TWO-DIMENSIONAL INTERPRETAION OF MT DATA FROM MID-MOUNTAIN AREA OF JEJU ISLAND, KOREA

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ABSTRACT

Two-dimensional magnetotelluric (MT) surveys have been carried out at the mid-mountain area of Jeju Island to figure out any possible structures or evidences for remnant deep geothermal energy. Though numerous drillings have been performed in Jeju Island for development of ground water, the wells are mostly located along the coast lines or at low altitude area, but can hardly be found on the mid-mountain area. Two-dimensional (2-D) inversion of MT data for four survey lines surrounding the Halla mountain showed a thick layer having around 10 ohm-m in the depth of a few hundred meters throughout the survey area, which can be considered as the unconsolidated sedimentary layer and the marine originated sedimentary layer. They also showed a conductive anomaly extending to more than 2 km depth at the central part of each survey line, which can possibly be related with old volcanic activities during the formation of Mt. Halla. Further geological/ geophysical investigations will be followed.

Keywords: two-dimensional, magnetotelluric (MT) survey, Jeju Island, geothermal

1. INTRODUCTION

Jeju Island is a Quaternary volcanic island located in the south sea of Korea and is one of the most famous tourist spot in Korea. It is 31 km wide and 75 km long in the ENE direction, and 1,800 km^2 in area (Fig. 2). It has Mt. Halla (1,950 m high) and over 360 parasitic cones (called "Oreum" in Jeju dialect) all across the island. Mt. Halla has gentle slopes in the east and west while steep slopes in the south and north. It last erupted in 1007 AD and the last volcanic activity (earthquakes) has been reported in 1570.

Several deep (>800 m) and more than a thousand of shallow boreholes that have been drilled to exploit hot springs and groundwater revealed that the basaltic lava flows are underlain by a few hundreds of meter thick sedimentary rocks (Seogwipo Formation,) and the U formation (Unconsolidated sediment formation) of Plio-Pleistocene age, and Cretaceous basement rocks (Fig. 1). The basement rocks are mainly welded tuffs and granites, which lie at depth about 250 ~ 300 m below the sea level.

Apart from the great mass of volcanic rock forming Mt. Halla which dominates the central part of the island, there are more than three hundred much smaller volcanoes scattered over its lower slopes. Like the main volcano, these were the source of both volcanic ash and lava flows. Near the coast, where hot molten rock, moving upwards to reach the ground surface, encountered cold seawater, violent explosions occurred and particular structures were formed. K-Ar ages of the volcanic rocks range generally between 1.2 and 0.03 Ma (Lee et al., 1994).

Seogwipo Formation (SF) is formed by sandstone and mudstone including fossil of shallow marine sediments. K-Ar age of the bottom most part is accumulated in 1.66 Ma and topmost part is 0.46 Ma. It lies more than 50 to 60 m below the sea level with average thickness of 100 m. Because of its low hydraulic permeability, SF is known to serve as a confining unit of groundwater (Koh, 1997). Particularly, the layer has not been found from the boreholes in eastern part of the island.
The SF is underlain by a Pliocene unconsolidated sedimentary sequence (UF), which is named the U Formation (Koh, 1997). The thickness of this formation is between 70 and 250 m (150 m on average) and it is composed mostly of well-sorted, quartzose fine sand and silt, which accumulated before the onset of Jeju volcanism.

Though more than a thousand of boreholes have been drilled within the island, most of drillings and geological investigations are concentrated only on the areas at low elevation or near the sea shore, where most of populations are accumulated, for development of groundwater or hot springs. Consequently, geology of the mid-mountain area has not been studied well.

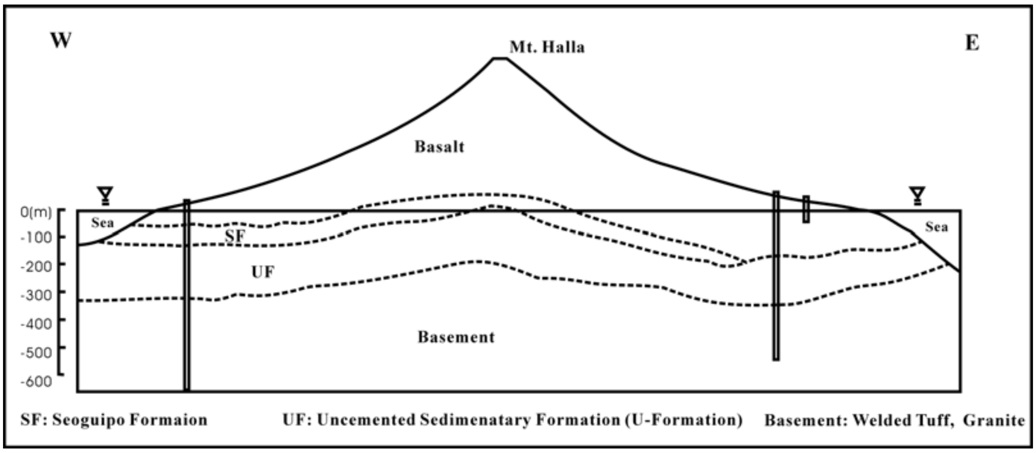

Fig. 1. Schematic model showing generalized stratigraphy of Jeju Island (modified from Koh, 1997)

In 2004 and 2005, Korea Institute of Geoscience and Mineral Resources (KIGAM) and National Institute of Advanced Industrial Science and Technology (AIST), Japan performed joint magnetotelluric (MT) surveys at mid-mountain area of Jeju volcanic island to cover the lack of geological information. The major purpose of the surveys is to figure out the deep geologic structures at mid-mountain area, which may related with remnant thermal regime associated with volcanic eruption.

During the MT survey, we tried a new but efficient methodology to acquire the AMT data together with the MT data. AMT and MT techniques are essentially the same, differing only in the frequency range captured. Thus, replacing the magnetic sensors (coils) and the sampling rate makes it possible to acquire the AMT data from the MT set-up that is already made at the site. MT survey mainly focuses on the deep geological targets rather than shallow ones. In most cases, MT survey data can give a good estimation of the subsurface structure from the shallow to the deeper part. Inhomogeneous shallow structures, however, will affect the interpretation of the deep structures as well because the measured quantity results from integration of EM fields over a certain depth range depending on operating frequency and resistivity structure. Supplementary high frequency data from AMT survey can improve the resolution of the shallow structures and eventually give help to resolve the deeper structures as well (Lee et al., 2006).

2. SURVEY DESIGN AND FIELD PROCEDURE FOR AMT & MT SURVEY

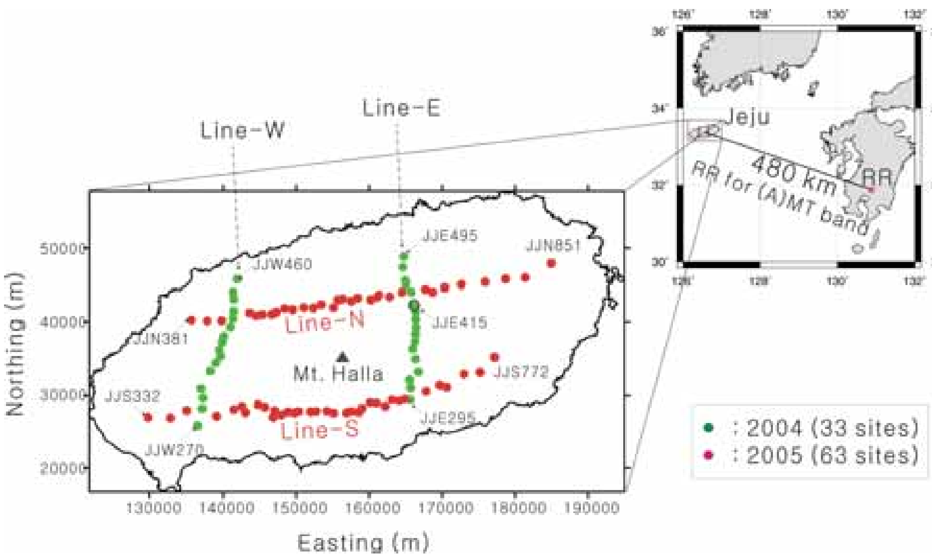

Fig. 2 Location map of MT survey lines. Remote reference for MT band is located in Kyushu, Japan (RR). Remote reference for AMT band can be either RR in Kyushu or the site among the other line, which is more than 25 km apart.

Fig. 2 shows the location map of the survey sites for MT measurements. The green dots forming two lines with north-south direction are the sites performed in the year 2004, while the red dots forming two lines with east-west direction are gathered in the year 2005. The four lines surround the mid-mountain area (< 600 m) of Mt. Halla. Four to seven sets of MTU-5A systems are used for the survey, one set for the far remote reference in Kyushu, Japan, which is about 480 km apart from Jeju (RR in Fig. 2), and the other sets for the field measurements in Jeju Island.

MTU-5A system is designed for AMT and MT survey with one full set of the system. The system can gather the AMT band (10.4 kHz ~ 0.35 Hz) as well as MT band (317 Hz ~ 0.00034 Hz) by substituting the magnetic coil sensors and the sampling frequency of time series. Four separate sampling frequencies are scheduled depending on the frequency ranges desired as shown in Table 1. Band 3 and 4 are overlapped and band 2 is only for AMT measurements while band 5 is only for MT. MTU-5A is designed for tensor measurement, 2 electric components and 3 magnetic components on the surface, with 24 bit resolution for both AMT and MT bands. GPS synchronization allows us to place the remote reference site as far as a few hundred kilometers so that the electromagnetic noise is not coherent anymore with the field stations. This will greatly improve the data quality (Song et al., 2006)

Table 1. Frequency ranges used in MTU-5A system.

Band	Sampling freq. (Hz)	AMT		MT	
		Range (Hz)	No. Freq.	Range (Hz)	No. Freq.
2	24,000	10,400 ~ 900	15	NA	NA
3	2,400	776.5 ~ 39.7	18	317.6 ~ 39.7	13
4	150	32.5 ~ 0.35	27	32.5 ~ 0.35	27
5	15	NA	NA	0.29 ~ 0.00034	40

MT measurements are performed for 15 hours from 17:00 to 08:00 next day, and AMT measurements are carried out for 4 hours from 10:00 to 14:00 after the MT measurements are finished. These acquisition schedules are the same for all the four systems, so that magnetic fields at each site can be used as a remote reference site for the others.

Fig. 3 shows an example of sounding curves for MT (a), AMT (b), and AMT & MT (c) measurement for the sites JJE-415 in the Line-E. In this case, RR in Kyushu, Japan is used for the remote reference in both AMT and MT survey. Note that overall data quality is very good over the whole frequency ranges except for several frequency ranges such as the power line frequencies (around 60 Hz) and the dead band (around 0.1 Hz). Noisy features at frequencies below 1 Hz in AMT result (b) are due to lack of sensitivity of AMT magnetic sensors in this frequency range. We could acquire very good quality data from most parts of mid-mountain area (at the center parts of each line). Some of the data showed noisy features, but most of them are from the margin of each line, where exist many artificial electromagnetic noise sources such as residential electricity, power lines, traffics, and so forth.

Note that estimations of apparent resistivity and phase by AMT survey (b) and MT survey (a) show very similar at the common band (about 1 Hz ~ 317.6 Hz). Thus only the AMT measurements will be enough when the target depth does not reaches the order of km. AMT & MT survey can give roughly 2 more decades of high frequency information, 317.6 Hz ~ 10,400 Hz, than the ordinary MT measurements.

The sounding curves shown in Fig. 3 is a typical curves that can be observed almost everywhere within Jeju Island. They commonly show resistive feature at high frequency, conductive in the middle, resistive below 1 Hz, and then again getting slightly low resistivity at frequencies below 0.2 Hz, which are typical curves for 4-layered structures.

(a) MT survey (b) AMT survey (c) AMT & MT survey

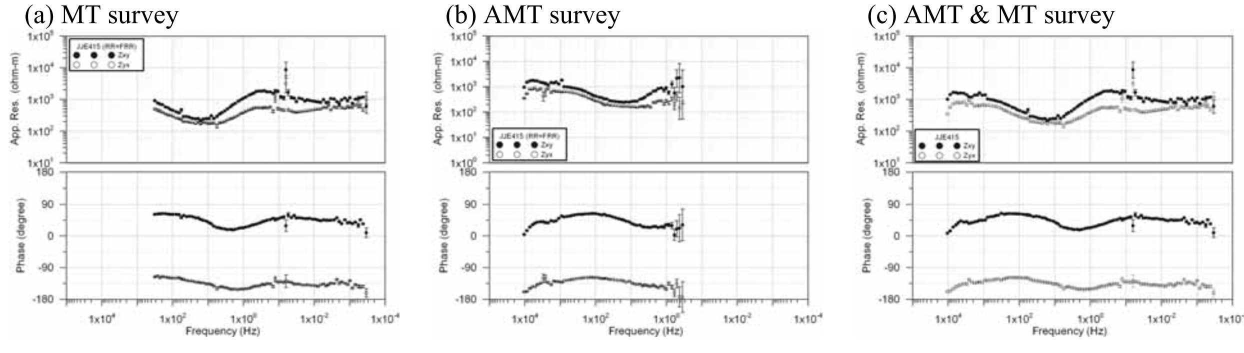

Fig. 3 Impedance estimations for MT (a), AMT (b), and AMT & MT (c) for the site JJE-415 with remote reference processing using the remote data from Kyushu, Japan (RR).

3. 2-D TM MODE INVERSION

For 2-D inversion of the observed data, the MT impedance is first rotated to the direction of the survey line, assuming that the strike direction is perpendicular to the line. The inversion used only TM mode data, in which an electric field aligns in the line direction and a magnetic field perpendicular to the line. The number of frequency used was 60 ranging from 0.011 to 4,400 Hz for all the four lines. The location of each site in a line was projected to the line so that the separation between the sites can be calculated for the inversion. Both apparent resistivity and phase were used for the inversion and minimum noise assumed was 3% in the apparent resistivity and an equivalent amount in the phase. The inversion algorithm used was the linearized least-squares scheme with smoothness regularization (Uchida, 1993). The forward modeling was done by the finite-element method and minimization of the data misfit and model roughness is simultaneously achieved by introducing Bayesian likelihood. Weighting for calculation of the data misfit was given according to the measurement error. Topography and the effects of surrounding sea were not considered in the inversion.

Fig. 4 shows TM mode inversion results for the (a) Line-E and (b) Line-W down to the depth of 5 km. As can be expected from the apparent resistivity curves in Fig. 3, roughly three different electrical layers can be found from both the inverted sections: (1) the topmost layer with a few hundreds of ohm-m extending to the depth slightly deeper than the sea level, (2) very conductive layer in the middle with a few tens of ohm-m with thickness of a few hundreds meters, and (3) the layer with resistivity more than a thousand ohm-m at depth. Comparing the inverted section with the generalized stratigraphy of Jeju Island shown in Fig. 1, we can tell the characteristics of the electrical layers.

The topmost layer with a few hundred ohm-m can be considered as the basalts forming the great mass of Halla Mountain and the surface of Jeju Island. The layer seems rather thin at the margin of the lines than the center of them. Considering that the elevation difference between the central parts and the marginal parts of both the lines is about 400 m, the bottom of the layer can be almost flat and its depth will be 100 ~ 200 m below the sea level, which is consistent with the generalized stratigraphy in Fig. 1 driven from the drilling results.

Very conductive layer beneath the basalt can be the SF and UF in Fig. 1. The low apparent resistivity at frequencies around 10 Hz (Fig. 3) will be the response of these conductive layers. Because SF has been formed in marine environment and because UF is unconsolidated layer saturated with sea water, the conductivity of the two layers will be very high and it will be very hard to separate the two layers from the MT inversion results. Actually, the layer appears in all around the Jeju Island at the depth of a few tens to a few hundreds meters deep below the sea level. Because the drilling results said that average thicknesses of SF and UF are about 100 m and 150 m, respectively, the conductive layer in the inversion results may have the thickness of about 250 m. Note, however, that the layer has more than 500 m thick in some parts of the lines in the inversion results. This can be from either the limitation of smoothed inversion or the reflection of real structures such as sea water intrusion through the fracture system beneath the layer.

The bottom layer with resistivity more than a thousand ohm-m can be the basement with welded tuff and granite. Note that a conductive structure at the central part (around the site 395 in Line-E and site 360 in Line-W) extends to the deeper part through the basement layer.

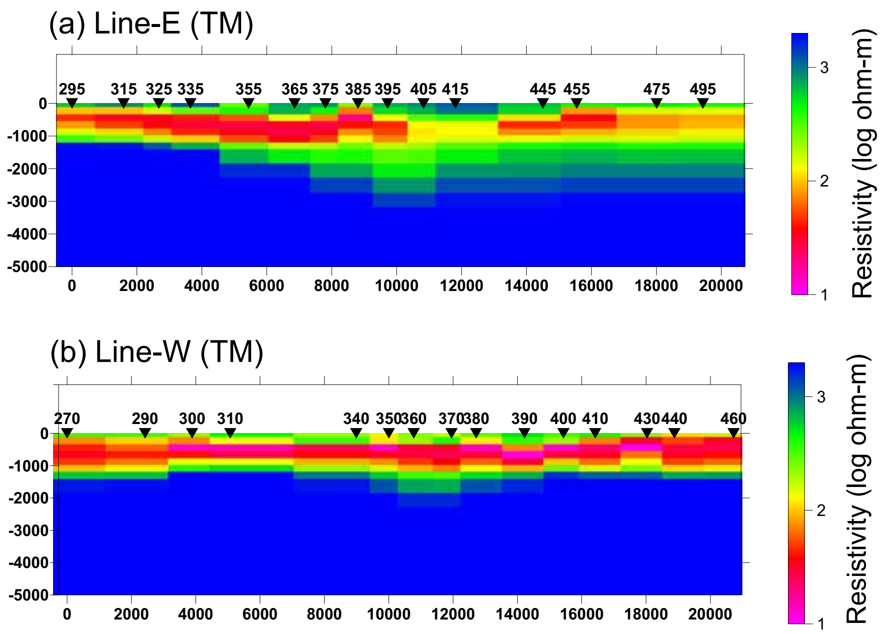

Fig. 4 Results of TM mode inversion for (a) Line-E, (b) Line-W. Left of each section corresponds to the south.

The layered structures appeared in the inversion results in Fig. 4 can also be found from the inversion results for Line-N and Line-W shown in Fig. 5. Again note that a conductive structure at the central part (around the site 531 and 701 in Line-N and site 532 and 682 in Line-S) extends to the deeper part through the basement.

These conductive structures that commonly appear at the center part of all the four survey lines can be either the geological structures related with the ancient volcanic activities forming the Mt. Halla or any fracture systems intersecting each survey line. We prefer the former interpretation with following reasons: (1) location of the conductive anomaly roughly coincides with the location of the crater (on the summit of the Mt. Halla) projected to each line (2) the anomaly is getting clearer as the survey line get closer to the Mt. Halla. As can be seen from the inversion results in Fig. 4 and Fig. 5, the conductive anomaly is extending to very deeper parts at Line-N and Line-S, which are much closer to the summit of Mt. Halla than the other survey lines, and it shows down to about 3 km in Line-E, and can merely be seen in Line-W, the farthest line. Those facts indicate that the conductive anomaly can be a reflection of the *off-the-survey-line* volcanic vent that can possibly be underneath the Mt. Halla.

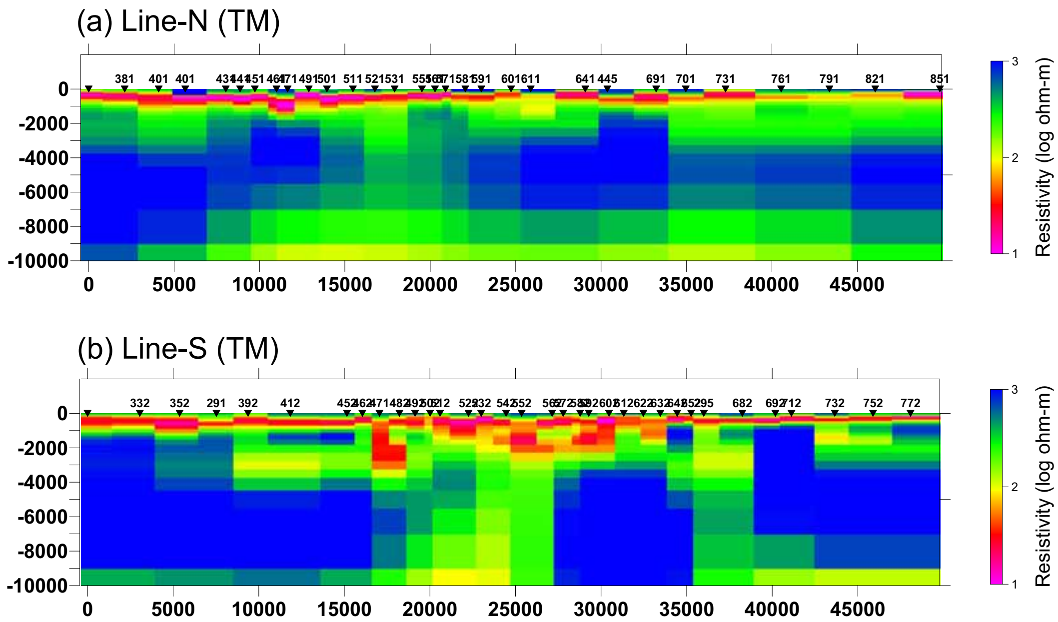

Fig. 5 Results of TM mode inversion for (a) Line-N, (b) Line-S. Left of each section corresponds to the west.

4. DISCUSSION AND CONCLUSION

Good quality data have been acquired from the MT and AMT survey in the mid-mountain area of Jeju Island. 2-D inversion of the data for four survey lines surrounding the Mt. Halla showed very clear layered structure, which showed very good consistency with the generalized stratigraphy of the island deduced from numerous drilling results. Topmost basalt layer has resistivity of several hundred ohm-m, and UF and SF a thick layer having around 10 ohm-m in the depth of a few hundred meters is overlain by the top layer, and then the basement with welded tuff and granite is followed with resistivity of order of thousand ohm-m.

And they also show a conductive anomaly extending to more than 2 km depth at the central part of each survey lines, which can possibly be related with old volcanic activities forming the Mt. Halla. Three-dimensional inversion with additional MT survey at the central part of Mt. Halla or further geological study with deep drilling efforts can reduce the ambiguity in interpretation of the anomaly in 2-D inversion results.

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