applying the RTP method, the magnetic anomaly data was subjected to the Kriging method for space interpolation. The earth's current magnetic field direction of the study area (E137° 02', N36° 27', elevation 500 m), which is the transformation parameter for the RTP analysis, is a declination (D) of -7.4° and an inclination (I) of 50.4°. Finally, a magnetic anomaly map of the Ohmametani area was created to compare the variation in magnetic force traversing the landslide region to the geological cross section.

3.2 Study of the boring core

Four boring cores were drilled in the study area. Cores No. 1 (length: 30 m) and No. 2 (length: 50 m) were taken at the northern sites in the fresh Funatsu granite, and cores No. 3 (length: 120 m) and No. 4 (length: 90 m) were taken at the Oshiba sites in the hydrothermally altered zone. The rock types and the alteration grading were examined through all the cores. The magnetic susceptibility was subsequently measured every 5 cm on the core, using a Bartington MS-2K magnetometer. Further, microscopic and x-ray powder diffraction analyses were conducted on samples from the clayey seam of core No. 4 to examine the relationship between the minerals and/or the alteration degrees of the clay and the mechanism of landslide.

We conducted two kinds of X-ray analysis using: 1) a whole-rock indefinite orienting method; and 2) an elutriation and orienting reaction method (ethylene glycol treatment). The airborne magnetic anomalies after IGRF and RTP corrections were then compared with both the geology and the data obtained from the boring cores.

4. RESULTS

4.1 Airborne Magnetic Survey Results

Figure 3 shows an IGRF residual magnetic anomaly map of the study area acquired by the airborne magnetic survey, and Fig. 4 shows the RTP distribution map. In Figs. 3 and 4, the strong magnetic field is shown in a warm color and the weak magnetic field is shown in a cold color. Distributions of the positive and negative anomalies are more obvious with RTP transformation. High magnetic anomaly zones are observed at the eastern to southeastern parts of the Iwaine formation as well as in a southwesterly direction from Kita-mamedani in the Funatsu granitic rock area (Fig. 4). Conversely, low magnetic anomalies are significant from northeast to southwest in the study area. Intense low magnetic anomalies are also observed in the southwesterly directions from Oshiba to the left bank of the Toga River. Linear magnetic anomalies with low and high values are observed clearly in the Kita-mamedani to Iwabuchi area.

The distributions of the magnetic anomalies are compared with the main landslide area and the other districts:

1. Oshiba: The bedrock in the Oshiba landslide area consists of Funatsu granitic rocks. No clear scarp is found in the study area. RTP transformation shows that low magnetic anomalies are observed from Oshiba to the Mametani dam (in a NE-SW direction), particularly in the middle of the slope. The upper slope is a high magnetic anomaly.

2. Kita-mametani and Ohmametani: Low magnetic anomaly is observed in the entire area of the landslide with the IGRF-corrected data. After RTP transformation, a clear low magnetic anomaly is found over the top of the hillside around the Ohmametani district and at the top of the Kita-mamedani district.

Figure 2(b) shows the magnetic field intensity for the A-A’ survey line in the Ohmametani district. The magnetic field intensity for this survey line is as low as -70 to -30 nT between the 0 m and 1300 m point on the distance table in the Funatsu granitic areas. The magnetic field intensity continuously decreases between the 1300 m and 2070 m points on the distance table, and the lowest value of -120 nT is observed at the 1800 m point in the detritus area. The magnetic field intensity then gradually increases between the 2070 m and 2500 m points on the distance table, and the highest value of 420 nT is observed at the 2420 m point within the Iwaine formation.

3. Toga and Iwabuchi: The magnetic anomaly at the bottom of the slope in the Toga-Iwabuchi district is detected as a strong low magnetic anomaly using RTP transformation. A strong low magnetic anomaly extends in a NE-SW direction along the fault. Conversely, the magnetic anomaly at the top of the slope is shown to be a high magnetic anomaly.

4.2 Magnetic susceptibility measurement results and boring core descriptions of boring cores

Figure 5 shows the results of the magnetic measurements and descriptions of cores. Cores No. 1 and No. 2 consist of unweathered Funatsu granite and cataclastic granite with clay seams in the fracture. The andesitic dyke with clay seams has intruded into core No. 2. The averaged magnetic susceptibilities at a depth of 30 m in core No. 1 and at a depth of 50 m in core No. 2 is 1.1×10^{-3} SI and 1.2×10^{-3} SI, respectively. A high average magnetic susceptibility of 1.3–1.7×10^{-3} SI is observed in the Funatsu granite. Conversely, the susceptibilities of the cataclastic Funatsu granite and andesitic dyke are a low average of 2.7–4.2×10^{-4} SI and 4.4×10^{-4} SI, respectively.

Cores No. 3 and No. 4 consist of weathered and fractured Funatsu granite, cataclastic Funatsu granite, and an unweathered andesitic dyke with a small white clay seam. The fractured and fine-grained cataclasite granite is browned by weathering. At a depth of 120 m in core No. 3 and at a depth of 90 m in core No. 4, the low averaged magnetic susceptibilities are shown to be 3.0×10^{-4} SI and 5.7×10^{-4} SI, respectively. The averaged susceptibilities for the weathered Funatsu granite and the cataclastic Funatsu granite are low values with an average of 1.2–6.6×10^{-4} SI and 1.4 –5.0×10^{-4} SI, respectively and the susceptibility of andesite is 2.2×10^{-3} SI.

4.3 Microscopic observation and result of x-ray powder diffraction

Based on microscopic observation of the five samples from the clayey area of core No. 4 (Table 1), it is clear that biotite changed to chlorite, and that feldspar

Table 1. The minerals observed by microscope of the boring cores No.4

Sampling position	Rock name	Main constituent mineral	Alteration mineral
64.55m	Cataclastic Funatsu granite	Quartz, Potassium feldspar Plagioclase, biotite	Chlorite, Calcite
67.60m	Cataclastic Funatsu granite	Quartz, Fine mineral	Calcite
68.80m	Cataclastic Funatsu granite	Quartz, Potassium feldspar Plagioclase, biotite	Chlorite, Calcite
74.00m	Funatsu granite	Quartz, Plagioclase Potassium feldspar, biotite	Chlorite, Calcite
85.90m	Funatsu granite	Quartz, Plagioclase Potassium feldspar, biotite	Chlorite, Calcite

Table 2. Clay minerals analyzed by X-ray Powder diffraction of the boring cores No.4

Mineral indetification		Sample①		Sample②		Sample③		Sample③		Sample④	
		58.55-58.70m		61.50-61.10m		67.55-67.58m		67.80-67.90m		68.35-68.40m	
		Whole rock	Elutriation	Whole rock	Elutriation	Whole rock	Elutriation	Whole rock	Elutriation	Whole rock	Elutriation
Alteration mineral	Chlorite	1※	6	1	2	1	2	1	3	1	9
	Sericite	2	13	4	15	4	15	2	14	2	13
	Calcite	1		1		1		4		3	
Juvenile mineral	Quarts	30		28		28		31		32	
	Feldspar	14		16		16					

※The numbers represent the quartz index.

changed to calcite. Calcite, chlorite, and sericite were determined for all five samples using x-ray diffraction (Table 2).

5. DISCUSSION

5.1 Relationship between magnetic minerals (classification, degree of alteration) and magnetic susceptibility

Magnetic anomaly depends on the magnetic susceptibility and natural remanent magnetization (NRM) of magnetic rock. Magnetic susceptibility is the ratio of induced magnetization that appears in response to the external magnetic field.

And magnetic susceptibility can be changed with the concentration, composition, and grain size of the magnetic minerals present in the materials (Sakai et al., 2001; Tarling et al., 1993). The remanent magnetization in igneous rock is primary thermal remanent magnetization, which is acquired in the cooling process during the formation of igneous rocks. Furthermore, subsequent secondary magnetization, such as viscous remanent magnetization, could be acquired since rocks have formed. Sugimoto et al. (2013) found that induced magnetization was very much stronger than residual magnetization in this study area, resulting in a major source of the magnetic anomaly. Hence, the effect on magnetic susceptibility due to alteration and the type of mineral was investigated. Based on a combination of the major altered minerals, the Oshiba district is likely affected by regional propylite mineralization under neutral hot water at between 100 and 300°C (Utada, 1990; Sugimoto et al., 2013), and the magnetic minerals in granodiorite were clearly altered to weaker magnetic minerals. As shown in Fig. 5(d), the 56.3–79.0 m section of core No. 4 is a strongly altered zone with a core of low magnetic susceptibility (10^{-4} SI).

Both the Funatsu granite and cataclastic Funatsu granite have been altered along numerous cracks to clay or clay seams by hydrothermal processes, resulting in lower magnetic susceptibility. As a result of observation of core No. 3, strengths and weaknesses were found in the alteration classification. In the andesitic dyke, the degree of alteration is relatively low overall, with andesite preserving the magnetic susceptibility of the source rock. However, the magnetic susceptibility of Funatsu granitic rocks is uniformly low. It is believed that this entire region was affected by hydrothermal alteration, which led to a reduction in magnetic susceptibility of the granitoids, so that major magnetic susceptibility changes are no longer preserved. In the drill core, alteration zone No. 3, which contains numerous clay layers, represents a slip surface. Within this zone, the 75.5–94.0 m depth range can be considered to be the horizon with the deepest slip surfaces.

Core No. 4 at a depth of 85.9 m consists of Funatsu granite and cataclastic Funatsu granite, which have been altered along a number of cracks to clay seams or clay beds due to hydrothermal alteration, resulting in a lowering of the magnetic susceptibility (10^{-4} SI). Hot water penetrates into cracks along the rock and, in places where the cracks have not been altered, the magnetic susceptibility is high (10^{-3} SI).

On the other hand, high magnetic susceptibility is observed in cores No. 1 and No. 2 (Figs. 5(a) and (b)) in the unweathered hard Funatsu granite in the northern part of the study area. However, a green-gray clay seam is found in the fracture, and low magnetic susceptibility is therefore observed in cataclastic Funatsu granite with many normal-sized and hairline cracks. In addition, the andesitic dykes of core No. 2 are seen to be green-gray, and have therefore been hydrothermally altered by the presence of clay, and have low magnetic susceptibility. These conditions are consistent with the alteration classification of this core. In contrast, the andesitic dykes of core No. 4 have high magnetic susceptibility in fresh black rock. In this way, the level of magnetic susceptibility reflects the degree of alteration and types of minerals in the Funatsu granitic and the andesitic dyke rocks.

5.2 Comparison of magnetic pole anomaly results, magnetic susceptibility measurement results, and results of the boring cores

The airborne magnetic survey results are compared to the magnetic susceptibility results and the observation results of the boring cores in the Funatsu granitic rock area. In the northern study area, at a depth of 30-50 m, cores No.1 and No. 2 at a depth of 30-50 m have high magnetic susceptibility (10^{-3} SI) with a high averaged magnetic susceptibility of 1.1 — 1.2×10^{-3} SI in fresh granite. The pole magnetic anomaly in this area is a low magnetic anomaly of -40 nT. In contrast, cores No. 3 and No. 4 at a depth of 120-90 m, consisting predominantly of Funatsu granite that has been hydrothermally altered with cataclasite facies, have low magnetic susceptibility of 3.0-5.7×10^{-4} SI, respectively. The magnetic anomaly of the Oshiba region is remarkably low at -90 nT. Therefore, the magnetic pole anomalies are clearly concordant with the magnetic susceptibilities of the shallow cores.

An airborne magnetic survey measures the integrated value of the magnetic field by the constituents of each depth. The magnetic field is attenuated in inverse proportion to the cube of the distance from the target material. Therefore, magnetic anomaly by airborne magnetic survey reflects the distribution of magnetization substances that are distributed more greatly in the shallow part. Sugimoto and Sakai (2013) reported the validity of the magnetic survey in the tunnel that is covered with soil of up to 150 m in this study area.

Locations of low magnetic anomaly are zones where rocks and colluvium are distributed predominately in the shallow subsurface. Therefore, using aeromagnetic survey data is suitable for identifying locations with unstable slopes, which have a risk of landslides.

Conversely, if strongly magnetized rocks are predominately present at the shallow subsurface, they would blind out any colluvium layers at the subsurface.

5.3 Relationship between geology and magnetic anomaly distribution

As shown by the magnetic anomaly map in Fig. 4, the boundary between the low and high magnetic anomaly values is located in a line passing from Kitamamedani to the Iwabuchi district, where Funatsu granitic rocks are on the northwest side of the boundary and early Neogene volcanic rocks are on the southeast side. This boundary corresponds to a normal fault trending north-northeast of the eastside moving downward (Figs. 1 and 2); the linear magnetic anomalies are concordant with the trend of the inferred fault location in the estimation of faults and the geological boundary. The fresh Funatsu granitic rocks in the northern study area show high magnetic susceptibility as observed in the core samples (Fig. 5). Conversely, the Funatsu granitic rocks of the Oshiba district have low magnetic susceptibility due to hydrothermal alteration. However, there is no significant difference in the susceptibilities of the Funatsu granite and the cataclastic granite, indicating that cataclasis does not change the susceptibility.

Hence, the intensity of the magnetic anomaly reflects the degree of alteration of the Funatsu granitic rocks. Low magnetic susceptibility is likely produced by hydrothermal alteration, weathering, and/or grain size reduction caused by disruption due to landslides. Therefore, the strength of the magnetic anomaly reflects the occurrence and history of landslides and the degree of deterioration of the Funatsu granitic rocks.

The magnetic anomaly is also compared with the regional geology of the A-A' cross section shown in Fig. 2(a), (b). The thicker the deposition layer of colluvium is, the weaker the magnetic field observed. The observed smallest magnetic field is found at the maximum thickness of the deposition. The Iwaine formation region consists of ash breccia curd and andesite, causing a strong magnetic field. In this area, there is a positive correlation between the magnetic field and the layer thickness, and there is a correlation with the layer thickness and the layer changes in the landslide colluvium. Ikeda et al. (1973) reported that the magnetic field changes with the geological structure. Here, we have shown a positive relationship between the magnetic field and geological structure in igneous-rock-distributed areas.

5.4 Relationship between landslides and other regions and the magnetic anomaly distribution

The airborne magnetic survey results are compared to the geological structures of the major landslide areas and other regions:

1. Oshiba: The landslide area clearly appears as a low magnetic anomaly area by RTP transformation. The Funatsu granitic rocks are obviously altered by hot water from deep underground to the surface, and especially significant alteration by hot water as well as extremely low magnetic anomaly was found at the middle of the slope. A hydrothermal alteration zone in the bedrock is found after RTP transformation. Moreover, two Igw locations show very different magnetic strengths. Based on geological reconnaissance as well as boring survey results, the layer thickness of Igw reached a maximum of 100 m near the bottom, whereas the Igw thickness was thinner in the upper part, reflecting the influence of the high magnetic anomaly of the Funatsu granite.

2. Kita-mamedani and Ohmametani: The extremely low magnetic anomaly area from the middle to the upper area of the landslide correlates with the layer thickness of the landslide colluvium. In addition, a thin depositional area of the landslide colluvium on the lower slope soil corresponds to the places where the Funatsu granite shows high magnetic anomaly. The thick detritus from the landslide collapse is concordant with the low magnetic anomaly found by RTP transformation. In addition, the thin detritus area in the lower part of the slope shows high magnetic anomaly, which is likely caused by the strongly magnetized Funatsu granitic basement.

3. Toga and Iwabuchi: The middle and upper parts of the slope show high magnetic anomaly. This region is consistent with the unaltered Iwaine formation. However, the lower slope of the landslide area shows a significant low magnetic anomaly, because the edge of the low-susceptibility Nirehara formation and Funatsu granitic rocks has been hydrothermally altered by the dyke and thick colluvium is distributed.

4. Other low magnetic anomaly area: Visual observation during tunnel construction indicates that low magnetic anomalies on the left-bank side of the Toga River are likely to have originated in the cataclastic Funatsu granitic and Funatsu granitic basement that contained numerous cracks, which were commonly altered by hydrothermal processes to clay seams and veins. Where alteration pervades the core of the rock, white clay is common and the rocks show low magnetic anomalies (Sugimoto and Sakai, 2013).

The Funatsu granite zone of the Toga region is characterized by many small faults. The dip of these faults is the dip slopes with a NW trend, causing one of the most important predisposing factors for landslides on the right-bank side. In contrast, on the left-bank side, the dips of the faults are opposite slopes and a slope failure region is therefore likely to occur in the surface layer portion undergoing deterioration.

In addition, intense low magnetic anomalies are observed within the Oshiba to Kita-mamedani area. This district, which consists of well-developed fractures and faults and contains numerous clay veins formed by hydrothermal alteration, is more likely to undergo slope failure. Hence, this area has become a thin-ridged terrain with deep erosion valleys.

6. Summary

An airborne magnetic survey has been conducted for a landslide area located at the boundary between the Hida belt and the green tuff region in southwestern Toyama Prefecture. In addition, boring cores taken from the region were subjected to susceptibility measurements and x-ray diffraction. RTP transformation clearly defines the magnetic anomaly distributions, and the results are compared with the geological structure of the unstable slope, i.e., the landslides.

The following results were obtained:

1) The high and low magnetic anomaly distributions are shown more clearly by RTP transformation than by solely using the IGRF residual magnetic anomaly. The area where igneous rocks are distributed shows high magnetic anomaly, and the hydrothermally altered zones and/or areas where there are colluvial deposits of landslides have low magnetic anomaly. This linear magnetic anomaly is clearly observed in such areas and the anomaly is concordant with the locations of the fault and geological boundary.

2) It was confirmed that the high and low magnetic anomalies of the Funatsu granitic rock distribution area are controlled by changes in layer thickness of landslide collapse material and extent of weathering and hydrothermal alteration along cracks and faults, as supported by data from boring core investigations. And magnetic anomalies observed by an airborne magnetic survey correlate with the distribution of remanent magnetization in the shallow part. In addition, the surface layer covered by thick colluvium deposited by collapse and landslides shows extremely low magnetic anomaly. The observed magnetic field intensities correlate with the geological structures of the Iwaine layer distribution and with the colluvium layer thickness in the landslide area. These results indicate that magnetic anomaly is useful for determining the predisposition of an area to a major landslide. Aeromagnetic surveys could identify the distribution of collapsed soil sediments in the Neogene as well as the areas of Funatsu granitic rock with a high potential for landslides. Low aeromagnetic intensities identified zones where the colluvium layer in landslide areas, as well as hydrothermally altered and weathered rocks, occurred predominately in the shallow subsurface. This method can be used to efficiently screen large areas for potentially unstable slopes that may lead to the occurrence of landslides.

3) The results of boring core investigations led to the development of an alteration classification for different rock units. In hydrothermally altered Funatsu granitic rocks, the magnetic susceptibility has decreased throughout the entire core demonstrating the effects of hydrothermal alteration. However, in areas where hot water had not penetrated the entire core, strong magnetism without alteration was preserved. The degree of hydrothermal alteration cannot be determined by core observations alone.

The degree of alteration with depth might easily by determined by measurement of the magnetic anomaly of drill cores at each depth. Magnetic survey of drill cores is effective because it would provide information about the correlation between the geology, lithology, and magnetism.

As future works, various topographical effects as well as variations in magnetic anomaly with depth should be considered. Further research is also suggested in order to test the applicability of such surveys to complex geological areas and sedimentary distribution areas with weak magnetism.

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