COOLING OF THE SHALLOW SUBSURFACE BENEATH KUJU VOLCANO, CENTRAL KYUSHU, JAPAN DEDUCED FROM GEOMAGNETIC CHANGES

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SUMMARY - Repeat geomagnetic measurements were started in 1999 at Kuju volcano located in central Kyushu, Japan. Geomagnetic changes, up to more than 30nT per year, were observed, and this result shows that magnetization and cooling have taken place in the shallower part beneath Kuju volcano after the 1995 phreatic eruption and that the rates of magnetization and cooling are becoming smaller with time. Combining the results of heat discharge measurements and repeat gravity measurements, it is concluded that this magnetization occurred by the cooling of the shallower part beneath Kuju volcano by the increased meteoric water circulation.

1. INTRODUCTION

A phreatic eruption occurred at Kuju volcano in October 1995. This volcano is located in central Kyushu, Japan and the new craters area (called D-region) formed 300 m south of the pre-existing fumarolic areas (called **A,** B and C-region; Figure 1). Continuous geomagnetic measurements started after November 1995, and geomagnetic changes, up to more than 40nT per year, were observed (Tanaka et al., 1998). Repeat geomagnetic measurements were carried out four times from 1999 to 2000 (Sakanaka et.al., 2001).

We started our repeat geomagnetic measurements in 2001, and have since carried out nine surveys. We discussed the observed magnetic data in earlier papers where we presented preliminary magnetic and thermal models (Ehara et al., 2000, Ehara et al., 2002). This paper discusses the detailed magnetic and thermal changes of the shallower part beneath Kuju volcano based on the results of repeat geomagnetic measurements, heat discharge, and gravity measurements.

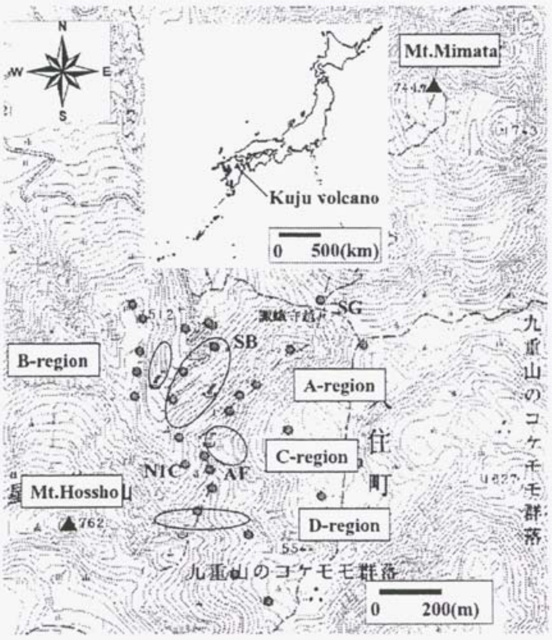


Figure 1. Location of Kuju volcano, central Kyushu, Japan and the positions of repeat geomagnetic measurements (solid circles). **A, B** and C-region are pre-existing fumarolic areas, and D-region is the new craters area.

2. GEOMAGNETIC MEASUREMENTS

There are about 30 observation points for repeat geomagnetic measurements **in** the central part of Kuju volcano (Figure 1). Geomagnetic intensity was measured using an Overhauser magnetometer (GSM-19). The reference point is at **Aso** Volcanological Laboratory, Kyoto University, which is about **30** km southwest of Kuju volcano.

The results of these measurements (Figure 2) clarified that the geomagnetic intensity decreased in the northern part (SB, SG) but increased in the southern part (N1C, AF), and that the rates of geomagnetic change are still very large, up to more than 30nT per year. These results show the tendency of magnetization beneath the central part of Kuju volcano. Moreover, the rates of geomagnetic change during the period from 2001 to 2002 are becoming smaller, compared with the rates of geomagnetic change during the period from 1999 to 2000; that is, the rate of magnetization is becoming smaller with time. The rates of geomagnetic change during the two periods are shown in Figure 3.

3. ANALYSIS AND DISCUSSION

3.1 Magnetic Model

The geomagnetic intensity decreased in the northern part of the survey area but increased in the southern **part,** during the two surveys. These geomagnetic changes can be explained by a magnetic dipole in the same direction of the present geomagnetic field. Therefore, the location

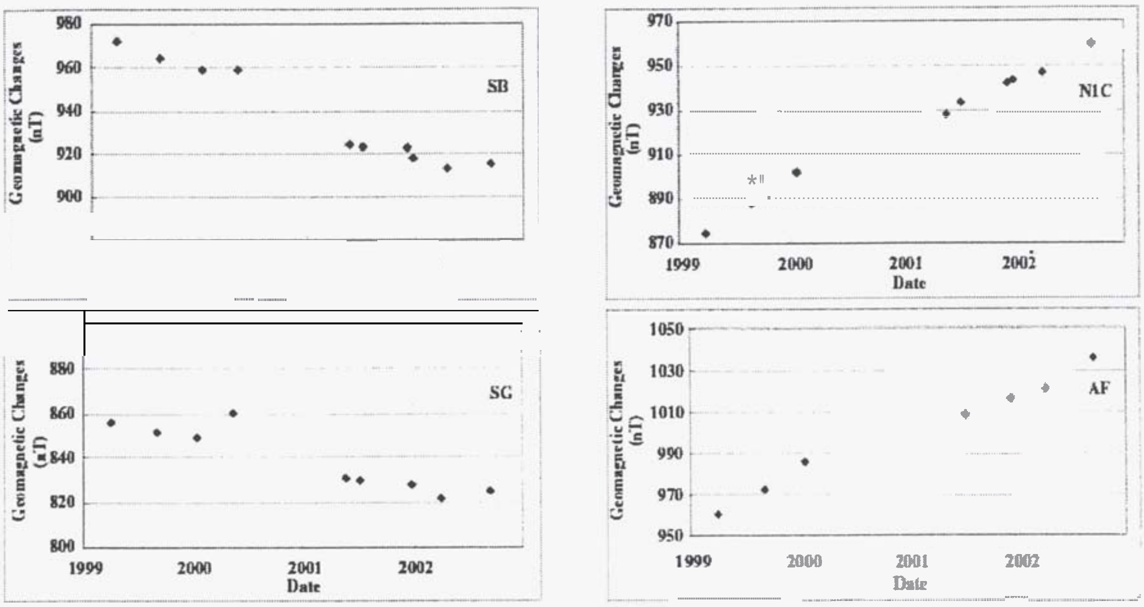
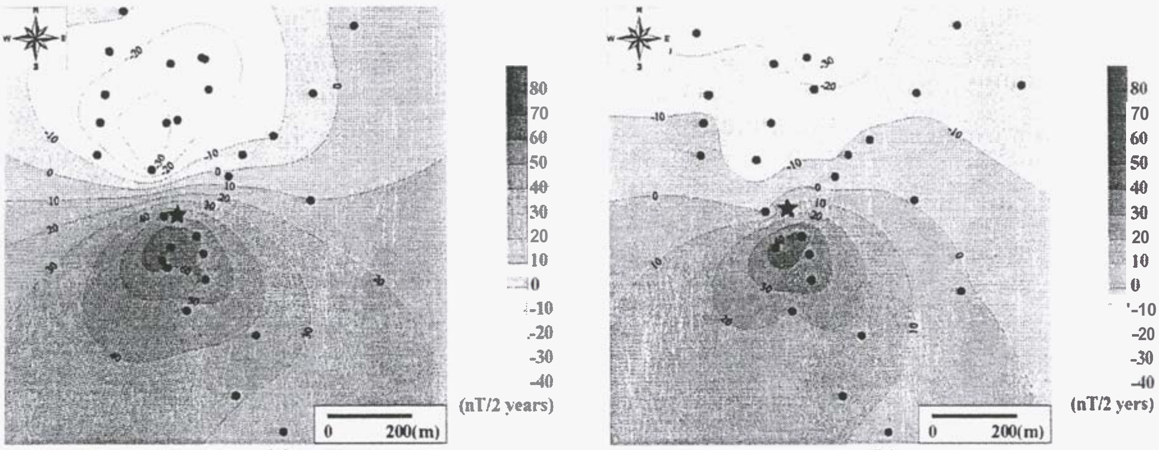
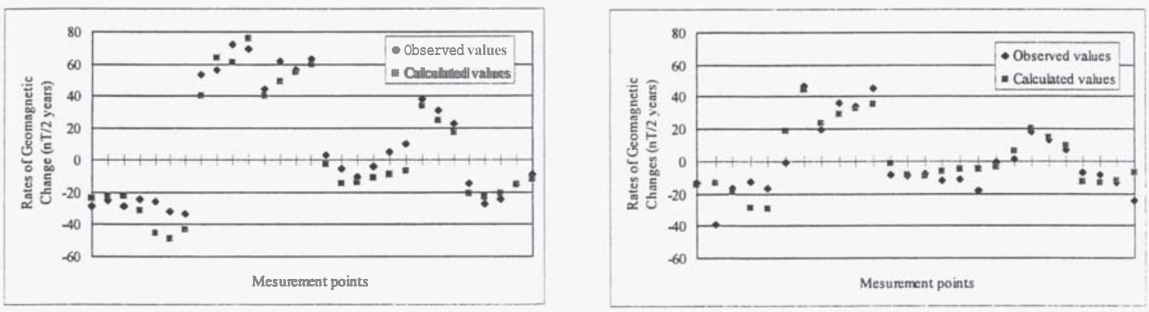


Figure 2. Geomagnetic changes at Kuju volcano. Values are referred to the geomagnetic intensity at Aso Volcanological Laboratory, Kyoto University, which is about 30km southwest from Kuju volcano.



(a) (b)

Figure 3. The rates of geomagnetic change during periods from 1999 to 2000 (a) and from 2001 to 2002 (b). The solid circles show repeat geomagnetic measurement points. The star shows the horizontal position of the estimated magnetic dipole.



(a) (b)

Figure 4. Comparison of the observed and calculated rates of geomagnetic change during the periods from 1999 to 2000 (a) and from 2001 to 2002 (b). Values are the rates of geomagnetic change during 2 years.

of the magnetic dipole was calculated. As a result, the magnetic dipole was estimated at approximately 400 m depth beneath the A-region of the active fumarolic area (Figure 3) during both periods.

The estimated position of the magnetic dipole is in the two-phase geothermal reservoir which is modelled by numerical simulation (Ehara, 1992). We assumed that the two-phase geothermal reservoir beneath the active fumarolic areas cooled and magnetized after the 1995 phreatic eruption. The radius and thickness of the cylindrical geothermal reservoir are 250 m and 2000 m, respectively. Preliminary calculations show that magnetization shallower than 200 m depth does not reflect the observed rates of geomagnetic change. Accordingly, we assumed that the magnetized region is between 200 m and 2000 m depth. This model was assumed to have magnetization of 2A/m and to magnetize in the same direction of the present geomagnetic field (inclination: 47°; declination: N6°W).

As a result, the magnetic changes from 1999 to 2000 and from 2001 to 2002 can be explained by the cooling of a cylindrical body with a radius between 250 m and 231 m (the volume is $5.2\times10^7 m^3$) and between 231 m and 219 m (the volume is $3.1\times10^7 m^3$), respectively. The cooling volume becomes smaller with time. Figure **4** shows the comparison of the observed and calculated rates of geomagnetic change.

3.2 Geomagnetic Changes and Heat Discharge Rates

We estimated the rates of heat discharged from the volume of the magnetized body. The discharged heat Q is estimated from equation (1):

$$Q = V \rho c AT \qquad (1)$$

where V is the magnetized volume ($5.2\times10^7 m^3$: from 1999 to 2000; $3.1\times10^7 m^3$: from 2001 to 2002), ρ is the density (2300 kg/m^3), c is the specific heat (1000J/kg deg K) and **AT** is the temperature decrease (200 deg K).

The rates of heat discharged from the magnetized body are estimated at 380 MW from 1999 to 2000 and at 220 MW from 2001 to 2002.

The rate of heat discharged at the surface is estimated independently using a remote sensing measurement method of steam and heat discharge (Jinguuji and Ehara, 1996), as shown in Figure 5. The heat discharge rates from 1999 to 2002 range from 500 to 1000 MW.

The difference in the heat discharge rate between the above two estimates is considered to be supplied from the deeper part beneath the geothermal reservoir.

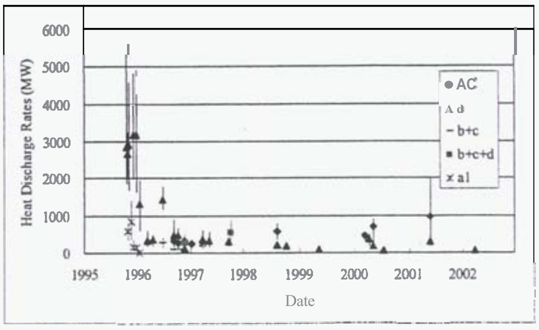


Figure 5. Heat discharge rates from the pre-existing fumarolic areas (shown in capital letters) and the new craters area (shown in small letters).

3.3 Geomagnetic Changes and Water Mass Balance

Nishijima et al. (2000) estimated the water mass balance based on gravity changes and steam discharge rates from December 1997 to May 2001 (Figure *6)*. From Figure 6, a large amount of underground water (21,500 t/day) is recharged from surroundings, and underground water (16,000 t/day) is heated, evaporated and discharged to atmosphere. Therefore, evaporation and discharge of the underground water are considered to cause the cooling and magnetization of the shallower part beneath Kuju volcano.

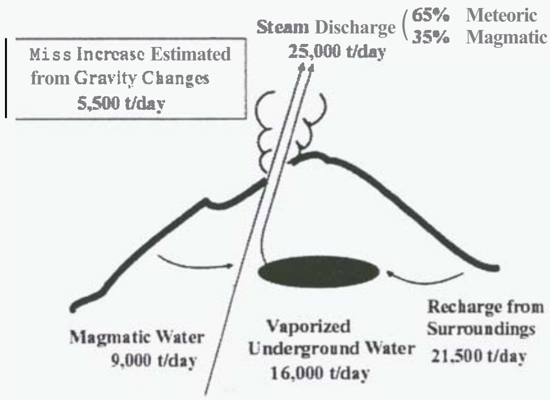


Figure *6*. Water mass balance from December 1997 to May 2001 (Nishijima et al., 2000).

4. CONCLUSIONS

Repeat geomagnetic measurements were started in 1999 at Kuju volcano. The observed geomagnetic changes clarified that the shallower part beneath Kuju volcano was magnetized and that the rate of magnetization was becoming smaller with time. The magnetization was interpreted in terms of cooling of the shallower part by the meteoric water recharged to the central part of Kuju volcano.

5. ACKNOWLEDGEMENTS

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