

Werk

Jahr: 1984

Kollektion: fid.geo

Signatur: 8 Z NAT 2148:55

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Werk Id: PPN1015067948_0055

PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948_0055

LOG Id: LOG_0042

LOG Titel: Analogue-model magnetic field responses of an ocean channel, an island and a seamount in the Hainan Island region

LOG Typ: article

Übergeordnetes Werk

Werk Id: PPN1015067948

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Analogue-model magnetic field responses of an ocean channel, an island and a seamount in the Hainan Island region

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Abstract. The electromagnetic responses of a shallow channel (Hainan Strait), an island (Hainan Island) in a shallow coastal sea, and a large flat-topped seamount (Zhongsha Islands) in a deep ocean were studied using a scaled laboratory analogue model. To examine the responses, in-phase and quadrature H_z and H_y magnetic fields are presented for traverses over the channel, the island and the seamount for simulated geomagnetic variations with periods in the range 5–500 min. The in-phase H_z and H_y channel and island responses were found to decrease rapidly with increasing period, reaching negligible values at about 60-min periods, while the in-phase H_z and H_y seamount responses had significant values over the entire 5–500-min period range. The quadrature H_z and H_y channel and island responses had maxima at a period of approximately 20 min when the 0.25 km depth ocean in the channel and surrounding the island was 0.025 skin depth (δ).

The shapes of the quadrature H_z and H_y seamount response curves showed a transition from a “channel response” to an “island response” at a period of approximately 20 min, the same period at which maximum in-phase responses occur. At this period the surrounding ocean depth is 0.2–0.4 δ and the ocean depth over the seamount is 0.05 δ . The quadrature H_z and H_y seamount responses were each at a maximum at approximately 100 min, when the surrounding ocean depth was 0.1–0.2 δ and the ocean over the seamount is 0.025 δ .

The addition of a conducting plate to simulate conducting mantle structure at a depth of 100 km led to much less attenuation for the case of the seamount than for the channel or island due to the deep ocean surrounding the seamount, effectively shielding the conducting mantle from the overhead primary source field.

Key words: Laboratory electromagnetic modelling – Electromagnetic induction – Geomagnetic variations

Introduction

Scaled laboratory-model measurements of electromagnetic induction can be used to aid in the interpretation of field station results for complex coastal regions. Previous labora-

tory-model studies for coastal regions involving islands near continents, and ocean channels between islands and continents, are provided by Nienaber et al. (1979) for Vancouver Island, Dosso et al. (1980a) for the British Isles, Chan et al. (1981, 1984) for the Queen Charlotte Islands, Dosso et al. (1980b) and Hebert et al. (1983, 1984) for Newfoundland, and Hu et al. (1984) for Hainan Island. These studies examine the effects of the island and mainland coastlines, the conductive sea channels, and the ocean bathymetry on the on-shore and off-shore electric and magnetic fields.

Considerable geophysical exploration has been carried out in recent years in the Hainan Island area of the South China Sea. Laboratory model results can aid in the analysis of field observations in this region, permitting some separation of the effect of the continental and island coastline contours, the effects of ocean bathymetry, and the effects of current channelling in the shallow strait and around, or over, the seamount, from the effects of anomalous conductivity substructure.

The present work is limited to studying the model magnetic fields for this Hainan Island region, and in particular examining the responses of the simulated shallow ocean channel (Hainan Strait), island (Hainan Island) in the shallow coastal sea and large seamount (Zhongsha Islands) for simulated periods of 5 to 500 min.

Model description

Since the South China Sea laboratory model used in the present work was described in detail earlier (Hu et al. 1984), only a brief description will be provided here. The scaling factors for frequency (f), linear dimension (L) and conductivity (σ) were chosen to satisfy the scaling conditions $(f_m/f_g)(L_m/L_g)=k$ and $(\sigma_m/\sigma_g)(L_m/L_g)=k^{-1}$, where k is the ratio of the model to the geophysical impedance. The subscript m refers to the model parameters and the subscript g to the geophysical parameters. In the model, saturated salt solution ($\sigma=21 \text{ Sm}^{-1}$) is used to simulate land ($\sigma=6 \times 10^{-4} \text{ Sm}^{-1}$) while graphite plate ($\sigma=1.2 \times 10^5 \text{ Sm}^{-1}$) is used to simulate the ocean ($\sigma=3.6 \text{ Sm}^{-1}$) and sediments. Thus the conductivity scale factor is $\sigma_m/\sigma_g=10^5/3$. The linear scale factor was chosen to be $L_m/L_g=10^{-6}$, so that 1 mm in the model would simulate 1 km in the geophysical scale. With these scale factors established, the frequency scale factor was determined to be $f_m/f_g=3 \times 10^7$. Thus a model frequency of 100 kHz simulates a geomagnetic variation of 5-min period.

The analogue model facility [see Dosso (1973) for a

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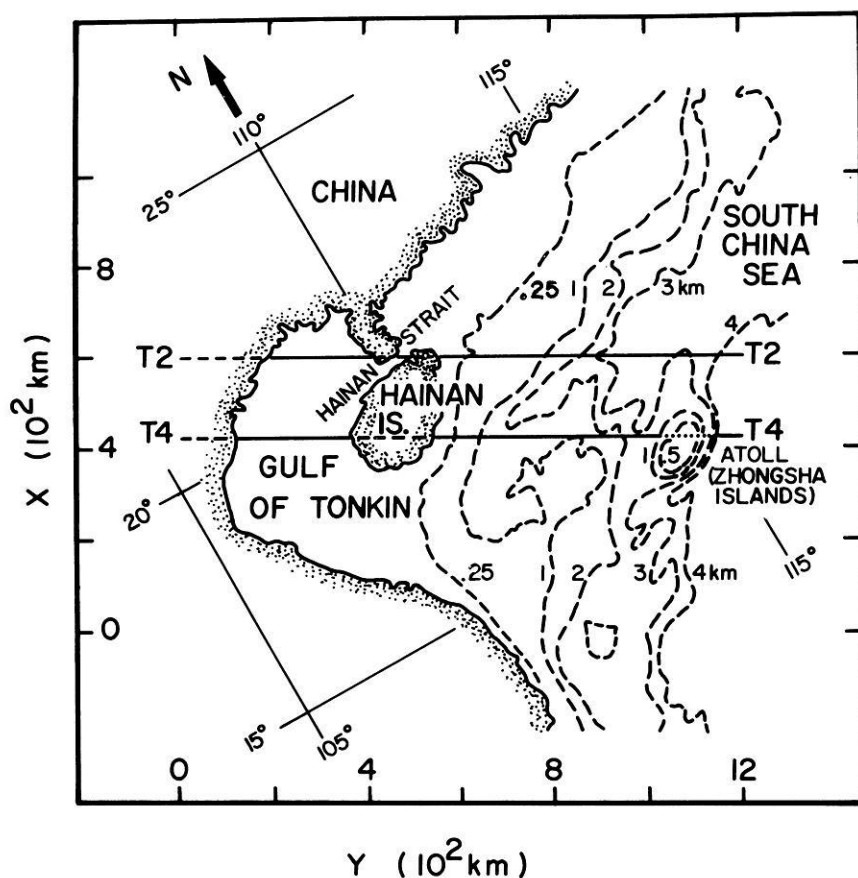


Fig. 1. A simplified map of the Hainan Island region with bathymetric contours, showing locations of the traverses for the model measurements

complete description] uses a plywood tank 2.44×1.68 m filled with concentrated salt solution to a height of 0.63 m and an overhead uniform, horizontal inducing field [see Ramaswamy et al. (1975) and Nienaber et al. (1976) for a detailed description of the source field].

Figure 1 shows the simplified map of the Hainan Island region used as a pattern in constructing the model ocean. The 0.25 km and 1 km depth contours shown are modified depths, that is, the model ocean depth has been increased by 0.15 km to include the effects of the extensive highly conductive sediments in the region (Ludwig et al., 1979; Nino and Emery, 1961). The ocean was thus modelled to be of constant 0.25 km depth from the mainland coastline to the 0.25 km contour shown in Fig. 1, and of increasing depth seaward. The Zhongsha Islands (coral islands) are modelled as a flat-topped seamount 0.5 km below the surface of the ocean. This seamount model should simulate the coral islands quite well since only a small ring-like coral reef projects above the surface of the ocean. The method of constructing the graphite model ocean (using the Fig. 1 pattern) and suspending it at the surface of the salt solution in the model tank has been described earlier (Hu et al., 1984). This model ocean suspended in the salt solution simulates the case of an ocean underlain by a uniform host earth.

The magnetic field components at the surface of the model were measured for a constant amplitude horizontal inducing field (in-phase $H_x = 1$ nT and quadrature $H_y = 0$ nT at an on-shore reference location at a simulated distance of 400 km from the continental coastline). Measurements were carried out for the case of the electric field of the overhead uniform source in the x -direction (Fig. 1)

and roughly parallel to the general direction of the ocean depth contours. In the present work this case is defined as the E-polarization of the source field.

Discussion of results

The present work is restricted to studying the in-phase and quadrature parts of the vertical magnetic field (H_z) and one component of the horizontal magnetic field (H_y) for traverses T2 and T4 (Fig. 1) to examine the responses of the ocean channel, the island and the seamount for the simulated period range 5–500 min. In all diagrams giving the model results, solid lines show measurements over sea (including the channel), dashed lines show measurements over lands (including the island) and dotted lines show measurements over the seamount between the 0.5 km contours (Fig. 1). The simulated periods studied in Figs. 4–7 are given in Table 1.

Analogue model in-phase and quadrature H_z and H_y field components for a simulated 5-min period for traverses

Table 1. Periods simulated in the model for frequency scaling $f_m/f_g = 3 \times 10^7$

Curve number	Period (min)	Curve number	Period (min)
1	5	6	60
2	8	7	100
3	17	8	170
4	20	9	500
5	30		

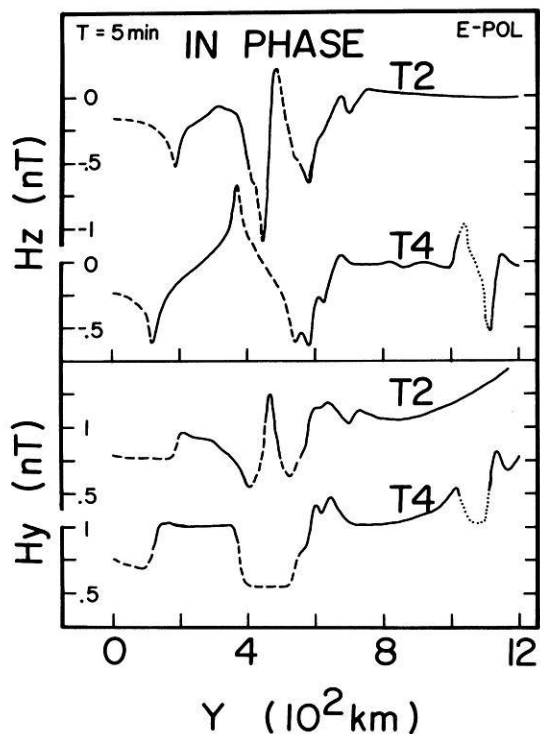


Fig. 2. In-phase H_z and H_y model fields for traverses T2 and T4

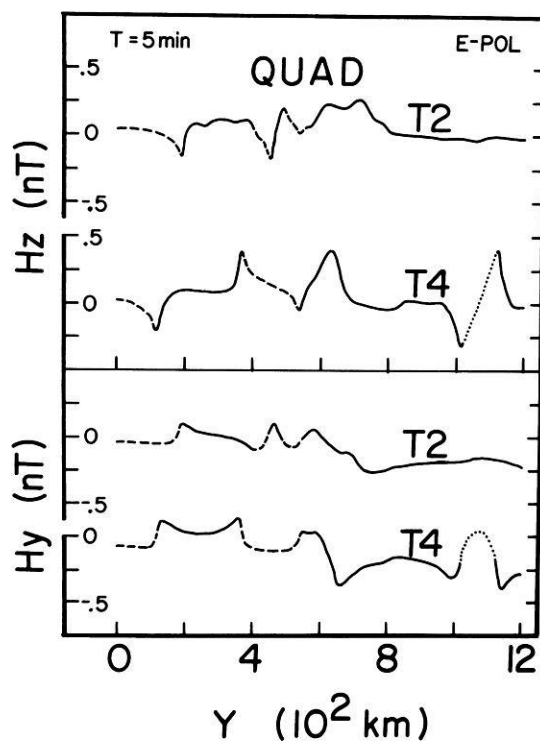


Fig. 3. Quadrature H_z and H_y model fields for traverses T2 and T4

T2 and T4 over the model (Fig. 1) are shown in Figs. 2 and 3. Traverse T2 shows the ocean channel (Hainan Strait) response, while traverse T4 shows the island (Hainan Island) response and the seamount (Zhongsha Islands) response. A general comment on the results of Figs. 2 and 3 is that for 5-min-period variations the magnitudes of the

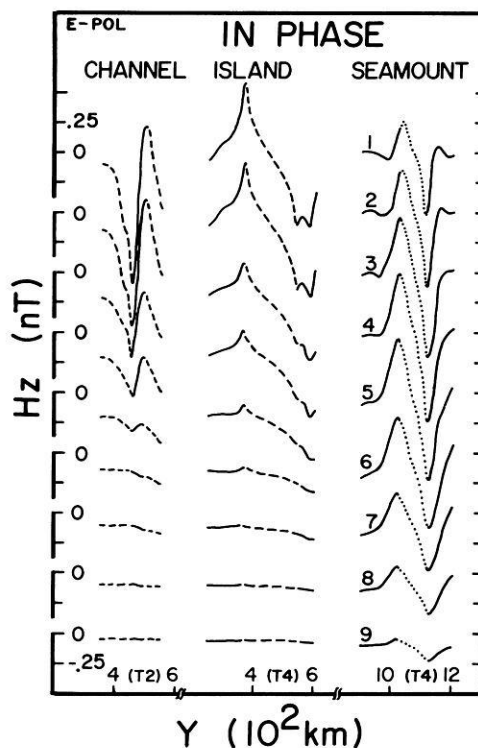


Fig. 4. In-phase H_z channel, island and seamount responses

channel and island in-phase responses are much greater than the quadrature responses, while the seamount in-phase and quadrature responses are roughly equal. This differs from the earlier results of Hu et al. (1984) for this South China Sea model, which showed that the magnitude of the in-phase response was approximately equal to the quadrature response for each of the three structures. The physical difference in the two models is that the present model simulates the case of the ocean and land underlain by a poorly conducting uniform host earth, while the earlier model included a 15-mm-thick conducting (graphite) plate mounted at a depth of 100 mm in the model tank to simulate the effect of increasing conductivity with depth in the geophysical case [the rationale for selecting the 100 mm depth, simulating 100 km, is discussed in the earlier work of Hu et al. (1984)]. Thus it can be concluded that for 5-min-period variations the in-phase channel and island responses are attenuated by the 100-km depth-conducting zone by a factor of about 2 more than the corresponding quadrature responses, while for the seamount the in-phase and quadrature responses are attenuated approximately equally.

In Figs. 2 and 3 the in-phase and quadrature H_z (and H_y) channel response curves (T2 solid line section) have essentially the same shapes, although the magnitudes of the in-phase and quadrature H_z (H_y) responses differ by a factor of about 4–5. The large in-phase H_z (H_y) channel responses can, in part, be attributed to local current concentration in the channel due to electric currents induced in the Gulf of Tonkin and shallow sea east of Hainan Strait and channelled through the narrow Hainan Strait. The shapes of the in-phase H_z (H_y) island (T4 dashed section) and seamount (T4 dotted section) responses are almost identical, while the shapes of the quadrature responses are roughly mirror images of each other.

Figures 4 and 5 show the in-phase H_z and H_y channel,

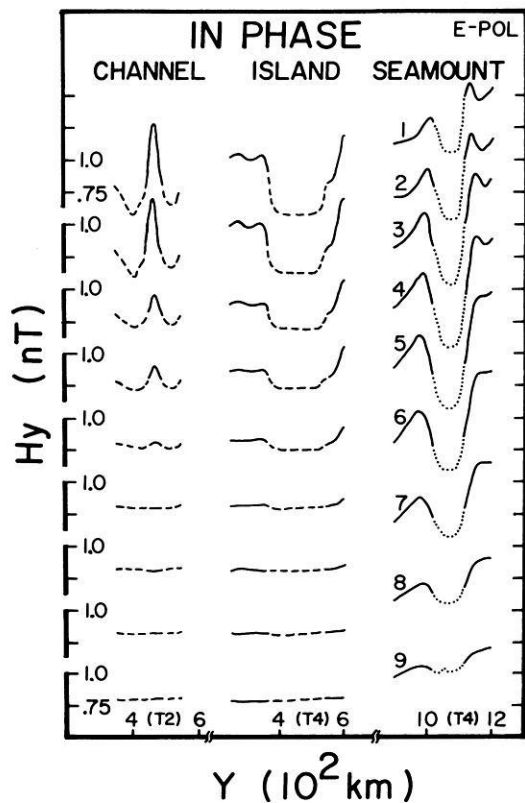


Fig. 5. In-phase H_y channel, island and seamount responses

island and seamount responses for periods ranging from 5–500 min (labels 1–9). The channel and island responses decrease rapidly with increasing period, with almost zero anomalous responses for a period of 60 min (curve 6). In each of Figs. 4 and 5, the seamount response is a maximum for a period of approximately 20 min (curves 3 and 4), decreasing for both shorter and longer periods. For this 20-min period, the 0.5-km-depth ocean over the seamount is approximately 0.05δ (skin depth $\delta = (2/\sigma\omega\mu)^{1/2}$), the 2-km-depth ocean landward approximately 0.2δ , and the 4 km depth ocean seaward approximately 0.4δ . This maximum response, occurring at the 20-min period, can be assumed to be due to the combination of the responses of the shallow ocean over the seamount and the deep ocean surrounding the seamount. The in-phase H_z and H_y seamount responses respectively have the same form as the in-phase H_z and H_y island responses for periods shorter than 60 min (curve 6).

Figures 6 and 7 show the quadrature H_z and H_y channel, island and seamount responses for periods ranging from 5–500 min. Each of the quadrature H_z and H_y channel and island responses shows a maximum at a period of approximately 20 min (curves 3–4), with decreasing responses for both shorter and longer periods. For this 20-min period the 0.25 km depth ocean (the channel and the shallow coastal sea) is approximately 0.025δ . The quadrature channel and island responses are significant for periods up to approximately 170 min (curve 8) as compared with 60 min for the in-phase responses (Figs. 4 and 5).

From the in-phase H_y channel responses in Fig. 5 and the quadrature H_y channel responses in Fig. 7, it can be seen that the magnitude of the anomalous H_y total field (though not provided) increases with decreasing period with

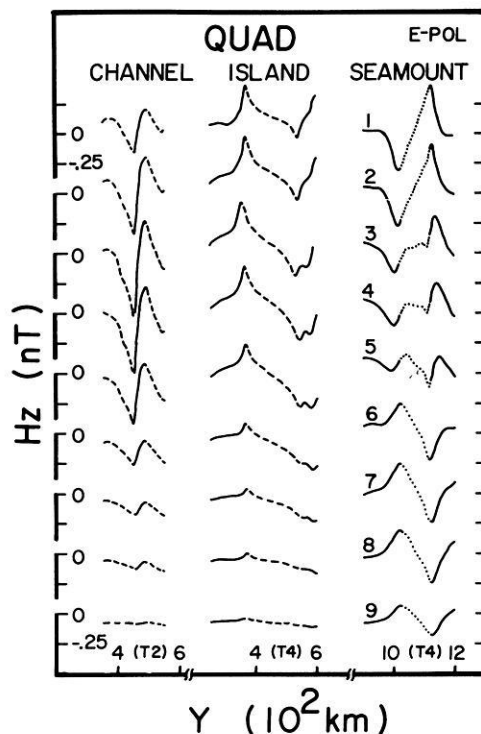


Fig. 6. Quadrature H_z channel, island and seamount responses

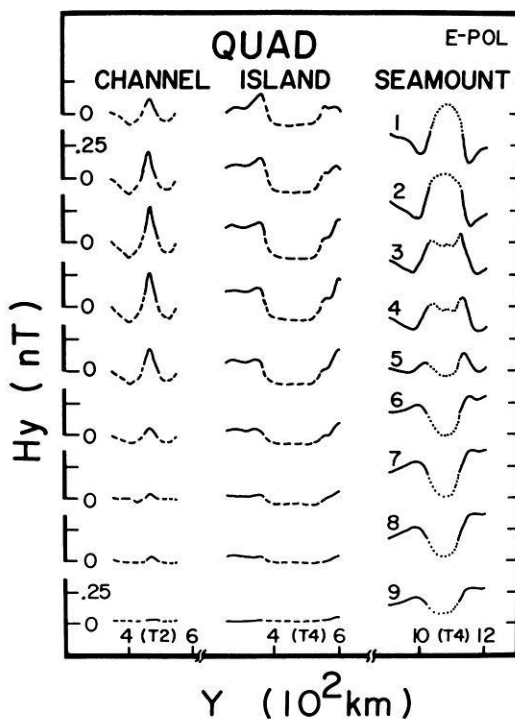


Fig. 7. Quadrature H_y channel, island and seamount responses

the largest anomalous field at the 5-min period, the shortest period studied in the present work. On the basis of numerical calculations and model measurements, Hebert (1983) and Hebert et al. (1983) conclude that a maximum in the magnitude of the anomalous horizontal magnetic field for a conductive channel should occur when the channel depth is approximately 0.15δ . At the shortest period (5 min) stud-

ied in the present work, the 0.25-km-depth channel is 0.05δ , considerably less than 0.15δ . Thus, in agreement with the present model results, a maximum in the magnitude of the anomalous H_y total field should not be observed for the present period range, but should occur at a much shorter period (~ 0.5 min).

The quadrature H_z and H_y seamount responses in Figs. 6 and 7 each show a channel response for short periods (curves 1 and 2) and an island response for long periods (curves 5–9), with a transition from a “seamount-channel” response to a “seamount-island” response in the neighbourhood of 20-min period (curves 3 and 4). The period for which the transition takes place should be related to both the overburden response, which contributes to a channel response, and the surrounding ocean, which contributes to an island response. For this 20-min transition period, the 0.5-km overburden depth is 0.05δ and the surrounding ocean depth ranges from 0.2 – 0.4δ . It is noted that the period for which the transition occurs is the same as the period for the maximum in-phase seamount response (Fig. 4) discussed earlier.

The quadrature H_z and H_y “seamount-island” responses (curves 5–9) are each at a maximum at approximately 100 min (curve 7) when the 2 and 4 km ocean depths (landward and seaward) are approximately 0.1 and 0.2δ respectively, and the 0.5-km-seamount overburden depth is approximately 0.025δ . Since for the longer periods the seamount response has taken the form of an island response, the surrounding conducting ocean should be responsible for the major contribution to the responses. Thus from the results of Figs. 6 and 7 it can be concluded that the maximum quadrature channel and island responses occur when the depth of the responding ocean (channel depth in the case of the channel, and the surrounding sea depth in the case of the island) is approximately 0.025δ , and the maximum quadrature “seamount-island” response occurs when the surrounding ocean depth is 0.1 – 0.2δ and the seamount overburden depth is 0.025δ .

Summary

Figure 8 shows, in summary form, the responses expressed as the absolute value of the difference of the H_z/H_y ratios in crossing the channel, the island and the seamount for a uniform, poorly conducting substratum (curve A), and for a conducting mantle zone at a simulated depth of 100 km in the otherwise uniform, poorly conducting substratum (curve B). In agreement with the results of Figs. 4–7, Fig. 8 shows that the in-phase channel and island responses decrease very rapidly with increasing period, and that the maximum in-phase seamount response occurs at a period of approximately 20 min. For each of the channel and island responses, the results show that adding a conducting plate to simulate conducting mantle structure results in the quadrature response maximum shifting to shorter periods. From the results of Fig. 8 it is seen that, in general, a conducting mantle layer leads to attenuation of the anomalous fields measured at the surface, and that the attenuation is much less for the case of the seamount than for the channel or island. Since this attenuation is a result of the partial cancellation of the anomalous fields by the fields of the eddy current induced in the mantle layer, the observed difference in attenuation for the case of the seamount, as compared with that of the channel and island,

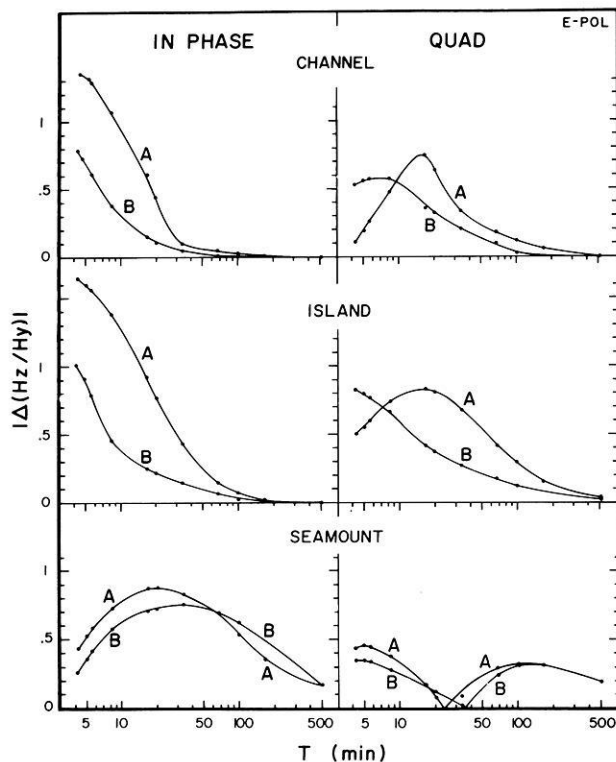


Fig. 8. $|\Delta(H_z/H_y)|$ channel, island and seamount responses for (A) uniform conducting substratum and (B) a conducting mantle zone at a simulated depth of 100 km

may provide information on the relative strengths of those induced eddy currents in the conducting mantle due to the primary external source field and those due to the secondary fields of the induced coastal anomalous currents. If the mantle eddy currents are primarily due to the secondary fields of the coastal anomalous currents, the anomalous field cancellation should be the same for each of the three structures since the depth to the mantle and the intermediate medium is the same for each structure. If the mantle eddy currents are primarily due to induction by the primary source field, the large, poorly conductive land masses in the neighbourhood of the channel and the island readily permit penetration of the primary source field and the induction of substantial mantle eddy currents. The secondary fields of these eddy currents would, by inducing currents in the ocean above, lead to considerable cancellation of fields at the surface of the ocean. For the case of the seamount, however, the deep ocean surrounding the seamount strongly shields the mantle from the primary source field, reducing the mantle eddy currents and the cancelling effects on the fields at the surface. The results of the present model study clearly support the view that it is primarily the external source-field-induced eddy currents in the conducting substratum that are responsible for reducing the field anomalies at the surface. This may be an important result in aiding efforts to separate the anomalous fields of near-surface conductivity structure from those of conductive structure at depth, and to determine the inductive coupling between conductive structures at the surface and at depth.

Acknowledgements. The financial support of an NSERC grant and a University of Victoria Faculty Research Grant is gratefully acknowledged.

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Received December 9, 1983; Revised version March 22, 1984

Accepted March 22, 1984