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Theoretical investigation of the ocean–coast effect at a passive continental margin

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The idea that oceanic lithosphere is thinner than continental lithosphere is widely accepted even though one would like to see clearer evidence to support it. In fact, the very concept of lithosphere is still a matter of some debate. If there is indeed a variation in the thickness of the lithosphere at continental margins and if this change is associated with a lateral variation in electrical conductivity one may envisage detecting it with electromagnetic soundings methods. A model of a passive continental margin has therefore been investigated to test whether this would be feasible. It has been found that the well-known but strong ocean–coast effect masks the minor lithospheric effect in magnetotelluric soundings performed on the shore. Inductive soundings, on the other hand, are highly sensitive to lateral variations in electrical conductivity. An analysis in terms of the induction arrow has shown that such soundings carried out on land would be perfectly suitable to reveal a changing lithospheric thickness, if the continents merely extended to the oceanic coast. However, the presence of only a narrow continental shelf of 100 km width under 250 m of sea-water produces an overriding coast effect ahead of the margin, and thus renders electromagnetic methods unsuited to reveal a changing lithospheric thickness.

1. Introduction

The past few years have seen a number of papers dealing with model calculations of the ocean–coast effect. For the most part these models were two-dimensional (2-D) and the ocean was simulated with a perfectly conducting semi-infinite sheet. Bailey (1977) gave an analytic solution of the B-polarization (B-POL) response of such a simple ocean at the surface of a uniform half-space. Nicoll and Weaver (1977) extended this work to include a perfect conductosphere at typical mantle depths of 50–600 km. The E-polarization (E-POL) response of the simple model was solved semi-analytically by Fischer et al. (1978, 1980) and an analytical solution in closed form was then given by Raval et al. (1981).

Paralleling these developments great progress was made in analytical and numerical calculations with models involving superficial thin sheets of finite conductance. These new methods are often used to tackle 3-D problems (cf. Vasseur and Weidelt, 1977; Dawson and Weaver, 1979b; Weaver, 1979, 1982; McKirdy and Weaver, 1983; McKirdy et al., 1985) in connection with regional studies and are very suitable for looking at various forms of the transition from land to ocean. Green and Weaver (1978) considered a model simulating a continental margin out at sea and McKirdy and Weaver (1984) generalized this method to include a stratified substratum. Dawson and Weaver (1979a) and Dawson et al. (1982), respectively, solved analytically the B-POL problems of two uniform thin half-sheets and of two generalized thin sheets over a uniform half-space, and Daw-

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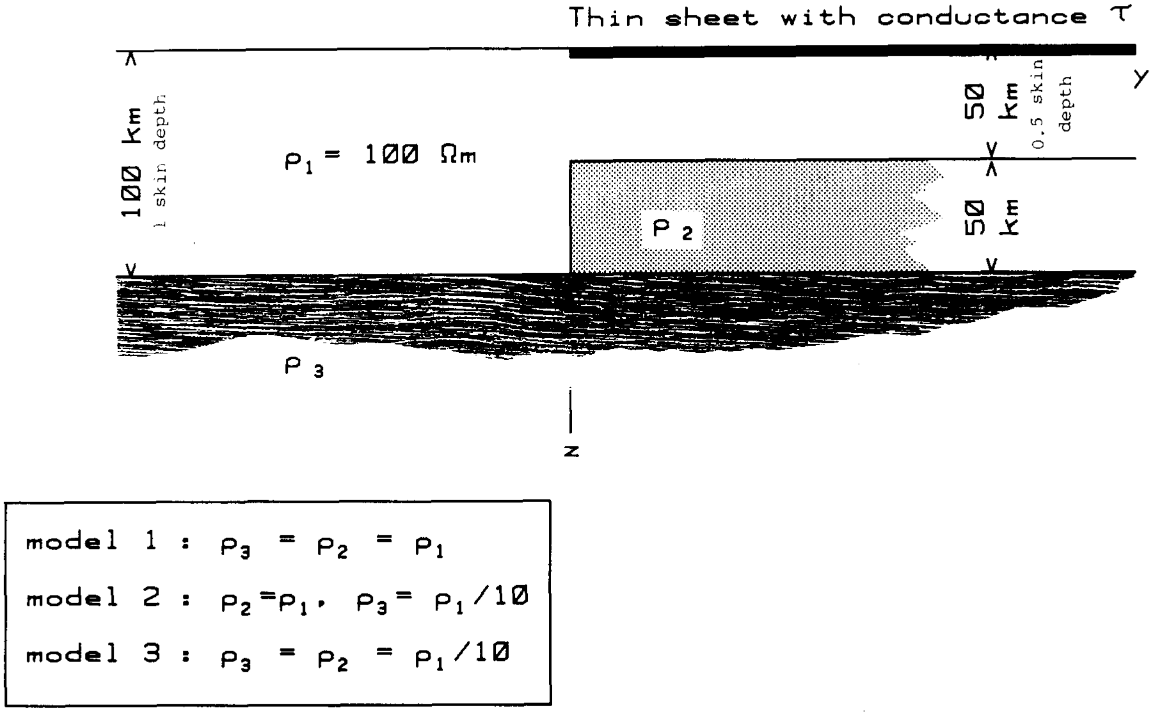

Fig. 1. Sketch of the models considered. The thin conducting sheet represents the ocean whose resistivity is taken to be 0.25 Ωm. The various oceanic depths assumed correspond respectively to a continental margin ($d = 250$ m, $\tau = 1000$ S) an intermediate ocean ($d = 1000$ m, $\tau = 4000$ S) and a deep ocean ($d = 4000$ m, $\tau = 16000$ S). With model 1 the perfect conductor ($\tau \to \infty$, $d \to 0$) is also considered for comparison. In addition a fourth model is studied, similar to models 2 and 3 with $\tau = 16000$ S, but involving a 100 km continental shelf where $\tau = 1000$ S and extending over the continent from its right-hand edge.

son (1983) obtained the analytic solution for the corresponding E-POL problem of two uniform half-sheets.

In the present paper we examine the coast-effect when oceans of different depths are simulated with uniform thin sheets of various conductances. For the substratum we choose either a homogeneous half-space (model 1) or assume an asthenosphere with a ten-fold increase in conductivity. In model 2 this asthenosphere is placed at a common depth of 100 km and in model 3 its depth is set at 100 km under the land and at 50 km under the ocean. These various models are sketched in Fig. 1. A fourth model is then considered, involving a continental shelf between the coast and the deep ocean.

What we have in mind for the present study is to investigate whether it might be possible with magnetotelluric and/or induction soundings to resolve changes in the structure of the lithosphere and the upper mantle at a passive continental margin. The thickness of the continental lithosphere has in general been taken to be in the range of 70–100 km and for the oceans figures as low as 20–30 km (cf. Maxwell, 1984) have often been proposed. In a recent study based on the response of the planet to the last deglaciation Peltier (1984) came forward with continental lithospheric thicknesses in excess of 200 km. If there is indeed an important reduction of this thickness at passive continental margins, and if this change is associated with a marked variation in electrical resistivity, it is worth verifying whether electromagnetic sounding methods could confirm it. Hitherto the ocean–coast effect has been studied primarily with a view to investigating the influence of highly conducting oceans on magnetotelluric or inductive responses. These effects are so large (cf. the reviews by Fischer, 1979 and Parkinson and Jones, 1979) that they are likely to mask the much less significant effect of a changing lithospheric thickness. In principle the oceanic lithosphere and upper mantle can be studied by sea-floor magnetotelluric soundings like those of Filloux (1980, 1982). However, such experiments are technically difficult and the shielding effect of the conducting ocean water reduces the available magnetic signal. Measurements on land would be far easier to carry out, but it remains to show whether they are likely to provide the information necessary to elucidate the structure of passive continental margins.

2. Method of computation

A series of analytical solutions (Dawson and Weaver, 1979a; Raval et al., 1981; Dawson, 1983) have provided exact results for the response of model 1 to a uniform field. However, since it has been established (Dawson and Weaver, 1979a; Dawson, 1983) that the numerical method of Green and Weaver (1978) in both the E- and B-polarization modes is extremely accurate, and since the numerical method is much faster on the computer than the evaluation of the closed form integrals in the analytic solution, it was decided to use this program to calculate the responses of model 1. Only for a perfectly conducting ocean were analytical results used since these have been tabulated by Raval et al. (1981). The calculations for model 2 were made with the aid of the computer program developed by McKirdy and Weaver (1984) which is based on an extension of the Green and Weaver theory to include a layered half-space beneath the thin sheet.

The only difficulty occurred with model 3 because, at present, the thin sheet programs cannot accommodate a substructure which includes lateral variations of conductivity. Thus these calculations were performed by using the full 2D finite-difference program of Brewitt-Taylor and Weaver (1976). The thin sheet representing the ocean was simulated by a layer of finite thickness with a given resistivity of 0.25 Ωm. Even though grid cells representing this ocean were extremely elongated in some parts of the model and the layer itself was only one cell in thickness in the case of the smallest conductance value used, no numerical problems arose in the finite-difference treatment of this extreme model. The finite difference method was also used in models 1 and 2 when computing the deep ocean response ($d = 4$ km), as this depth would violate the thin sheet approximation which presupposes that d is much less than the skin-depth.

3. The magnetotelluric response

In Figs. 2, 3 and 4 the respective responses of the three models are reproduced. Assuming a sea-

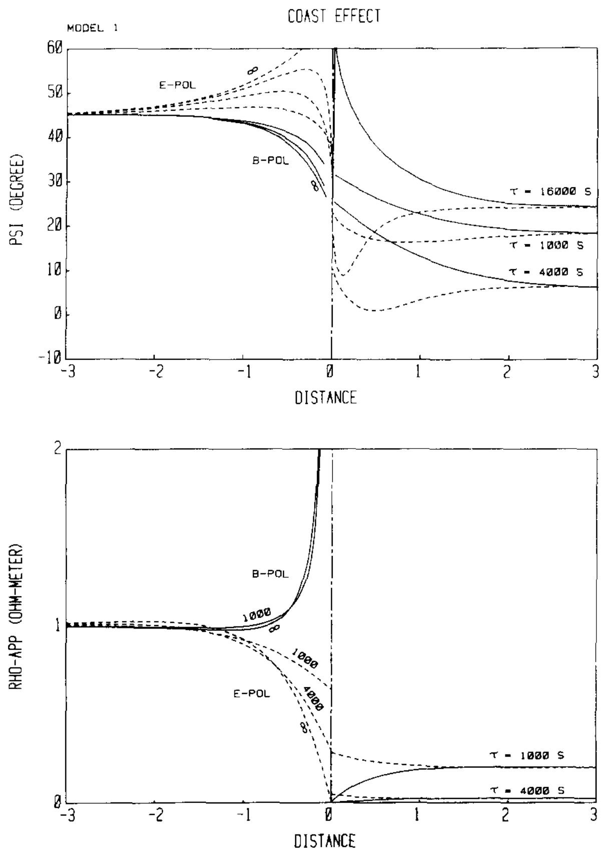

Fig. 2. MT response of model 1. To avoid crowding the graph the curves corresponding to $\tau = 16000$ S have not always been plotted. We recall that the horizontal distances are given in terms of the skin-depth in lithospheric material. One unit therefore amounts typically to 100 km for material of 100 Ωm resistivity at a period of $40\pi^2 \approx 400$ s. The same scale length applies to all the following figures.

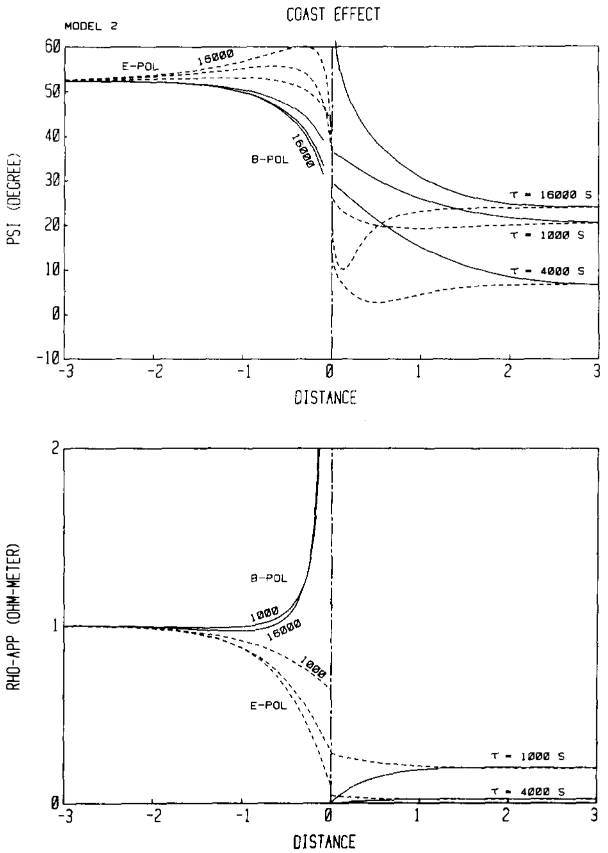

Fig. 3. MT response of model 2. To avoid crowding the graph some curves are left out.

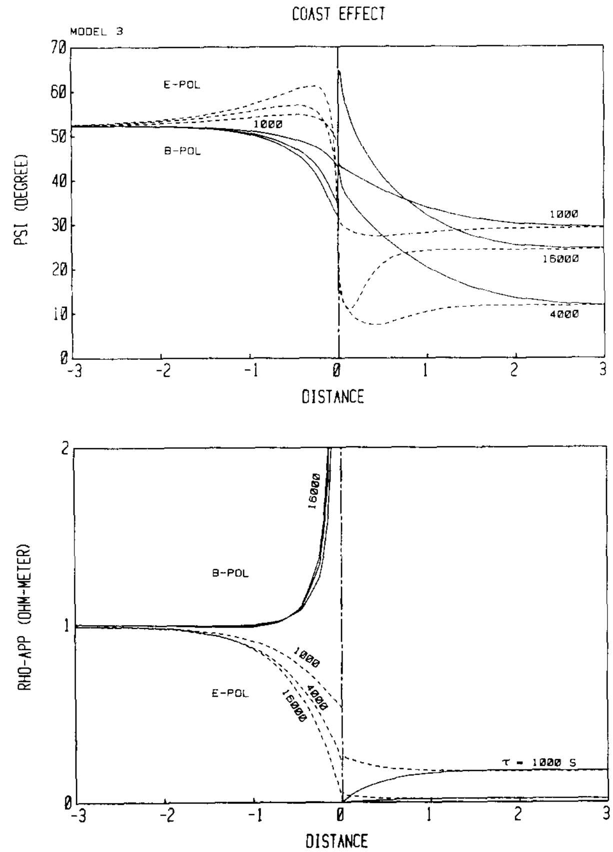

Fig. 4. MT response of model 3. To avoid crowding the graph part of the $\tau = 16000$ S curve is left out in the apparent resistivity plot.

water resistivity of 0.25 Ωm the assumed ocean conductances of $\tau = (1, 4, 16) \times 10^3$ S correspond to bathymetric depths of $d = (2.5, 10, 40) \times 10^2$ m, i.e., respectively, a very shallow sea (e.g., a typical continental margin), an intermediate and a deep ocean. In Fig. 2 (Model 1) we have also plotted for reference the response of a perfectly conducting ocean ($\tau = \infty$, $d = 0$). The distance scale is given in terms of the skin-depth δ_1 in lithospheric material, and at the chosen period of $T = 2\pi/\omega = 40\pi^2$ s yields a unit of 100 km for the assumed lithospheric resistivity of $\rho_1 = 100$ Ωm. The apparent resistivities in Figs. 2–4 have been normalized with respect to their value at infinity on the left, and the horizontal scale is in units of skin-depth $\delta_1 = \sqrt{(2\rho_1/\omega\mu_0)}$ so that the various graphs can, to some degree at least, be scaled to other periods and other resistivities. For, if the dimensions of the model measured in units of δ_1, the resistivity ratio $\rho_3/\rho_1 = 1/10$, and the conductance of the ocean measured in units of δ_1/ρ_1 are all held invariant then the curves plotted in Figs. 2–4 will remain unchanged for all models obtained by varying T and ρ_1. (Note that since the sea-water resistivity must have the same value 0.25 S m^{-1} in all models, holding the dimensionless conductance of the ocean constant causes the ocean depth to scale like $\sqrt{T/\rho_1}$.)

The most striking feature of the ocean–coast effect, as displayed in Fig. 2, is the large anisotropy of the apparent resistivity on land close to the shore, even for a very shallow ocean, and the abrupt change of the B-POL apparent resistivity ρ_B (or ρ_{yx}) at the coast. Just on the landward side of the coastal boundary ($y \to 0-$) the electric field has a singularity like $1/|y|^{1/2}$, whereas on the seaward side ($y \to 0+$) it remains finite (Dawson and Weaver, 1979a). It follows that since

$$\rho_B = \frac{\mu_0}{\omega}\left|\frac{E_y}{B_x}\right|^2 \tag{1}$$

the apparent resistivity exhibits a similar behaviour. These properties are easily understood. In B-POL the surface magnetic field is uniform whereas the current, which is distributed to depths of order δ_1 far inland, tends to accumulate at the coast to concentrate in the ocean. This results in a strong increase of the electric field on land near the shore. Crossing into the sea the large discontinuity of conductivity produces a great drop in the surface electric field. These features are further magnified in the apparent resistivity ρ_B as this parameter is proportional to the square of the electric field amplitude. As $\tau \to \infty$, ρ_B becomes smaller over the ocean, and vanishes altogether on a perfectly conducting ocean. The phase falls below 45°, as expected for a structure with a highly conducting overburden (cf. Fischer, 1985).

With E-POL the surface magnetic field is no longer uniform near the coast, but the behaviour of ρ_E (or ρ_{xy}) is still controlled largely by the electric field. Continuity of its tangential component means continuity of E_x, which must drop steadily to the low values typical of the ocean surface. Again this translates into stronger variations for ρ_E. However, the ocean edge is a point of jump discontinuity for B_y (Dawson, 1983) and since ρ_E is given by

$$\rho_E = \frac{\mu_0}{\omega}\left|\frac{E_x}{B_y}\right|^2 \tag{2}$$

it experiences a jump discontinuity at the coast as well. This is also true for the phase.

What is most striking in a comparison of Figs. 2–4 is their similarity. The dominant effect by far is the presence of the ocean; variations in the structure of lithosphere and upper mantle have only a minor influence on the response curves of apparent resistivity and phase. Magnetotelluric measurements on land near an ocean coast are therefore unlikely to shed much light on the nature of any structural change of the lithosphere and upper mantle which may occur at the transition associated with a passive continental margin.

4. The induction arrow

Whereas the magnetotelluric apparent resistivity and phase describe the relation between horizontal electric and magnetic fields the induction arrow depends only on the vertical and horizontal components of the magnetic field. Soundings of the three magnetic components are usually performed with arrays of synchronous stations and are called induction soundings. With B_x and B_y the horizontal and B_z the downward pointing vertical components we define the induction arrow in the horizontal plane

$$\boldsymbol{P}_r = (\mathrm{Re}A, \mathrm{Re}B) \quad \boldsymbol{P}_i = (\mathrm{Im}A, \mathrm{Im}B) \tag{3}$$

where A and B are given by

$$B_z = AB_x + BB_y \tag{4}$$

Here we note that we have assumed a time dependence of the form $\exp(+i\omega t)$ (cf. Lilley and Arora, 1982; Chen and Fung, 1985).

For the simple 2-D geometry that we have chosen in Fig. 1 the E-POL configuration involves only the magnetic components B_y and B_z; so

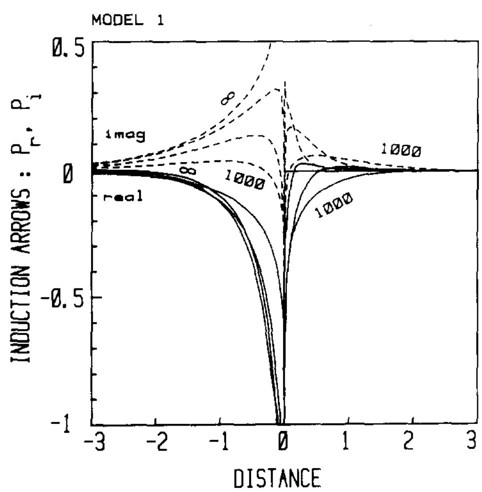

Fig. 5. The inductive response of model 1 represented in terms of the induction arrow.

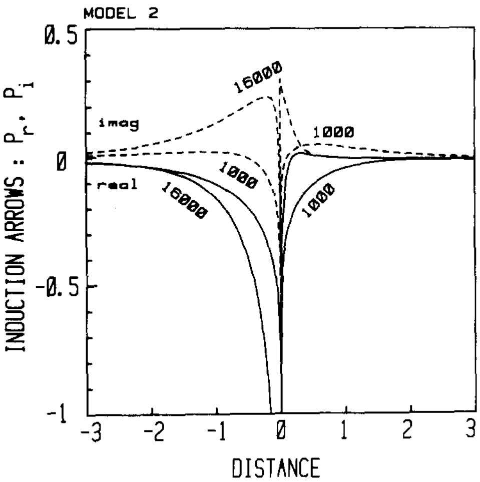

Fig. 6. The inductive response of model represented in terms of the induction arrow. For the sake of clarity the intermediate curve with $\tau = 4000$ S is left out.

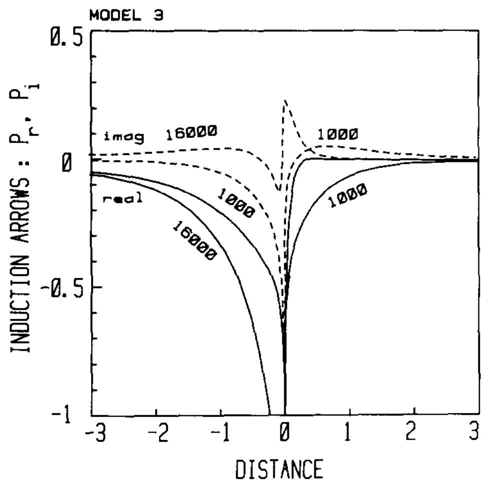

Fig. 7. The inductive response of model 3 represented in terms of the induction arrow. For the sake of clarity the intermediate curve with $\tau = 4000$ S is left out.

there is no factor A. In the B-POL configuration there is only a B_x component and thus no arrow at all. The induction vector is therefore directed along the y axis, i.e. it is perpendicular to our assumed straight coastline.

Figures 5, 6 and 7 display the behaviour of the real and imaginary parts of the induction arrow for our three models. While there are again obvious similarities among these three figures, there are also important differences. On land the real component always points away from the sea, but the range over which there is an important component is much larger in model 3 than in model 1. With the deep ocean ($\tau = 16000$ S) for example one has $-P_r > 0.5$ for $-y < 0.30$, 0.36 and 0.65 for models 1 to 3, respectively, and $-P_r > 0.2$ for $-y < 0.78$, 0.82 and 1.44. At sea the real component reverses direction at some distance from the coast, except for $\tau = \infty$ when there is no induction arrow over the perfect conductor. Since $B_z = 0$ on the surface of a perfect conductor, it is to be expected that the greater the conductance of the ocean, the smaller the length of the induction arrow. In other words we expect to find a longer induction arrow over a shallow sea than over a deep one.

The magnitude of the imaginary component of the induction vector is, in general, smaller on land, and larger at sea, than the magnitude of the corresponding real component. For a deep ocean it points toward the coast on land, except for a short range close to the coast where it reverses direction and becomes very large. This reversed range widens for shallower seas, but the component then weakens. A nearly antisymmetric behaviour occurs at sea: the imaginary vectors generally point away from shore, except in a narrow range close to the coast. For shallow seas this range is only slightly wider, but here it exhibits a stronger amplitude. Beyond the narrow range of reversed imaginary components the arrows at first are stronger for deep oceans, but far out to sea the arrows for shallow oceans again predominate. For a perfect conductor the width of the coastal ranges narrows to zero and the imaginary arrow completely vanishes over the ocean.

As with the real component the imaginary arrow undergoes an important change between model 2 (Fig. 6) and model 3 (Fig. 7), suggesting that induction soundings may indeed be suitable to resolve variations in the structure of the lithosphere and upper mantle at a passive continental margin.

5. The effects of a submerged continental margin

In the models discussed so far we have set the edge of the continent at the sea–coast. As is well known, however, these two edges do not coincide, especially at passive margins. In most instances the continental margin is situated several hundred kilometres on the seaward side of the coast. Only along the shores of Africa can long coastal sections be found where the continental shelf is less than about 100 km in width. But the coast effect of even a shallow ocean is so strong that a submerged continental shelf of only 100 km could well destroy any hope of observing a changing lithosphere at the true margin of the continent.

To test this hypothesis we have analysed a fourth model involving a 100 km shelf. Model 4 is therefore identical with models 2 and 3, except that now the thin conducting sheet is prolonged a distance of 100 km to the left. From its new left edge the sheet conductance is set at $\tau = 1000$ S for the first 100 km and then at $\tau = 16000$ S to the right-hand model boundary. In the actual 2-D model the ocean resistivity is maintained at $\rho = 0.25$ Ωm but the bathymetric depth is taken as 250 m over the shelf and 4000 m above the oceanic crust.

Magnetotelluric or induction measurements would be difficult to perform at the surface of the ocean. At the same time, however, these measurements will have to be carried out as close to the continental margin as possible if one hopes to derive any information about the oceanic lithosphere. We have, therefore, computed the model responses in the continental shelf area both at the ocean surface and at the ocean floor. Our computations show, as expected, that magnetotelluric soundings would be totally inadequate to reveal a changing lithospheric thickness, regardless of whether the measurements in the shelf area are carried out at the ocean bottom or at its surface. Unfortunately, as Fig. 8 shows, the same conclusion is also obtained for induction soundings when measurements are carried out at the ocean floor over the shelf area (the answer is also negative for sea-surface soundings over the shelf).

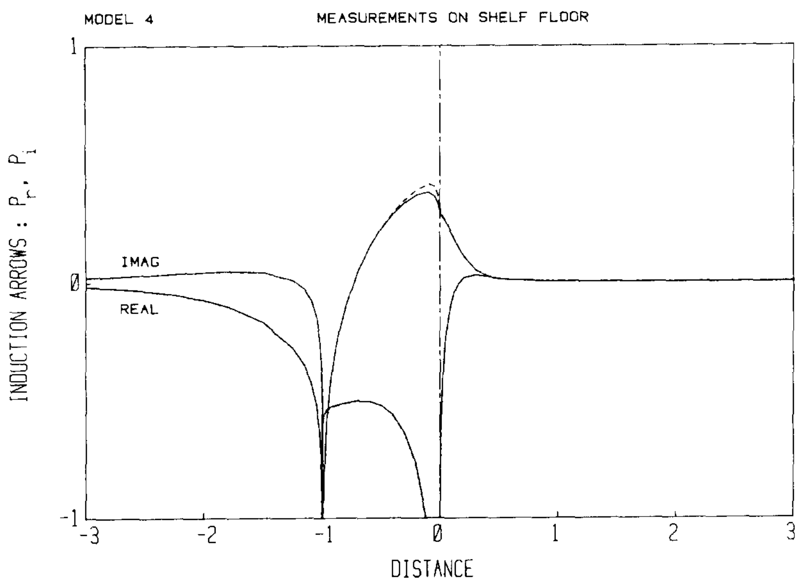

Fig. 8. The inductive response of model 4 represented in terms of the induction arrow. Over the continental shelf the arrow is computed at the ocean floor. The full line corresponds to an extension of model 3, i.e. with a changing lithospheric thickness. The dashed line arises from an extension of model 2. Note the minute difference between the two curves.

6. Conclusions

Continental lithosphere is usually taken to be thicker than oceanic lithosphere, although even today there are highly divergent opinions as to what constitutes the lithosphere and how thick it really is (Maxwell, 1984; Peltier, 1984). If the changing lithospheric thickness at a passive continental margin is associated with a marked variation of the depth profile of the electrical resistivity, electromagnetic sounding methods may be deemed capable of revealing this margin structure. However, the simultaneous occurrence of the strong ocean–coast effect masks the lithospheric effect. This is especially true for the magnetotelluric response which is therefore ill-suited to reveal the changing lithospheric thickness through measurements on land. The inductive response, on the other hand, is well known for its sensitivity to lateral changes within conductive structures and we have shown that in the absence of a continental shelf under the ocean surface it could constitute a suitable method to reveal a changing lithospheric thickness. However, a narrow submerged shelf of only 100 km width under 250 m of sea-water produces such a strong coast effect ahead of the continental margin, that it also renders inductive methods unsuited to reveal a changing lithospheric thickness, even when these measurements are carried out at sea on the shelf floor right up to the edge of the continent.

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