Heterogeneous electrical structure of Kozu-shima volcanic island, Japan

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(Contributed by Seiya UYEDA, M.J.A.)

Abstract: Nearly twenty anomalous geoelectric field changes were observed before earthquakes at Kozu-shima Island, Japan, from 1997 to 2000. In order to help locating the current sources of the observed anomalous changes, a bipole-dipole resistivity survey was conducted. From the resistivity survey, including current injection into the ground, it was found that various features of the anomalous changes were systematically different from those of changes caused by artificial sources and induction of geomagnetic disturbances. Moreover, it is suspected that the currents of anomalous changes were generated not near the ground surface but deep under the ground.

Keywords: geoelectric field changes, geoelectric potential difference, bipole-dipole resistivity survey, heterogeneous electrical structure

Introduction

Anomalous geoelectric field changes, termed seismic electric signals (SES), have been observed before earthquakes in Greece.1)–4) Greek scientists have predicted large earthquakes by observing the SES. This methodology is called VAN method. The SES are discriminated from other changes caused by geomagnetic disturbances, instability of electrodes, artificial noises, and so on by using a set of short and long measuring dipoles.5) On Kozu-shima Island, approximately 170-km south of Tokyo, anomalous geoelectric field changes were observed before earthquakes which occurred around the island.6),7)

Ioannina station in the northwestern Greece is one of VAN's stations where many SES have been observed.4) Therefore, some field surveys have been carried out around Ioannina station to investigate the physical properties of SES, including comparison of electric field intensity of SES and lightning-induced signals8) and experiments of electric current injection to the ground several kilometers away from the station.9) These results showed that the current origin of SES might be located within a few kilometers from Ioannina station if the current was generated very near the ground, which seems unlikely. Furthermore, a highly heterogeneous conductivity structure was revealed around Ioannina station by a bipole-dipole mapping.10) Thus, it may be conjectured that high heterogeneity of the electrical structure around a station may play some important role in the last stage of long-distant propagation of SES generated in the hypocentral zone. This conjecture is consistent with the suggestion5) for the homogeneities found in the Keratea station in Greece, as well as, additional observations at Ioannina station.11),12)

At Kozu-shima (KZU) station, nearly twenty simultaneous anomalous geoelectric field changes were observed in the three long dipoles and some short dipoles at GND (See Figs. 1 and 2b). However, geoelectric potential differences in the two N-S directed long dipoles, AIR-NTT and AIR-DMP, were not at all proportional to their dipole lengths.5) This striking result might have been caused by either or both of the source location of the anomalous changes and subterranean electrical heterogeneity. Although an underground resistivity structure survey using the VLF-MT method had been carried out in Kozu-shima Island, it did not cover the area between NTT and DMP.13) Therefore, in this study, we investigated the electrical structure between NTT and DMP by the bipole-dipole method. The reason why the bipole-dipole method14),15) was selected instead of VLF-MT is shown later.

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doi: 10.2183/pjab.85.476
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Properties of observed geoelectric field changes

Kozu-shima Island is one of Izu volcanic islands, Japan. Size of this island is approximately 5 km in EW and 6.5 km in NS directions with 24 km of circumference. The island is composed of several rhyolitic monogenetic volcanoes and the topography is rugged. For the purpose of SES monitoring, we had installed five short dipoles at GND site, and three long dipoles covering the southwestern part of the island. Sampling rate of the observation was 10 seconds. The monitoring period was from May 14, 1997 to July 7, 2000 when the observation hut at GND, housing our recording units, was destroyed by large falling rocks caused by the seismic swarm activity, 2000. In general, geoelectric monitoring is strongly disturbed by leakage current from DC driven trains. At Kozu-shima Island, the level of artificial electric noise is quite low because there is no train. However, we carefully pay attention to artificial electric noises emitted possibly from the only village in the western part of the island where the NTT (Nippon Telegraph and Telephone Corporation) station and most of population reside.

Figures 2a, 2b, and 2c show examples of a magnetotelluric geoelectric potential change, a SES-like pre-seismic anomalous change, and a suspect artificial noise respectively. The lengths and polarity of arrows in Figs. 2a, 2b, and 2c are relative to those of GND-115m dipole in each case. Note that the arrows mean the component of the geoelectric field in the direction of dipoles. First, the geomagnetic disturbance had a serious influence on the geoelectric field component in all of the short and long dipoles (Fig. 2a). It may be seen that the amplitudes of EW component were much larger than those of NS component, the amplitude of AIR-NTT long dipole was about 0.7–1 times those of NS short dipoles at GND, and the amplitude of GND-NTT long dipole was 1–2 times those of EW short dipoles. When the NS components of the two long dipoles AIR-DMP and AIR-NTT are compared, the amplitude of AIR-DMP was 0.5–0.7 times that of AIR-NTT. Therefore, the resistivity in the area around NTT and DMP was expected to be highly heterogeneous.

As to the SES-like anomalous change in Kozu-shima Island, following criteria were defined. (1) $\Delta V/L = \text{constant (to within 80–125\%)}$ for short-dipoles at GND, (2) Simultaneous appearance on short and long dipoles, (3) Polarity of long dipoles compatible with that of short dipoles, (4) the ampli-
At a magnitude greater than $2 \times 10^{-6}$ V/m, which is the normal noise level at the station, and (5) Longer duration than 40 s (more than three data points with 10 s sampling). From May 14, 1997 to November 30, 1999, 21 anomalous changes satisfying the criteria were recorded before 26 earthquakes (with $M > 3$). Figure 2b shows an example of such anomalous changes. In none of the cases, the anomalous change was observed in the EW oriented short dipoles at GND. The anomalous changes showed that the amplitude of AIR-NTT long dipole was 1–2 times those of NS short dipoles at GND, the amplitude of AIR-DMP long dipole was approximately 0.1 times that of AIR-NTT long dipole. These features were considered extremely peculiar. We will discuss about them later.

The typical suspect artificial noises showed that their polarity directions of short dipoles were not consistent with those of long dipoles, and the amplitudes of long dipoles were 7–10 times those of short dipoles (One example is shown in Fig. 2c.). So, this observation result suggested that the source of these noises was in the vicinity of NTT site. Therefore, it was considered important to clarify the underground resistivity distribution in the area between NTT and DMP which was not measured previously. In order also to understand the observed behavior of the typical suspect artificial noise possibly emitted near NTT, we, in this study, preferred the bipole-dipole method, which uses electric current injection, to the VLF-MT method.

**Resistivity survey**

A bipole-dipole resistivity survey was conducted on December 17 and 18, 1997. We installed two electric current bipoles in orthogonal directions roughly 250 m south of NTT. Bipole length was 81 m in NW-SE direction (“A-B” in Fig. 3) and 77 m in NE-SW direction (“A-C” in Fig. 3). Both ends of each bipole were composed of multiple steel rods. Contact
Fig. 2b. An example of anomalous changes: Measured on May 21, 1997.

Fig. 2c. An example of artificial noise changes: Measured on May 21, 1997.
resistance of bipoles A-B and A-C was 280 to 300 $\text{W}$ and 150 to 160 $\text{W}$, respectively. Bipolar rectangular oscillation current with amplitudes of 0.5 Amps and 10-second cycle was injected. The period of continuous current injection was 30 minutes for each bipole direction.

Seven receiving stations were installed between NTT and DMP as shown in Fig. 3. At each of them, two dipoles with 20-54 meter length, depending on surface conditions, were orthogonally installed to measure the direction and amplitude of the electric field. Handmade Cu-CuSO$_4$ electrodes were used as receiving probes. The data was recorded with 1 Hz sampling rate by a data-logger DATAMARK LS3300ptV (Hakusan, Tokyo). The observed electric field $\vec{E}$ was derived from stacking 30-minute record.

Under the assumption of homogeneous ground, the observed electric field intensity $|\vec{E}|$ and apparent resistivity $\rho$ is written by $^{15}$

$$|\vec{E}| = \frac{\rho I}{2\pi r_1^2} \left[ 1 + \left( \frac{r_1}{r_2} \right)^4 - 2 \left( \frac{r_1}{r_2} \right)^2 \cos \theta \right]^{1/2}$$

where $r_1$ and $r_2$ shown in Fig. 4 are the distances between receiver and one and the other of transmitted electrodes with an angle $\theta$, and $I$ is injected electric current. Thus, the apparent resistivity $\rho$ is rewritten with a constant $K$ as

$$\rho = K \frac{|\vec{E}|}{I}$$

where $K$ with a bipole length $m$ is

$$K = \frac{2m^2 r_1 r_2}{(r_1^4 + r_2^4 - r_1 r_2 (r_1^2 + r_2^2 - m^2))^{1/2}}.$$ 

Therefore, the apparent resistivity $\rho$ is obtained by the injected current $I$ and the observed electric field intensity $|\vec{E}|$.

**Results and discussion**

In Figs. 5a and 5b, each solid arrow shows the direction of the observed electric field while each dotted arrow shows that of the electric field calculated for a homogeneous resistivity structure. They are very different for both cases of current directions. For both directions of injected current, observed field at S3, S5, and S7 pointed SE direction, while at S1, S2, S4, and S6 it pointed NW to W direction. This observation unambiguously shows that Kozu-shima Island consists of highly heterogeneous electrical underground structure. It may be a characteristic of Kozu-shima Island because the island is composed of several rhyolitic monogenetic volcanoes.$^{16}$ The fact that the direction of observed electric field is almost the same regardless of directions of injected source current seems to suggest that the current propagation is through conductive channels dictated by the complicated heterogeneous resistivity structure.

Apparent resistivity value at each receiving station is indicated by an attached number in Figs. 5a and 5b. Considering the large scatter of the values at each receiving station for different current injec-
tion directions (i.e., Figs. 5a and 5b), we took the geometric mean 
\[ r = \sqrt{r_{A-B}r_{A-C}} \] 
\r to represent the apparent resistivity value of a site as shown in Fig. 6. Here \( r_{A-B} \) and \( r_{A-C} \) are apparent resistivities for A-B and A-C current bipoles, respectively. In Kozu-shima Island, apparent resistivity was measured at twenty points by a VLF-MT survey in 1989.\(^{13}\) In Fig. 5, these apparent resistivities are also shown. It may be seen that both groups of the apparent resistivity values are generally consistent. For instance, \( r \) at S3 are in harmony with the conspicuously high VLF-MT apparent resistivities around Mt. Tenjo. Moreover, only one of the apparent resistivities measured by VLF-MT obtained inside the area of S1, S2, and S4, i.e. 340 \( \Omega \cdot m \) was close to the resistivities at S1, S2, and S4.

From Fig. 6, it can be estimated that the resistivity of the area between NTT and DMP would roughly be a half of that of the area between AIR and NTT. This difference may provide an explanation on the observation that the field intensity of AIR-DMP long dipole is smaller than that of AIR-NTT long dipole (See Figs. 2a and 2b).

Figures 7a and 7b show the changes of electric field component along the dipoles for pre-seismic geoelectric monitoring due to the current injected from the source near NTT during the bipole-dipole survey. The field change was recognizable only in the two long GND-NTT and AIR-NTT dipoles and GND-115m short dipole even after stacking. The directions of changes on short and long dipoles were the same as in the case of Fig. 2c. The amplitude of the two long dipoles was 3 to 10 times as large as that of GND-115m dipole. This also is very close to the case of Fig. 2c. It can be safely concluded that the change in Fig. 2c was also due to some surficial current from near NTT. The only difference between the cases of current injection (Fig. 7) and the suspect artificial noise (Fig. 2c) is that the change was not recognized on the two short NS dipoles at GND in the current injection case, probably because the amplitude (0.5 A) of our injected current was too small to produce clearly observable changes in the two short NS dipoles. In fact, even the voltage variations in GND-115m dipole were only slightly larger than those of the resolution of the recorder. We, therefore, considered that the artificial noise was generated in the area of NTT.

At the same time, it should be pointed out that the results shown in Figs. 2b, c and 7 suggest that the source of the pre-seismic anomalous changes was not near NTT, because the pattern of changes shown
Fig. 6. Apparent resistivities obtained by the present bipole-dipole survey and earlier VLF-MT survey. Solid circles are the locations of receiver dipoles at bipole-dipole survey and solid diamond points are VLF-MT observation points. Numbers show apparent resistivity [$\Omega \cdot m$]. In the case of bipole-dipole survey, the apparent resistivities are presented by geometric mean of the values obtained by bipoles A-B and A-C.

Fig. 7. Reproduction experiment of artificial noise. Electric field component recorded by long and short monitoring dipoles when current injection was made by (a) bipole A-B and (b) bipole A-C.
in (Fig. 2b) is drastically different from those in Figs. 2c and 7a, b. Namely, the changes on the long dipoles were in the same direction as those of GND short dipoles in the case of pre-seismic change, whereas they were in the opposite directions for the artificial noise and current injection. This result seems impossible to occur if the pre-seismic change was originated from the same area. Whereas the induction of geomagnetic field was observed in the whole short and long dipoles (Fig. 2a), and the directions of changes in short dipoles were consistent with those in long dipoles. This is in support that the generation mechanism of currents of the magnetotelluric change was different from those of noise, injection, and pre-seismic anomalous changes. The magnetotelluric current was induced by global-scale geomagnetic field change, while the currents of artificial noises and anomalous changes were locally generated and propagated through the ground with extremely heterogeneous electric structures. The large difference in the amplitude of long and short dipoles in the case of artificial noise (Fig. 2c) would mean that the source current dissipates during propagation to the GND site, while almost the same amplitude of long and short dipoles in the case of anomalous change (Fig. 2b) would mean that the current propagated from a far-distant underground source.

Conclusion

We conducted a preliminary bipole-dipole survey to investigate the origin and the transmission of pre-seismic anomalous changes at Kozu-shima Island, Japan. The results were consistent with the VLF-MT survey data obtained earlier by an independent group. Although the data are far from sufficient, it has been shown that the volcanic island has an extremely heterogeneous underground electrical resistivity structure. Furthermore, possibly aided by the heterogeneous resistivity structure, the geo-electric field variations recorded by long and short dipoles, previously set for the monitoring purpose, revealed distinguishable characteristics for changes with different origins, namely magnetotelluric current, artificial and injected currents and anomalous changes.

Acknowledgments

The present geoelectric research in Kozu-shima was carried out as part of International Research Program on Earthquake Prediction of the Institute of Physical and Chemical Research (RIKEN). We thank Dr. M. Hanada, Mr. K. Kawabata, Dr. I. Takahashi, Mr. Y. Noda, Mr. T. Yamaguchi for operating the long-term monitoring. The authors are also grateful to Dr. W. Kanda (Kyoto University), and Dr. Y. Sasai (Disaster Prevention Division, Tokyo Metropolitan Government Bureau of General Affairs), Mr. T. Kodama (JAXA, Japan) for their helps and useful comments. This research was partially supported by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Young Scientists (B), No. 21710180, 2009 (M. K.), and Scientific Research (C), No. 20510171, 2008 (S. U. and M. K.), Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, 2009 (T. N.), and Ito Science Foundation, 2007 (M. K.) and Grant-in-Aid of Fukada Geological Institute, 2009 (Y. O. and M. K.).

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(Received Sep. 29, 2009; accepted Nov. 2, 2009)