Two-Dimensional Conductivity Model Study of the Izu-Bonin Arc Based on Seafloor Electromagnetic Observations

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Abstract: Electromagnetic (EM) response functions obtained by the seafloor EM observations around the Izu-Bonin arc from 1986 through 1991 were interpreted by a two-dimensional (2D) conductivity model of the east-west profile on 31°N along which the observed induction vectors show some 2-dimensionality compared with the other profiles (on 32°N and 33°N). Numerical calculations for the periods from 15 min to 120 min were made for the B-values of E-polarization with a constraint at y-infinity that the depth to the asthenospheric conductor below the Philippine sea plate is shallower than below the Pacific plate, which was revealed by the direct magnetotelluric (MT) observations on the oceanic plates. As a result, a forearc conductor was found and related to another thin conductor appeared at the top of the Pacific plate in terms of a possible dehydration process from the subducted thin conductor.

1. Introduction

The northwest Pacific is well known as one of the typical subduction zones on the Earth with many island arc-trench systems characterized by intensive seismicity and volcanic activities. There are three such island arcs in the vicinity of Japan, namely, the Japanese islands, the Ryukyu arc and the Izu-Bonin arc.

Utada derived the most reliable 2D conductivity model of the Japanese islands for north-east Japan and for central Japan by non-linear least squares inversion which appreciated the contribution of the parametric partial derivatives as well as the squared sum of the residuals (Utada, 1987). Seafloor data were also used in his study for the first time in Japan.

Shimakawa proposed an interesting model of the Ryukyu arc based on seafloor geomagnetic observations (Shimakawa and Honkura, 1991). She used not only the traditional geomagnetic transfer function but also the attenuation of the horizontal geomagnetic components between the seafloor and the sea surface. She showed through 2D forward modelling that the conductivity anomalies around the Ryukyu arc were explained by two columnar conductors beneath the fore-arc region and beneath the active volcanic front superimposed on a basic 2D model representing the large-scale tectonic environment of the arc. Her model is very suggestive in the sense that it has brought about a new sight for volcanism of island arcs in terms of EM induction.

As for the Izu-Bonin arc, however, no significant EM observations were carried out before 1985 because of the difficulties associated with the seafloor EM observations although this island arc has conspicuous tectonic features. The Izu-Bonin arc forms a plate boundary between the two oceanic plates, the Pacific plate and the Philippine sea plate, and has a very immature crust without significant crustal accretion. Hino studied the crustal structure of the Izu-Bonin arc using air-guns and OBS's to find rather thin 6 km/s layers scattered mainly below the back-arc rift zone. These layers, however, were not able to be identified as whether they are made of granite or granodiorite (Hino, 1992). In terms of structural geology, Fujioka argued the possibility of the patched formation of the entire arc, that is, considering the Izu-Bonin arc as consisting of a few segments in stead of a continuous island arc (Fujioka, 1992, personal communication).

In 1986, we started the seafloor EM observations around the Izu-Bonin arc to reveal the conductivity structure of the island arc. Basic understanding of the structure has been attained by those observations though it was very difficult to cover the wide area by a dense observation network. In this paper, the data obtained so far will be described in the following section and the method, assumptions and result of the 2D forward modelling will be presented in section 3. Finally, geophysical implication of the 2D model will be briefly summarized in the last section.

2. Data

Time series of the variations of the seafloor EM fields were collected at 18 sites on three profiles at the latitudes of 31°N, 32°N and 33°N using both ocean bottom magnetometers and ocean bottom electrometers developed in this institute. Sampling intervals were selected as either 1 min or 2 min to observe short-period EM variations (periods ranging from 15 min to 120 min) at the seafloor since high frequency EM signals rapidly decay in the ocean due to the high conductivity of seawater. Duration of the data differs depending on the sampling rate and power consumption of each instrument and ranges from 8 days to 158 days (73 days in average).

All the data obtained were analyzed by a robust scheme based on a non-linear least squares method to evaluate the EM response functions of the Earth at each site, i.e., the geomagnetic transfer function and/or the MT impedance tensor. The robust scheme was applied to eliminate possible biases arising from both isolated outliers and local non-stationarity in each dataset (Chave et al., 1987). The scheme uses two kinds of weight function, namely, Huber weight function of the form,

$$w_H(x) = 1 \text{ for } |x| \le k \text{ and } \sqrt{\frac{2k}{|x|} - \frac{k^2}{x^2}} \text{ for } |x| \ge k \text{ where } k = 1.5,$$

(Huber, 1981) and Thomson weight function, $w_T(x) = \exp\{-e^{\beta(|x| - \beta)}\}$, where β was chosen as the Nth quantile (Thomson, 1977) and is 'robust' in the sense that it completely removes isolated outliers and downweights the contribution of anomalously enhanced record sections due to non-stationarity of the geomagnetic activity provided that such non-stationarity is 'local' enough to be less frequent than seemingly 'normal' sections.

Figures 1 and 2 show the amplitudes and phases of the B-values of the geomagnetic transfer function, respectively. The contour maps were derived by interpolating the observed B-values at 15 sites using Akima's method (Akima, 1978) although pseudo eye-shaped anomalies appear at sites, e.g., JK20, JK21 and JK24 due to overfitting of the ill-distributed sparse data over such a broad area. However, abrupt enhancement of the amplitudes on the landward slope of the trench and less steep slope of the amplitudes on the foot of the back-arc ridge crest are clearly seen in Fig. 1. Phase reversals on both sides of the arc associated with so-called 'coast effect' are also apparent in Fig. 2.

The A-values of the geomagnetic transfer function are not shown here because the Izu-Bonin arc has an almost north-south strike and the amplitudes of the A-values become significantly small for the period of 60 min at the latitude of 31°N. This is the reason why the conductivity structure of the Izu-Bonin arc was interpreted by a 2D model using the projected B-values onto an east-west profile at 31°N. Results from MT observations will be described in the next section in terms of boundary conditions required in 2D modelling.

3. 2D Modelling

The seafloor EM fields always lack in high frequency signals such as VLF, ELF and ULF variations on land due to the presence of the conductive ocean. Hence, it is very difficult to determine the shallower structure simply by passive EM measurements at the seafloor. The shallower structure of our 2D model was assumed by referring other geophysical information. First, the ocean was modeled by reading depths along 31°N from the TUG87 dataset which is an edited world-wide 5' mesh digital topographic data and assigning a conductivity of 4 S/m. Honza and Tamaki made intensive air-gun surveys around the Izu-Bonin arc and their seismic profiles were used to model the sedimentary layers with a value of 1 S/m (Honza and Tamaki, 1985). The sediments mainly distribute in the back-arc rift zone and the fore-arc basin, where the deepest hole in the history of ODP was dug (ODP 126 shipboard scientific party, 1989). Rest of the crustal structures is difficult to resolve because of their resistive nature and the poor spatial distribution of the data points and included in the lithospheric layers with a value of 0.002 S/m.

Various boundary conditions are required for the 2D calculation of the E-polarization mode (Jones and Price, 1970). Most of them are satisfied automatically by coding a program according to analytical formulae. Those at lateral infinity, however, should be given explicitly because the amplitude of Ex in the E-polarization case can take different values for large negative or positive y-values. Here, we specified them by assigning appropriate one-dimensional (1D) conductivity structures at lateral infinity determined through direct MT observations on the two oceanic plates.

The MT measurements conducted in 1989 and 1990 revealed the 1D structure beneath the Pacific plate which was understood by, to first approximation, a three-layered structure of the conductive, resistive and conductive configuration from top to bottom. The middle resistive layer has a thickness of approximately 150 km indicating the age of the old seafloor of the northwest Pacific as has been pointed out by Yukutake (Yukutake et al., 1983). The conductive layer beneath the resistive layer corresponds to the asthenospheric conductor while another thin conductor as thick as 10 km at the top of the plate is considered to consist of the sedimentary layers and the porous upper crust saturated with seawater. The 1D structure beneath the Philippine sea plate was read from Utada's model which was also determined by the seafloor MT measurement and had a similar three-layered structure with a rather thinner resistive layer of 30 km thick.

Computation of 2D forward models was conducted by a finite difference method originally evaluated by Jones and Pascoe (Jones and Pascoe, 1971) and modified for the application to super computers. Figure 3(b) shows the result of the calculation with respect to the 2D model shown in Fig. 3(a) for the periods from 15 min to 120 min as well as the observed EM responses. This model was derived by superimposing lithospheric thickening beneath the back-arc side of the arc and a fore-arc conductor on a basic model representative of the tectonic setting determined by the distribution of hypocenters in this region and the 1D conductivity models of the oceanic plates. The calculation showed that the model in Fig. 3(a) explained the observed B-values fairly well within the error bars except for the discrepancies of the amplitude on the back-arc side which were not much improved in spite of introducing the lithospheric thickening while the amplitude on the fore-arc region was significantly suppressed by the fore-arc conductor and acquired a better fit.

4. Summary and Concluding Remarks

The 2D model described in the former section is characterized by three conductors. The asthenospheric conductors have a depth contrast according to the age of each oceanic plate. The other two conductors are speculated to have an intimate relation to each other. The thin conductor at the top of the Pacific plate could be understood as a source of water which is dehydrated from the subducted slab beneath the fore-arc region and causes the fore-arc conductor. Shimakawa has already suggested the possibility and related the two columnar conductors to a petrological model proposed by Tatsumi which represents a general feature of volcanism in island arc-trench systems (Tatsumi, 1989). In this context, Tatsumi's model can be considered as a three-stage dehydration model, first two of which correspond to Shimakawa's columnar conductors.

Finally, we make a comparison of the three island arcs in the vicinity of Japan, namely, the north-east Japan, the Ryukyu arc and the Izu-Bonin arc. It is north-east Japan that has the resistive fore-arc different from the other two island arcs. This, however, can be understood as the bulk of resistive granitic rocks characterizing the fore-arc region of north-east Japan were formed by accretion of a patch of an old continent as a body. Considering north-east Japan as an exception, it can be speculated that fore-arcs of young island arc-trench systems are intrinsically conductive as a general feature of an island arc as in the cases with the Ryukyu arc and the Izu-Bonin arc provided that the fore-arc conductors found in the two regions will be further confirmed.

Computation of the 2D model was conducted on a HITAC S820/80 super computer at the computer center of the University of Tokyo.

REFERENCES

Akima, H., A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points, *ACM Trans. Math. Software*, **4**, 148-159, 1978

Chave, A. D., D. J. Thomson and M. E. Ander, On the robust estimation of power spectra, coherences and transfer functions, *J. Geophys. Res.*, **92**, 633-648, 1987

Honza, E. and K. Tamaki, The Bonin arc, in: *The Ocean Basins and Margins*, eds., A. E. M. Nairn, F. G. Stehli and S. Uyeda, 459-502, 1985

Huber, P. J., *Robust statistics*, John Wiley, New York, 1981

Hino, R., A study of the crustal structure beneath the Izu-Bonin arc using air-guns and OBS's, Ph. D. Thesis, Tohoku Univ., 1992

Jones, F. W. and L. J. Pascoe, A general computer program to determine the perturbation of alternating electric currents in a two-dimensional model of a region of uniform conductivity with an embedded inhomogeneity, *Geophys. J. R. astr. Soc.*, **24**, 3-30, 1971

Jones, F. W. and A. T. Price, The perturbations of alternating geomagnetic fields by conductivity anomalies, *Geophys. J. R. astr. Soc.*, **20**, 317-334, 1970

ODP Leg 126 shipboard scientific party, Arc volcanism and rifting, *Nature*, **342**, 18-20, 1989

Shimakawa, Y. and Y. Honkura, Electrical conductivity structure beneath the Ryukyu trench-arc system and its relation to the subduction of the Philippine sea plate, *J. Geomag. Geoelectr.*, **43**, 1-20, 1991

Tatsumi, Y., Migration of fluid phases and genesis of basalt magmas in subduction zones, *J. Geophys. Res.*, **94**, 4697-4707, 1989

Thomson, D. J., Spectrum estimation techniques for characterization and development of WT4 waveguide, I, *Bell Syst. Tech. J.*, **56**, 1769-1815, 1977

Utada, H., A direct inversion method for two-dimensional modeling in the geomagnetic induction problem, Ph. D. Thesis, Univ. Tokyo, 1987

Yukutake, T., J. H. Filloux, J. Segawa, Y. Hamano and H. Utada, Preliminary report on a magnetotelluric array study in the northwest Pacific, *J. Geomag. Geoelectr.*, **35**, 575-587, 1983

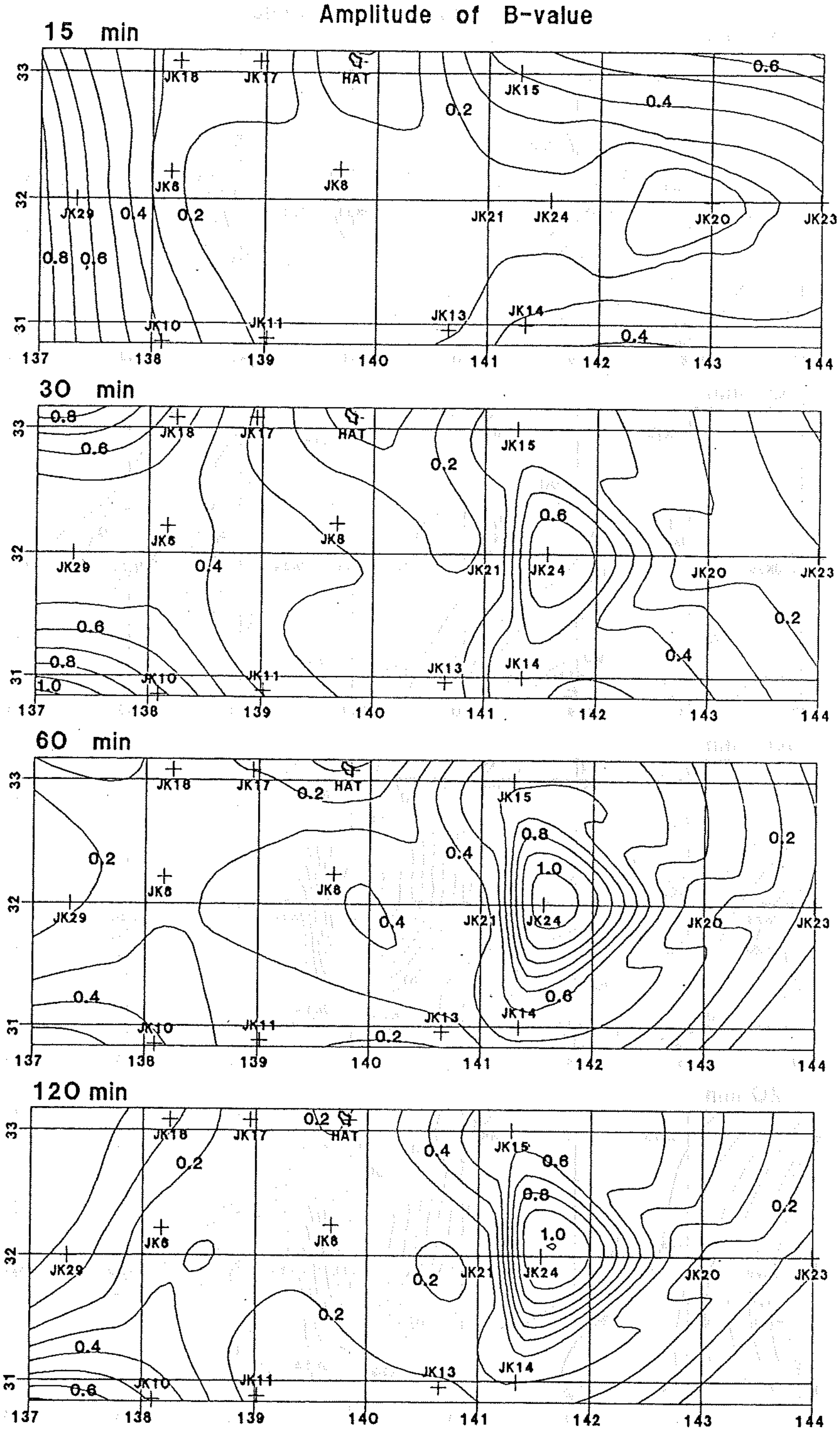

Fig. 1 Amplitudes of the observed B-values of the geomagnetic transfer function for the periods from 15 min to 120 min. Crosses indicate the observation sites. Contour interval is 0.1.

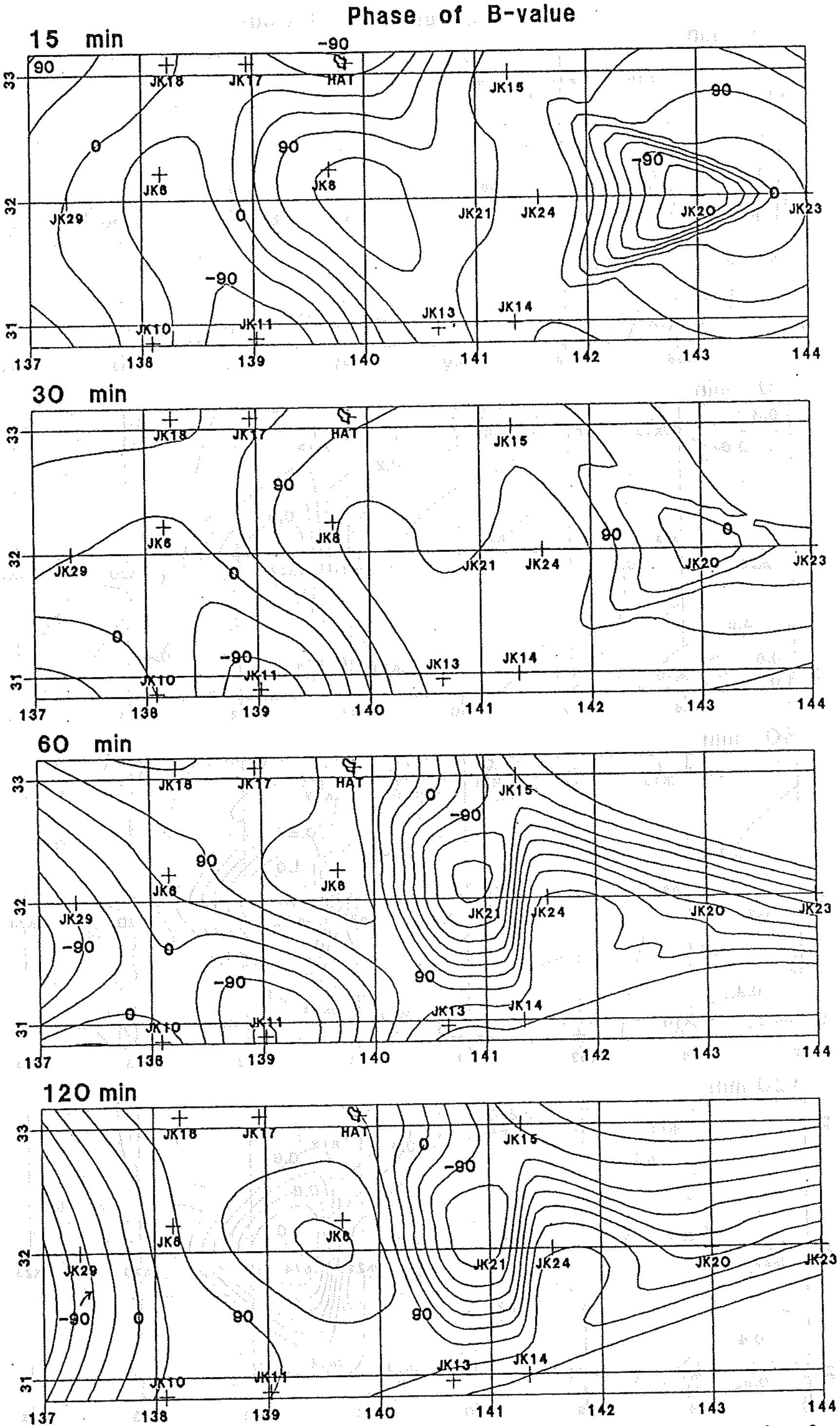

Fig. 2 Phases of the observed B-values of the geomagnetic transfer function for the periods from 15 min to 120 min. Crosses indicate the observation sites. Contour interval is 45°.

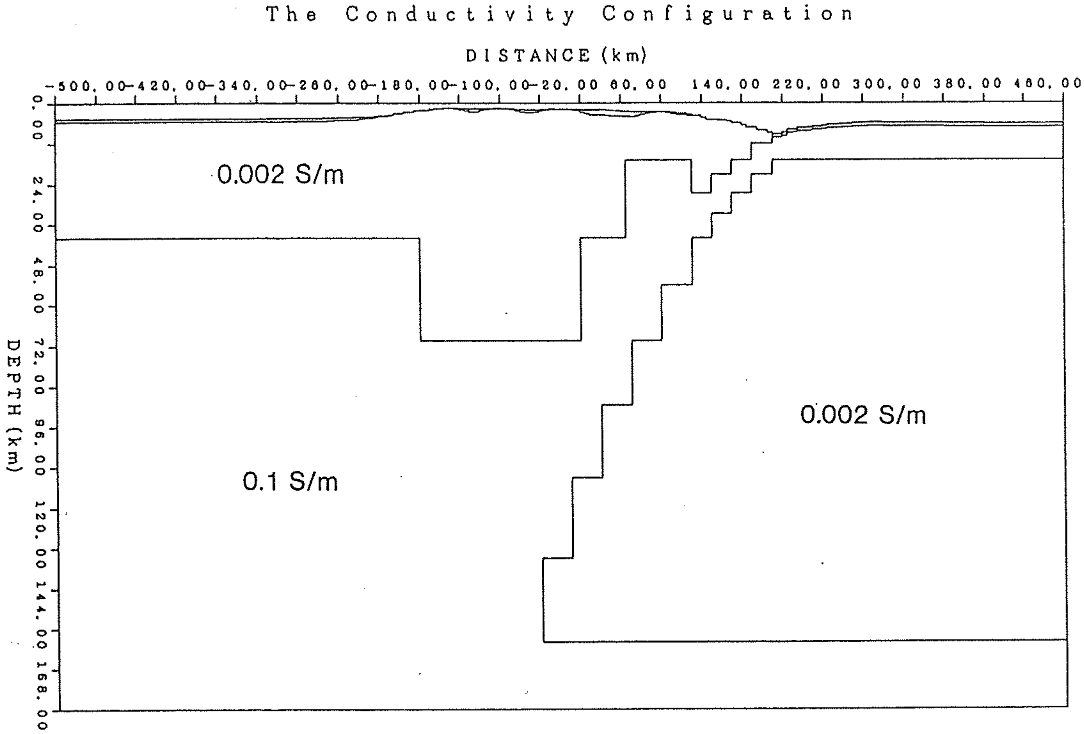

Fig. 3(a) The 2D conductivity model of the Izu Bonin arc. The abscissa is the horizontal distance measured from the present active volcanic front.

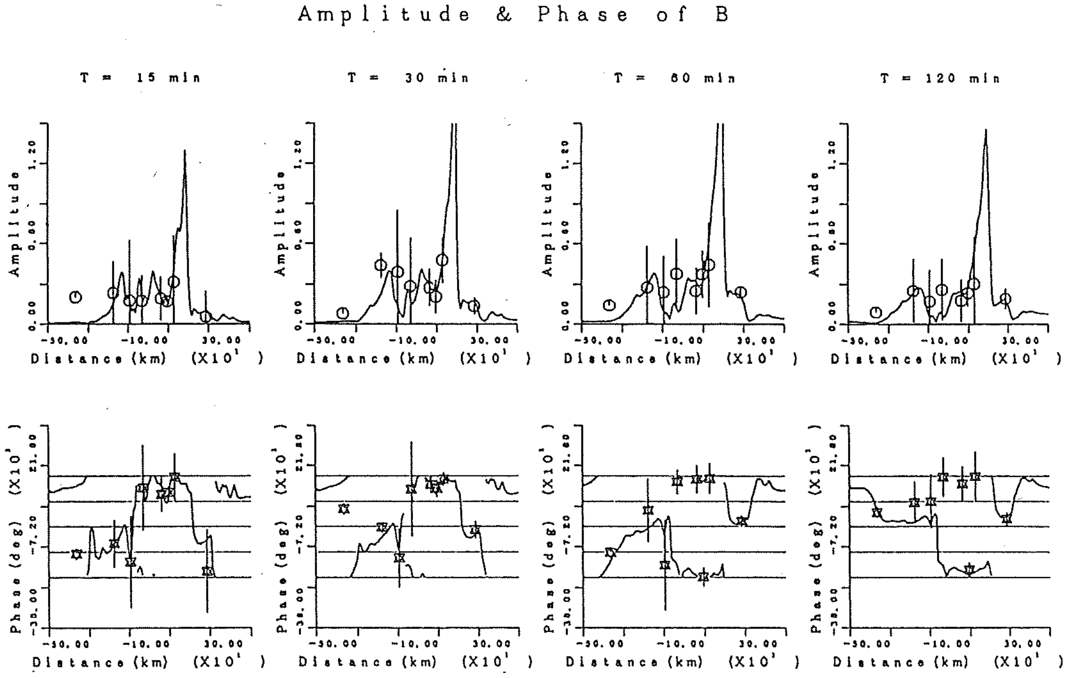

Fig. 3(b) Amplitudes and phases of the observed and the calculated B-values for the model shown in Fig. 3(a).