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Geomagnetic Depth Sounding to Investigate the Trend of Electrical Conductivity in and around the Korean Peninsula

Seok-Hoon Oh*, Jun-Mo Yang, Duk Kee Lee and Jae-Cheol Nam
Marine Meteorology & Earthquake Res. Lab./METRI

지자기 수직 탐사에 의한 한반도 주변의 전기전도도 구조

오석훈* · 양준모 · 이덕기 · 남재철
기상연구소 해양기상지진연구실

한반도에 위치한 5곳의 정밀 지자기 관측소에서 수집된 자료를 이용하여 지자기 수직탐사를 수행하였다. 측정된 지자기 자료는 0.01 nT의 정밀도를 가지며, 1초 혹은 5초 간격으로 측정되었고 이번 해석을 위해 16일 분량의 자료를 이용하였다. 지자기 수직 탐사는 그 특성 상 주변에 해양이 존재할 경우 그에 의한 영향이 매우 크지만, 본 연구를 위해 관측자료를 처리한 결과, 인근 해안에 의한 효과 보다는 심부의 전기적 구조에 의한 효과를 많이 반영하였다. 자료 해석 결과, 전기 전도체의 방향을 표시하는 유도 표시자(induction arrow)는 한반도의 대표적 지구조를 가리켰으며, 이를 통해 한반도의 심부 구조를 지전기학적으로 이해할 수 있는 증거를 확보할 수 있었다.

주요어 : 지자기 수직탐사, 유도 표시자

Geomagnetic depth sounding (GDS) was performed to analyze the characteristics of deep resistivity structure in and around the Korean Peninsula. The data that have 0.01nT precision were collected from 5 geomagnetic observatories and measured every one or five second. In this study, amount of 16 days of geomagnetic data were used for analyzing. Generally the sea affects the GDS data seriously due to its high conductivity. However, though the Korean peninsula is surrounded by seas in three sides, the results given by induction arrow strongly show that the trend of electrical conductivity at neighborhood of the Korean Peninsula is reigned by some geological features. Also it is believed that observation in Jeju island is related with the electrical structure around the East China Sea.

Key words : GDS, induction arrow

1. INTRODUCTION

In Korea, the investigations of electrical structure have more targeted on the depth within 1 km for development of hot waters or groundwater rather than deep structure reached to upper mantle. This was due to the limitation of available devices that are mainly concentrated on galvanic methods. However, recent improvements in device made it possible to investigate the deeper structure of earth's interior. Magnetotelluric (MT) method, for example, can provide a detailed information on the deep structure of the Earth. In this study, we used the geomagnetic variations that have been intensively observed recently in Korea for investigation of deeper earth's interior.

Since the early 1950's it has been noticed that the vertical component of geomagnetic variations having periods shorter than a few hours differs considerably in its behavior from one site to another within a distance of some tens kilometers. This kind of anomaly in the geomagnetic variation can be accounted for neither by spatial dependence of external fields nor by internal fields arising through electromagnetic induction in a laterally uniform earth. Anomaly has thus been interpreted

*Corresponding author: gimul@metri.re.kr

as indicating lateral heterogeneity in the conductivity distribution; denoted by the term 'Conductivity Anomaly' (CA). Investigation of conductivity anomalies of local nature have been undertaken in Japan and Germany and systematic studies of conductivity anomalies were initiated using GDS (Geomagnetic Depth Sounding) and MT(Magneto-Telluric) (Arora, 1982; Rikitake, 1985; Arne *et al.*, 2001) methods.

GDS is a way of determining the electrical conductivity structure of subsurface from measurements of natural transient magnetic variations on the surface, measuring only perpendicular three components (northward, eastward, downward) of geomagnetic variations. Generally, GDS provides qualitative electrical conductivity information of subsurface, but electrical conductivity structure of upper mantle can be acquired because the period of interest reaches to 60-100 minutes (Shimoizumi *et al.*, 1997; Chen *et al.*, 1997; Hitchman *et al.*, 2001).

Although investigations and interpretations of geoelectrical structure in terms of plate tectonics have been actively carried out in Japan, Brazil, New Zealand, Australia etc. (Shimoizumi, 1997; Antonio, 2000; Dosso, 1996; Pringle, 2000; Chamalaun, 1999), the geophysical studies of CA have not been performed in the Korea Peninsula due to difficulties of geomagnetic data acquisition. This paper tries to study global geoelectrical structure of Korea, furthermore associates Korea with areas ranging from East China Sea to western Japan in tectonic view.

In Japan, observations of geomagnetic variations have been intensively carried out since the early 1950's and investigations of subsurface electrical conductivity structure have been extensively conducted to give models tightly connected to the subduction system (Shimoizumi *et al.*, 1997). Generally induction arrows in Japan Island indicate to Pacific Ocean except Kyushu and Hokkaido region. Northeastern induction arrows in Hokkaido region are interpreted as being affected by the partial melting zone inferred to be located near east of Hokkaido (Satoh *et al.*, 2001). In Kyushu region, the arrows suggest highly conductive layers beneath the East China Sea (Shiomizumi, 1997) and this pattern is confirmed by our data measured in Jeju observatory.

The trend of electric conductivity in and around the Korean Peninsula by induction arrows shows some patterns according to the location of observatories and the sea effect does not seems dominant for these observations. Considering the constant direction of induction arrow to NE-SW independent of period, it is believed that the trend in shallow and deep structure is connected.

2. PRELIMINARY STUDIES FOR DEEP STRUCTURE OF THE KOREA

Various geophysical study have been applied to investigate the deep structure of the Korean Peninsula such as seismic and gravity method. Lee (1979) analyzed the travel time data of the Ssanggye-sa earthquake and concluded that the crustal thickness is about 35 km. Kim (1983) suggested the crustal model which has the discontinuities of Conrad and Moho at the depth 15 km and 32 km, respectively, by earthquake data. And Kwon and Yang (1985) studied the crustal structure of the southern Korean peninsula by gravity data. The study showed that the Bouguer anomalies presented a lineation in the NE-SW direction that is the same to that of most mountains and tectonic lines of this area, and the depth of the crustal base is varying in the estimated range of 26 km to 36 km with a thinner crust below the east coast than that of the west coast.

Unfortunately, electrical study for deep structure of the Korean Peninsula is not fully available. However, various methods for interpreting shallow characteristics of the electrical structure of interested region were applied to geological features such as faults, belt, basin, etc. Lee and Kim (1994) conducted geoelectric survey to study the major faults in the Ogcheon belt and Lee and Han (1999) delineated the geoelectric structure of the Yangsan fault in the Kyeongsang basin. The result showed that the apparent resistivity generally decreases towards the fault boundary.

Fig. 1 shows the simplified tectonic map around the Korean peninsula. In Korea, most of the geological structure line has direction of NE-SW, including the most prominent lineation, Ogcheon belt.

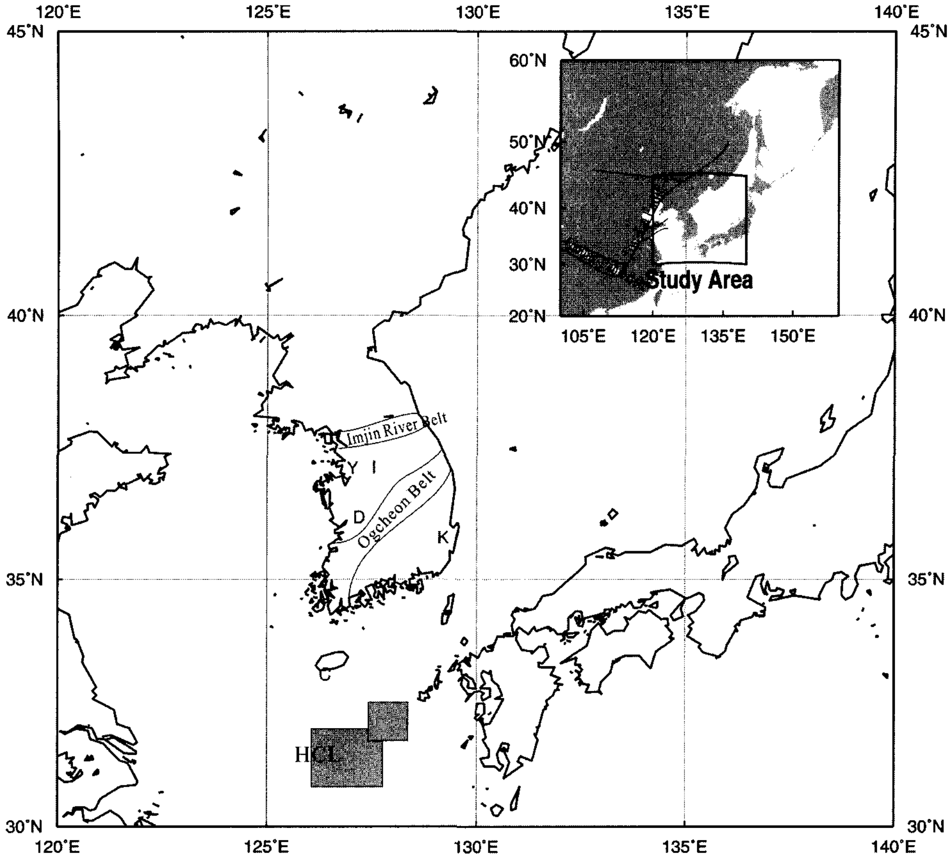

Fig. 1. Tectonic and location map showing the tectonic characteristics and geomagnetic observation sites in and around the Korean Peninsula. The box map represents the Qinling-Dabie belt and Tan-Lu fault in China. The two belt and HCL (Shimoizumi *et al.*, 1997) in the west of Kyushu Island are included in the 3-D MT model. From a total of 13 sites, three component geomagnetic data were collected; Y: YIN (Yongin), I: ICN (Icheon), D: DJN (Daejeon), K: KNJ (Kyeongju), C: CHE (Jeju). Compiled from the tectonic map of Cho *et al.* [1995], Kim [1970), and Shimoizumi *et al.* [1997].

3. DATA ACQUISITION AND PROCESSING

3.1. Data acquisition

Data of geomagnetic variations have been obtained for sixteen days at five fixed-observatories located in the Korea Peninsula. The location of each fixed-observatory is shown in Figure 1: one is located in Jeju island, the others are in the inland of the peninsula. Table 1 shows date, duration (hour) and sampling interval of observation at each observatory. Three components of geomagnetic variations were recorded digitally every five second with a resolution of about 0.01 nT. But sampling interval was determined at each observatory according to quality of observed data. In addition, certain basic editing, mainly data spikes, have been carried out in time domain.

Table 1. The measurement information of five fixed-observatory used in this study.

Observatory	Date	Durations (hour)	Sampling interval (sec)
Jeju (CHE)	2001, 12, 16-31.	384	1
Daejeon (DJN)	2001, 12, 16-31	384	5
Icheon (ICN)	2001, 12, 16-31	384	1
Kyeongju (KNJ)	2001, 12, 16-31	384	60
Yongin (YIN)	2001, 12, 16-31	384	1

3.2. Data processing

Basic theory : The vertical and horizontal geomagnetic components perpendicular to each other satisfy following relation, if anomalous conductivity structure exists in the subsurface.

$$H_z=T_{zx}H_x+T_{zy}H_y \qquad (1)$$

T_{zx} and T_{zy} are usually called tipper. Because existence of tipper refers to two or three dimension of subsurface structure, the basic principle of GDS is to disclose geoelectrical structure by means of tipper. In fact, the transfer function was used for GDS rather than the tipper. In terms of the transfer function, following equation mainly used,

$$H_z=AH_x+BH_y \qquad (2)$$

where H_x, H_y, H_z are geomagnetic variations of northward, eastward, downward components, respectively, with respect to geomagnetic coordinates. A and B are frequency dependent coefficients. In most case, Eq. (2) is treated in frequency domain, so that A and B are complex functions of frequency.

The qualitative information can be acquired from transfer function A and B, and the induction arrow is a general method of representation A and B. The induction arrow, known as Parkinson's convention (Parkinson, 1964), is a way of standing for qualitative length and direction of conductivity anomalies, and in general, tends to point the high conductive anomalous body. The length of induction arrow increases in proportion to the absolute value of A and B. Because A and B are complex functions of frequency, they can be expressed in two ways: induction arrow of the real and imaginary component. Commonly, the real part is much larger than the imaginary part, hence the real part arrows is used more often and used for quality check of data. The length and direction of induction arrow is defined by following equations.

$$\text{Length}: \sqrt{A_r^2+B_r^2} \ \text{- real part} \qquad (3)$$
$$\sqrt{A_i^2+B_i^2} \ \text{- imaginary part}$$

$$\text{Direction}: \tan^{-1}(B_r/A_r) \ \text{- real part} \qquad (4)$$
$$\tan^{-1}(B_i/A_i) \ \text{- imaginary part}$$

where subscript r denotes the real part, i the imaginary part.

In coastal regions, a coast forms a clear conductivity boundary separating a highly conductive sea from a poorly conductive land. In these circumstances, induction arrow tend to point to coastal side due to its high conductivity. This phenomenon has been called the coast effect. In the other regions except coastal regions, if data contain no noise, the direction of induction arrow is perpendicular to conductivity contrast boundary. Hence geoelectrical structure of subsurface can be inferred from results of geomagnetic observations distributed spatially.

Data processing : Since A and B in Eq. (2) were calculated in frequency domain by using the spectral analysis method, Fourier transformation of time series of geomagnetic field has been performed for A and B. In spectral analysis, the time dependence is taken as exp(−iωt), then A and B were calculated in frequency domain. Duration of geomagnetic variations analyzed here were about 25 hours, which was sufficiently long enough to obtain reliable estimates of the transfer functions at the period of up to 6000 sec.

The calculation of A and B in Eq. (2) is similar to the method of calculating impedances in Magneto-Telluric method. First, the complex conjugates of two source polarizations are imposed on Eq. (2), then two linear equations are obtained. Then the solutions of two linear equations are A and B, which are represented by following equations,

$$A=\frac{\langle H_y\cdot H_y^*\rangle\langle H_z\cdot H_x^*\rangle-\langle H_y\cdot H_x^*\rangle\langle H_z\cdot H_y^*\rangle}{\langle H_y\cdot H_y^*\rangle\langle H_x\cdot H_x^*\rangle-\langle H_y\cdot H_x^*\rangle\langle H_x\cdot H_y^*\rangle} \qquad (5)$$

$$B=\frac{\langle H_x\cdot H_y^*\rangle\langle H_z\cdot H_x^*\rangle-\langle H_x\cdot H_x^*\rangle\langle H_z\cdot H_y^*\rangle}{\langle H_y\cdot H_x^*\rangle\langle H_x\cdot H_y^*\rangle-\langle H_y\cdot H_y^*\rangle\langle H_x\cdot H_x^*\rangle} \qquad (6)$$

where H_x^* and H_y^* are the complex conjugates of H_x, H_y and $\langle H_xH_x^*\rangle$ and $\langle H_xH_y^*\rangle$ are auto-power spectra and cross-power spectra, respectively. The calculation method of auto-power spectra and cross-power spectra follows the band averaging technique by Vozoff (1972).

4. RESULTS AND DISCUSSION

Fig. 2 shows the induction arrows for each period and observatory site. Most of them are correspondent between real and imaginary values except some erroneous point or period. The length of the

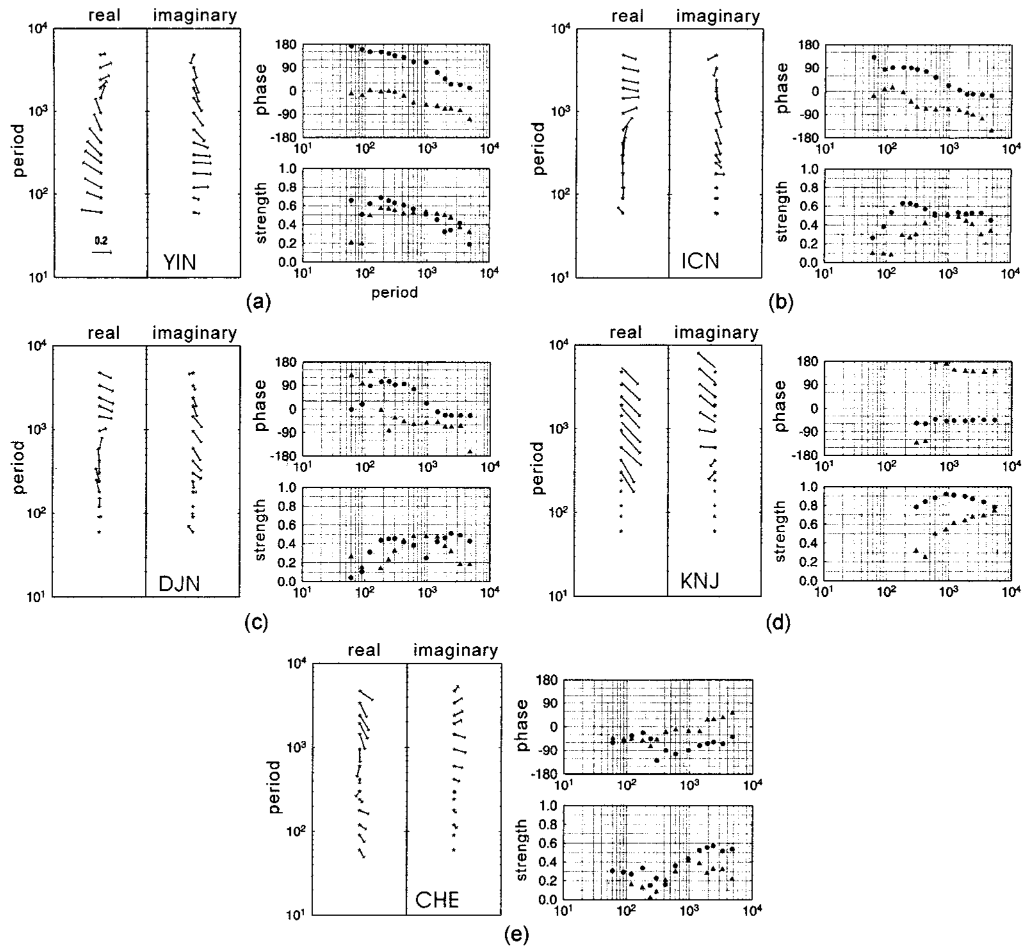

Fig. 2. The real and imaginary induction arrows plotted with periods and phases for five geomagnetic observations. (a) YIN; Yongin (b) ICN; Icheon (c) DJN; Daejeon (d) KNJ; Kyeongju (e) CHE; Jeju.

arrow means the relative strength of induction. Seen from the figures, the arrows are changing with smooth pattern, so that the data have reliable quality for interpretation.

As sea is extremely conductive than rocks or soils, it should be dealt with carefulness for interpretation. Generally, the sea effect is simulated by thin-sheet model for approximation of sea conductivity. By Bapat *et al.* (1993), overall pattern of sea effect in the Korean Peninsula is toward the East Sea (Sea of Japan) and monotonically increase due to the bathymetry. Bapat *et al.* (1993) modeled that the central-western region of the peninsula including three observatory, Icheon, Yongin and Daejeon sites, is not greatly affected by sea, counterbalancing the Yellow Sea near and the East Sea far apart but deep. This pattern is re-calculated by our three-dimensional MT model calculated for sea effect of GDS data (Fig. 3), and it coincides well with the model. The three-dimensional model has advantage to describe the complex subsurface structure in future.

Fig. 4 and 5 show the induction arrows on the map of the Korean Peninsula for 10-minute and 60-minute periods. The pattern of the observed arrows may be classified into four categories for convenience. At the northernmost two sites, YIN and ICN, the induction arrows show similar characteristics, but the YIN site seems to be more affected by the adjacent sea considering the 10-minute period arrow. Considering the eastward regional pattern with the regional sea effect (Fig.

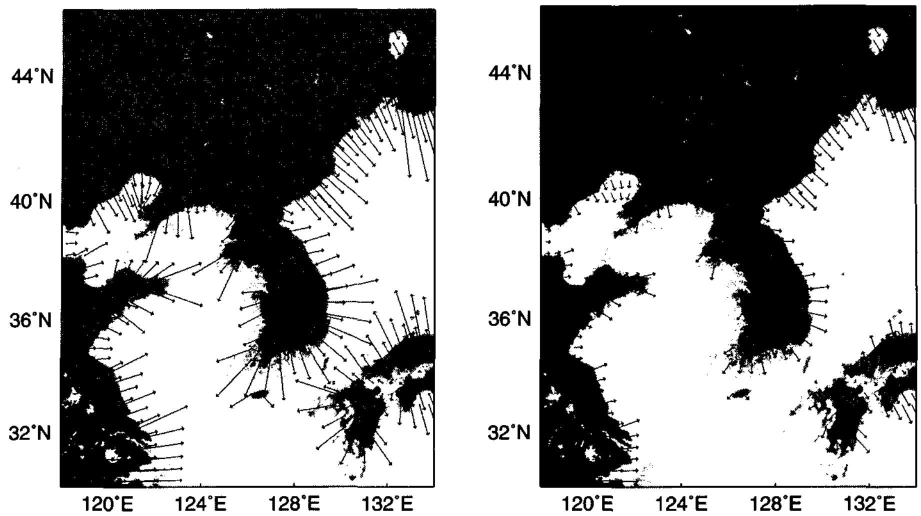

Fig. 3. Calculated sea effect by three-dimensional MT modeling. The bathymetry is approximated to have the East Sea twenty times deeper than the Yellow Sea.

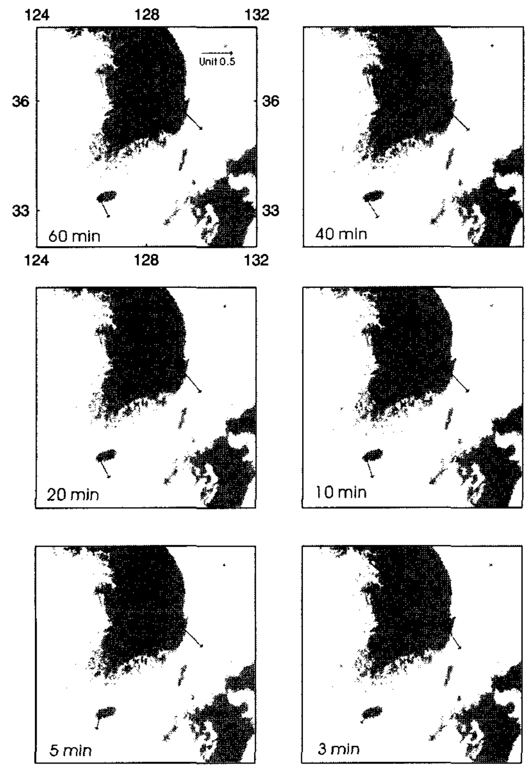

Fig. 4. The induction arrows of real component displayed on the map of the Korean Peninsula.

3), this observed direction of the induction arrow suggests a deep geoelectrical structure located to the north of the sites.

The arrow observed in the DJN has a southeastward direction, except for minor short period arrows distorted by the sea effect. This pattern seems to reflect the thick sediment layer and deep structure of the adjacent Ogcheon Belt with the NE-SW trend.

The site near the coastline tends to be affected by the adjacent sea. However, the pattern at the KNJ cannot be explained merely as a simple sea effect considering our MT model (Fig. 3) and the results of Bapat *et al.* (1993). According to the previous study (Min, 2001; Nakada *et al.*, 1997), there are many faults and a low-velocity zone in the strait between the southeastern coast of Korea and Kyushu Island of Japan. These evidences support the anomalous pattern in the KNJ.

Finally, the induction arrow observed at Jeju Island shows a seaward direction. As expected, in-phase induction arrows of the short period coincide with the sea effect model. The direction of the long period arrow, however, seems to be rotated and the pattern matches the results from Kyushu, Japan (Shimoizumi *et al.*, 1997). This result strongly suggests the existence of highly conductive layers (HCL) beneath the East China Sea, which may be considered to be a part of mantle upwelling as supposed by Nakada *et al.* (1997).

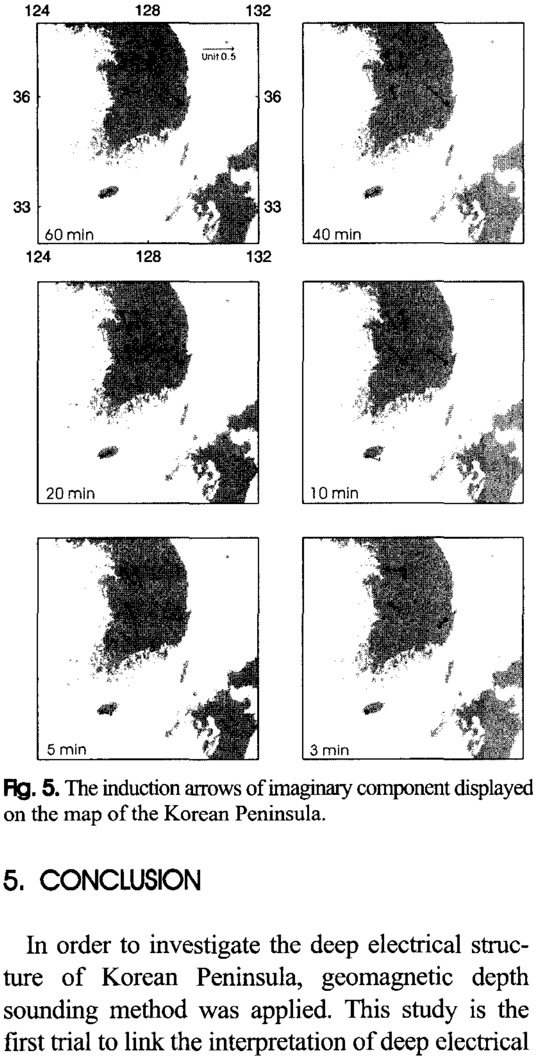

Fig. 5. The induction arrows of imaginary component displayed on the map of the Korean Peninsula.

5. CONCLUSION

In order to investigate the deep electrical structure of Korean Peninsula, geomagnetic depth sounding method was applied. This study is the first trial to link the interpretation of deep electrical structure between Japan and China, and showed well-behaved results, which consistent with the observation previously done in Kyushu, Japan. From a total of 5 geomagnetic observatories, data were collected for this study, which are located impartially in the Korean Peninsula.

The GDS results show that the characteristics of arrows may be categorized into some patterns depending on gross geological structures. The observation in the middle of the peninsula suggests the Imjin River Belt now in geological debate. And the pattern at Daejeon site suggests the structure whose direction indicates NE-SW in the peninsula. The direction of induction arrows is considered to be related with the thick sediment of Ogcheon belt and other geological events like directional characteristics of granites intrusion. And the data observed at Kyeongju were affected by seas comparing with other data. But trimming the sea effect, the induction arrow seems to indicate a geological structure suspected as low-velocity zone (Min, 2001). Finally result from Jeju observatory provides similar pattern with those of Kyushu, Japan, that is existence of highly conducting layers considered to be a part of mantle upwelling beneath the East China Sea. However, for more quantitative interpretation of deep electrical structure of the Korean peninsula, MT exploration or geomagnetic data for other sites are required.

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