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COPROD2 Revisited: Can the B-Polarization Phase Distinguish between Single- and Multi-Body Anomalies?

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The small local minimum in the long-period B-polarization phase responses above the NACP anomaly in the COPROD2 data is re-examined with a view to understanding its role in determining whether the anomaly is a multi-body or continuous conductive structure. It is found by trial-and-error numerical modelling and by further optimization of a model with continuous structure that the B-polarization phase response is not profoundly affected by the NACP anomaly itself, but is extremely sensitive to the resistivity distribution in the sedimentary layer to the extent that quite minor resistivity variations can turn a local minimum into a local maximum and *vice versa*, without necessarily affecting the short period responses in an unreasonable manner. A further modelling exercise with a multi-body anomaly shows that its response does not necessarily give rise to a local minimum in the phase response, as sometimes claimed. The investigation presented here is not intended to establish whether the NACP anomaly is a continuous or broken conductive structure but it does suggest that the evidence that has been cited in favour of a multi-body anomaly may not be sufficient by itself to settle the question with certainty.

1. Introduction

In his discussion of the COPROD2 dataset, Jones (1993) has stressed the importance of a "very small but critical" minimum in the B-polarization phase responses for periods 56.9 s and 85.3 s in the region stretching from coordinate −50 km to the origin. He claims this is the key to deciding whether the NACP anomaly is a horizontally continuous structure or whether it comprises a number of electrically isolated conductive bodies. His conclusion is based on the fact that it is the B-polarization phases that are sensitive to lateral changes in conductivity and that the minimum in the phase curves indicates a resistive feature. By comparing the phase responses (Jones, 1993, Fig. 9) of Agarwal and Weaver (1993) (whose model he labels *agarwal*) with those of Wu *et al.* (1993) and Uchida (1993) (labelled respectively as *wu* and *uchida*) he concludes that the evidence for a multi-body is compelling because the first authors' responses show a small maximum in the critical region whereas the other two exhibit the required minimum, albeit laterally displaced in the case of *wu*.

That is certainly one possible interpretation, but we suggest there is another which, to us at least, is equally plausible. It should be noted first that the five-column model of Agarwal and Weaver (1993, Fig. 9) also represented a split body with a narrow, highly resistive region between the two blocks, but that this model was rejected as not yielding a significantly improved fit over that provided by the simpler, and continuous, four-column model. In fact, it has been found that the overall fit of the B-polarization phase response is remarkably insensitive to changes in the substructure. This is hardly surprising, because for typical conductivity values pertaining to the host region, the penetration depth barely reaches the top of the NACP anomaly even at the relatively

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long periods of 56.9 s and 85.3 s on which Dr. Jones focused his attention. The reason for this behaviour is the presence of a conductive sedimentary cover, which is common to all the models found in the COPROD2 exercise; it exerts a strong influence on the B-polarization response, and effectively shields it from the influence of the underlying structure. Indeed, Jones (1993, p. 934) acknowledged that "...the B-polarization responses appear to be virtually insensitive to the presence of either the NACP or the TOBE anomalies".

Given that the sediments play such a dominant role and that the NACP anomaly appears to exert such little influence on the B-polarization response, it is pertinent to ask what happens if small adjustments are made to the resistivity values in the surface layer itself, and whether a multi-body anomaly necessarily causes a minimum in the B-polarization phase as observed. In this paper we attempt to answer these questions with the aid of some two-dimensional modelling and optimization.

2. Resistivity Variations in the Surface Layer

2.1 *Trial and error modelling*

In the *agarwal* model of the NACP anomaly (which is the same as the model shown in Fig. 6(a) without the layering in the sedimentary cover present), the surface layer was divided into four segments with successive resistivities of 3.4, 3.1, 3.4 and 3.6 Ωm from west to east (left to right). If the second value is adjusted to, say, 3.7 Ωm, the B-polarization phase responses at 59.6 s and 85.3 s become those shown in Fig. 1 where they are compared with the corresponding responses for the original *agarwal* model, which have also been reproduced with error bars by Jones (1993) in his Fig. 9. It is apparent from his figure that the data errors in the phase were larger at sites at the western extreme of the profile. For example, at the site located at −93 km, the errors are ±0.5° and ±1° for the periods 56.9 s and 85.3 s respectively, while the corresponding errors in the region of the minimum (site −35 km) are only ±0.2° and ±0.3° respectively. The effect in the critical region is very noticeable; in fact the maximum in the original phase response clearly becomes a small minimum more in line with the real data. As expected, the misfit value, defined as in Agarwal and Weaver (1993, Eq. (1)), increases slightly from 1.23×10^{-3} to 4.06×10^{-3} as a result of a small deterioration in the fit of the other responses—the B-polarization apparent resistivity and the E-polarization apparent resistivity and phase. The resulting behaviour of the B-polarization phase response is reminiscent of that described by Fischer *et al.* (1992)—"At a vertically outcropping resistivity contrast the B-polarization phase undergoes a positive excursion on the more conducting side of the interface and a negative excursion on the more resistive side."

The location of the minimum can be changed by adjusting the positioning of the segments in the surface layer, and its prominence reduced or enhanced by respectively decreasing or increasing the resistivity contrast. Thus if the edges of the second segment of resistivity 3.7 Ωm are placed at −44 km and 22 km, while the resistivity of the third segment is modified to 3.5 Ωm, then the B-polarization phase responses at 56.9 s and 85.3 s become those shown in Fig. 2 where again they are compared with the corresponding responses for the original model. Here the slight reduction in resistivity contrast between the second and third segments and the elongation of the second has both dampened and spread out the minimum over a wider range above the NACP anomaly. The misfit value for this model was 3.55×10^{-3}—somewhat better than for the the first modified model.

Jones (1992, private communication) doubted the validity of the arguments that led to the responses shown in Fig. 1, on the grounds that the observed minimum is a long period effect whereas a minimum produced by tinkering with the resistivity of the sedimentary layer would be present at all periods. Indeed, in his subsequent article introducing the COPROD2 papers, he wrote: " The phase minimum ... is a long period phenomenon, which is unequivocal evidence that it is a *basement*-related feature, and nothing to do with variation in the sedimentary sequences"

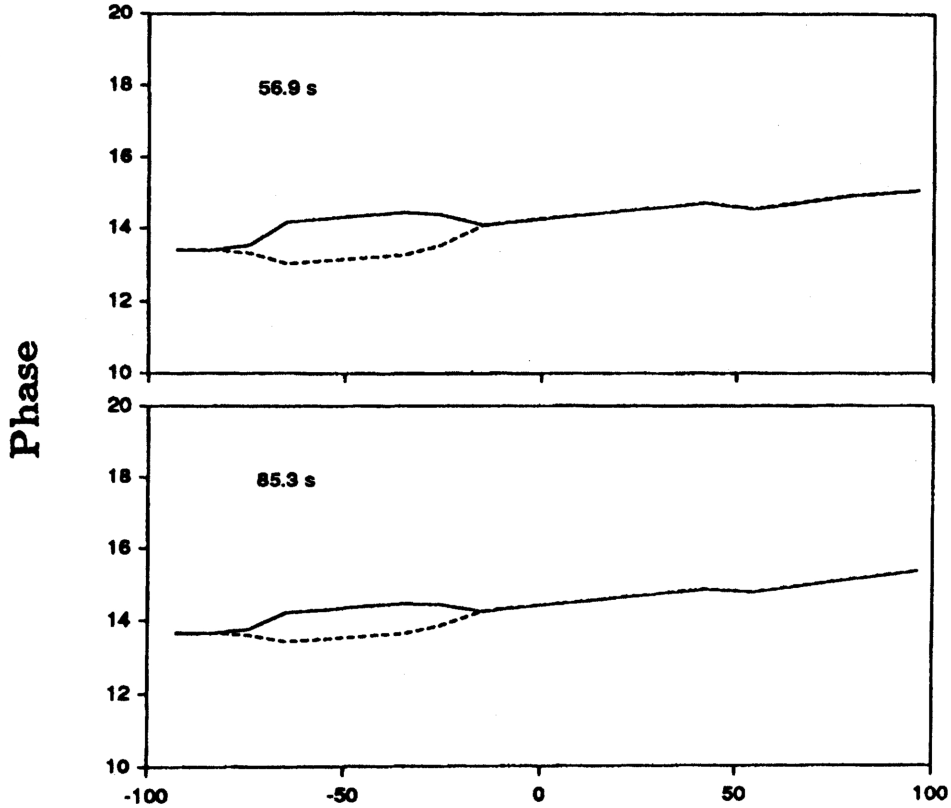

Fig. 1. The B-polarization phase responses at periods 59.6 s and 85.3 s for the four-column model *agarwal* (solid line) and the same model with the resistivity of the second segment in the surface layer changed to 3.7 Ωm (broken line). The horizontal distance scale is in km; phases are in degrees.

(Jones, 1993, p. 948). The period dependence of the phase responses can be better gleaned from pseudosections—contours of constant B-polarization phase plotted on diagrams in which the horizontal axis measures the site position in km and the vertical axis represents the period increasing downwards on a logarithmic scale, as depicted in Fig. 3 where contour plots for the *agarwal* model are presented. (An alternative presentation is to plot the phase variation with period for each site on separate diagrams, as in Fig. 3 of the paper by Agarwal and Weaver (1993).) In Figs. 4 and 5 similar contour plots are shown for the two modified models described above. They may be compared with the corresponding plots for the real data published by Jones (1993, Fig. 8) who drew particular attention to "the minimum with phases less than 14° in the period range 40 to 125 s above the NACP anomaly".

Two characteristics of the contour plots in Fig. 3 are worth commenting on. First, and perhaps surprisingly, there clearly exists at periods around 65 s, a minimum of less than 14° over the NACP anomaly, even for the unmodified *agarwal* model. The maximum which is apparent in Fig. 1 and on which Jones (1993) based his arguments, is the result of the contour lines 20 and less closing together (i.e. deflecting downwards for periods shorter than 65 s and upwards for longer periods) slightly to the west of the minimum, a feature which seems to be as much associated with the one-dimensional structure at the extreme western edge of the two-dimensional model as with the NACP anomaly itself. This minimum is, in fact, visible in the response curves of Fig. 1 at a position of about −15 km, and would have been the only discernable feature in this region

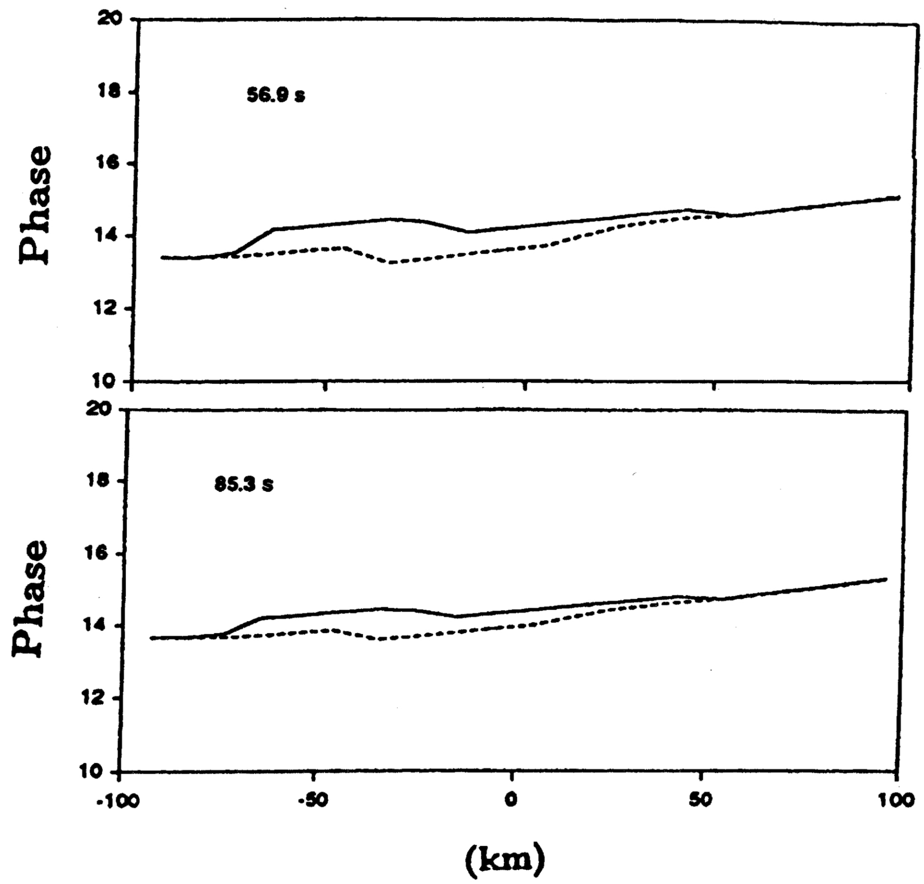

Fig. 2. As in Fig. 1, except that the broken line now represents the response for the other modified model in which the second surface segment still has a resistivity of 3.7 Ωm but now stretches from −44 km to 22 km, and the resistivity of the third segment is 3.5 Ωm.

had the responses fitted the data better at the western edge of the profile (where, as we have seen, the relatively large errors in phase allow for greater flexibility in the fit). An examination of the response curves plotted by Jones (1993, Fig. 9) shows that this minimum also appears in the real data as a secondary feature displaced slightly to the east of the main minimum. It is tracked by the responses of *agarwal*, but not by those of *uchida* or *wu* with which they are compared. Second, the short period contours are depressed in the critical region indicating a local maximum in phase in excess of 30° at periods around 10 s, and roughly in agreement with the behaviour of the short period contour plots for the real data.

Turning to the plots in Fig. 4 for the first modified model, we note that the contours surrounding the long period minimum of less than 14° are opened up to give the observed primary minimum above the NACP anomaly. As predicted by Jones, however, this minimum is also present at short periods where, it will be noted, the contours now deflect upwards rather than downwards as in Fig. 3, thereby suggesting a minimum in the critical region of about 29° at the 10 s period. The prominence of this short period minimum is partially suppressed in Fig. 5 while the pronounced long period minimum of less than 14° is retained. Nevertheless, the short period contours are still deflected slightly upwards in contrast to the trend observed in the real data as displayed in Fig. 8 of the Jones (1993) paper.

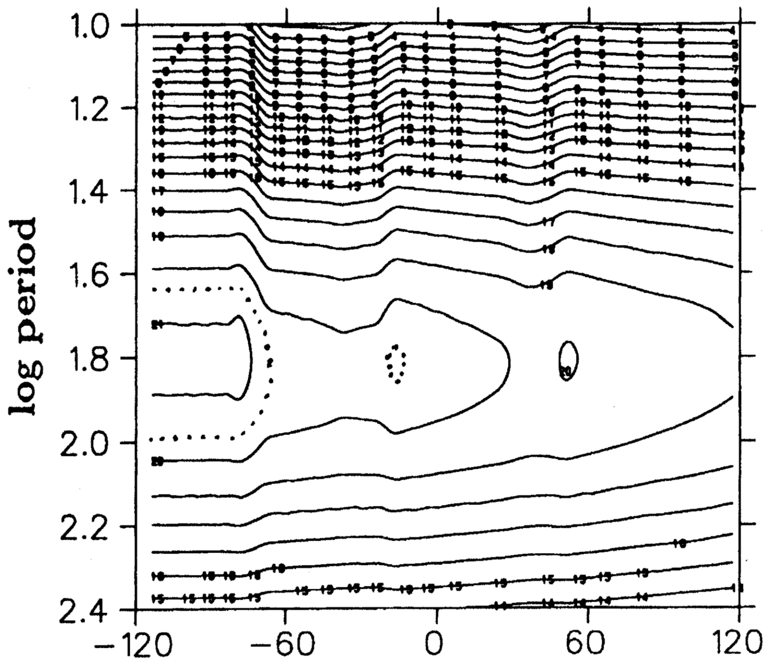

Fig. 3. Contour plots of the B-polarization phase response for the *agarwal* model. The horizontal axis represents the range in km, and the vertical axis is the logarithm of the period increasing downwards. The contours are plotted at 1° intervals and are labelled 1 to 21 representing phases, in descending order, from 33.5° to 13.5°. The 14° contour is indicated by the dotted line.

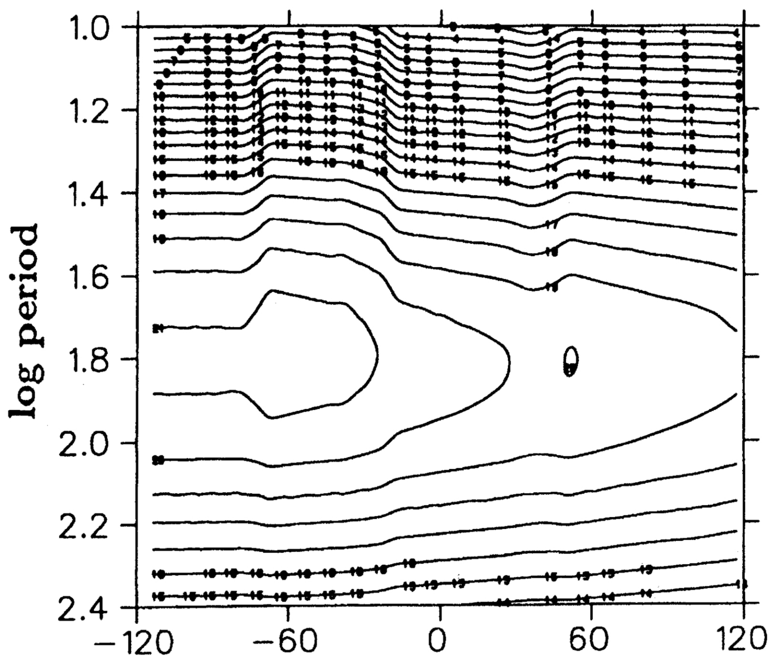

Fig. 4. Contour plots as defined in Fig. 3 for the first modified model in which the resistivity of the second segment in the sedimentary layer is 3.7 Ωm.

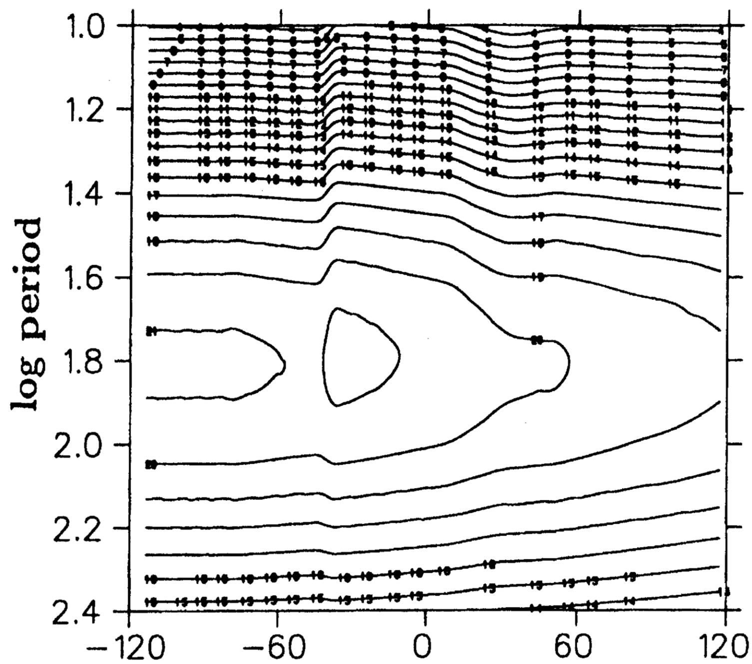

Fig. 5. Corresponding contour plots for the second modified model in which the width of the second segment is extended from −44 km to 22 km while the third segment is given a new resistivity of 3.5 Ωm.

2.2 Further minimization of the misfit

The lesson learnt from the preceding numerical experiments is that the B-polarization phase response is *extremely* sensitive to even minute adjustments of the resistivity distribution in the thin surface layer. So far, only lateral variations in the resistivity of the surface layer have been considered. In order to accommodate vertical variations as well, a new starting model was constructed from the model *agarwal* by dividing each surface segment in half horizontally while leaving their resistivities unaltered, as shown in Fig. 6(a). There are now 8 more adjustable parameters than before—4 new resistivity values and the 4 horizontal boundaries—thereby introducing some new freedom to minimize the misfit further with the same optimization routine which originally yielded the final model. The advantage of taking this approach instead of the trial and error modelling described earlier is that the overall misfit of all the responses can only improve, not deteriorate as previously. Note, however, that the method requires the vertical segment boundaries to be tied to the main columns in the model. Thus horizontal extensions or contractions of the surface segments are largely controlled by adjustments of the vertical boundaries of the NACP anomaly itself. The optimized model found after minimization of the misfit at the same 20 sites and 7 periods used in the COPROD2 exercise (Agarwal and Weaver, 1993) is shown in Fig. 6(b). The new misfit value has decreased slightly from 1.23×10^{-3} to 1.15×10^{-3}.

The obvious features of the new model are (i) that there is no significant change in the deeper structure representing the main NACP anomaly, (ii) that the resistivity contrast between the first two segments in the lower layer of the sediments has been reversed, increasing in resistivity from west to east rather than the other way round as in the upper layer, and (iii) that the two segments in each layer on the eastern side have all merged into one single segment (i.e. they all have equal resistivities).

The B-polarization phase responses at the periods 56.9 s and 85.3 s of the starting (i.e.

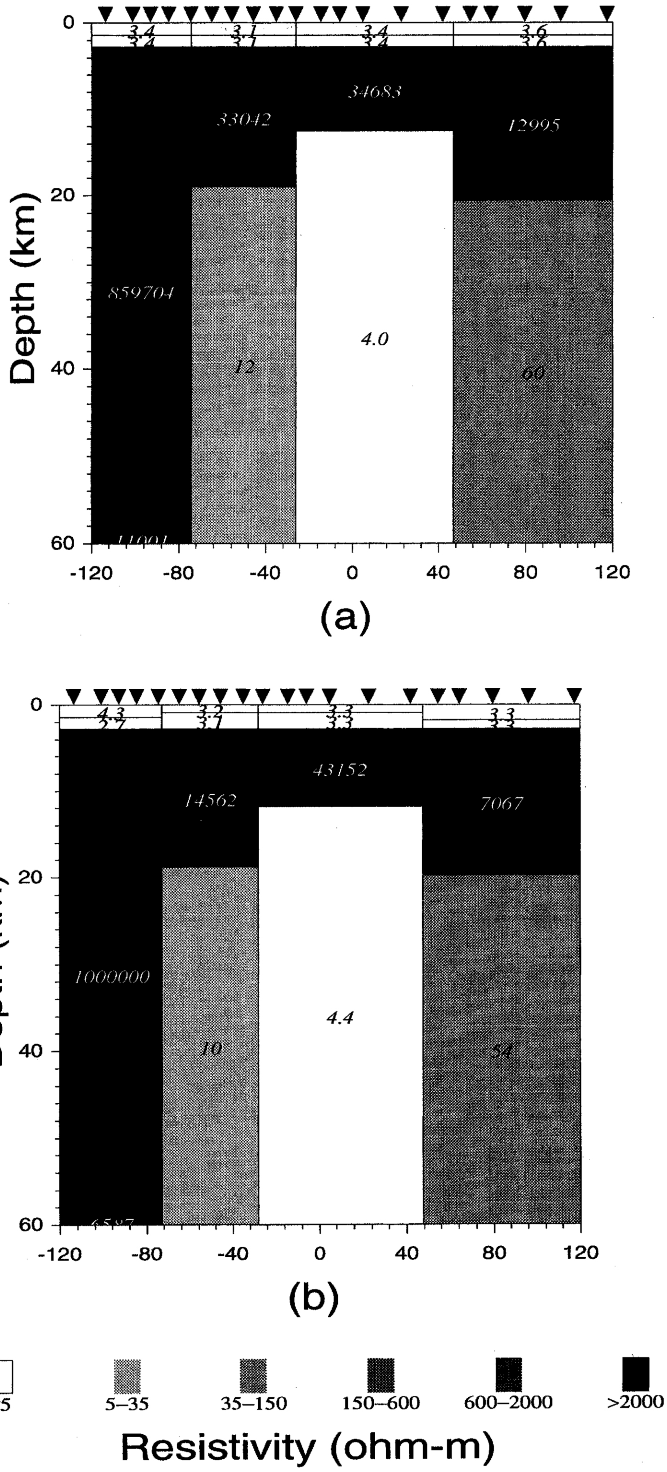

Fig. 6. (a) Model *agarwal* of the NACP anomaly with each segment in the surface layer divided in half in order to form a new starting model. (b) The final model obtained from (a) by further minimization of the misfit of the apparent resistivity and phase responses for both E- and B-polarized fields.

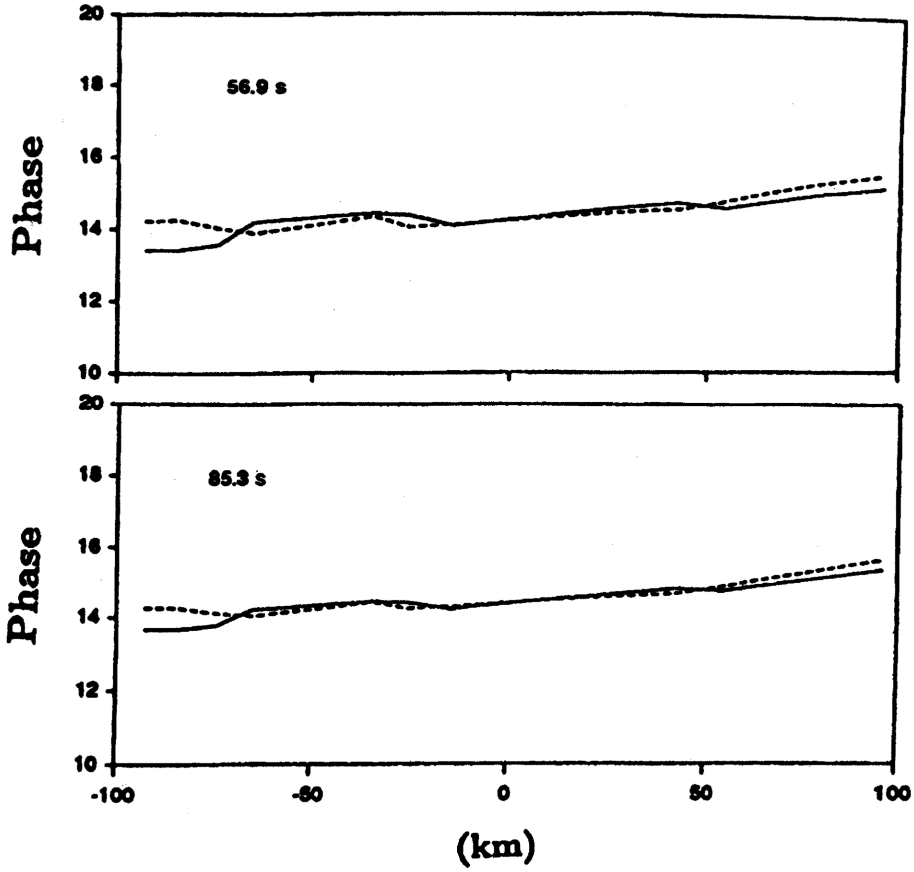

Fig. 7. As in Fig. 1, except that the broken line now depicts the B-polarization phase responses for the final model in Fig. 6(b).

agarwal) and final models are compared in Fig. 7 (cf. Fig. 1), and in Fig. 8 the phase contours for the final model are plotted (those for the starting model have already been given in Fig. 3). The responses in Fig. 7 now reveal both the primary and secondary minima discussed earlier. The primary minimum is small and will not fit the data points at sites −35 km and −45.8 km as well as the *uchida* response, but it is a much closer fit and follows a better trend than the *wu* response which, according to Jones (1993, p. 949), does "...display the correct curve *shape* with a local minimum". The perception of the primary minimum in Fig. 7 has been considerably enhanced by the changes in (and the better fitting of) the one-dimensional response on the left-hand side of the model as a result of the resistivity adjustments in the sedimentary layer in that region. Likewise, the long period minimum of less than 14° is seen in the contour diagram of Fig. 8 while the short period phase contours are now somewhat flatter.

We wish to stress that we do not regard any of the model variants proposed in this section as 'better' than the original model submitted to the COPROD2 exercise, or, for that matter, as superior to the various multi-body models that have been proposed. The slight improvement in the response-misfit for the final model in Fig. 6(b) is simply not significant enough to worry about; indeed, to do so would defeat the whole purpose of our 'least-blocked' scheme which seeks the *simplest* model composed of the smallest number of blocks of different conductivity that is

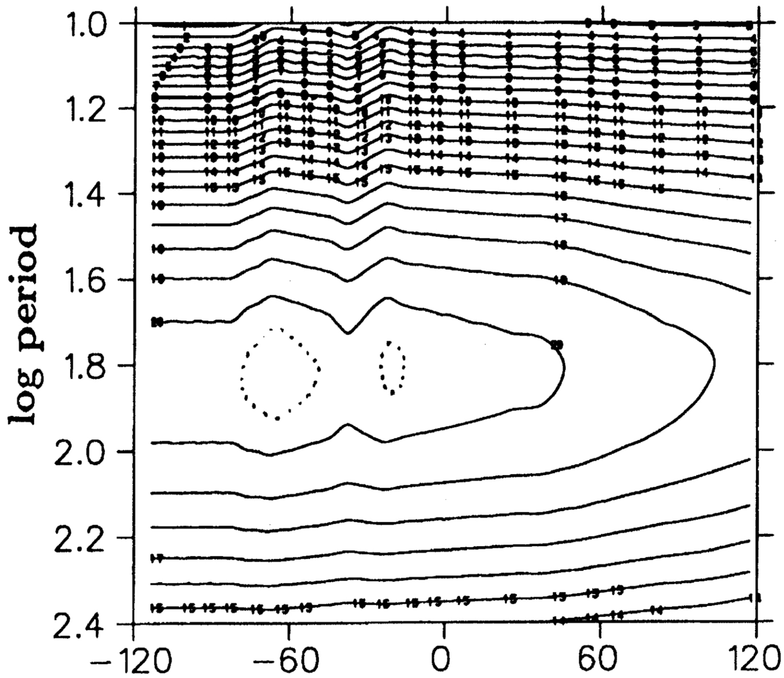

Fig. 8. Contour plots, as described in Fig. 3, of the B-polarization phase response for the final model in Fig. 6(b). The dotted line shows the 14° contour.

consistent (at some prescribed level) with the data. What we have attempted to show with these numerical experiments is that the long period phase minimum is present to some extent in all the models proposed, and that the B-polarization phase response is so sensitive to minor variations in the resistivity of the sediments (and, by extension, to that part of the upper crust which lies within the penetration depth) that it may not be possible to draw conclusions about the nature of the deep NACP anomaly from small features displayed in the behaviour of the B-polarization phase. Even the two-body model *uchida*, whose B-polarization phase response fits the real data so well, includes significant resistivity variations in the sedimentary layer and upper crust, while Takasugi *et al.* (1993), using logging data as a control, found the resistivity of the sedimentary layer to have quite a complex pattern with strong lateral changes in the critical region over the anomaly. As our numerical calculations have shown, the phase response curves for both of these models are most assuredly influenced by the resistivity of the sediments and upper crust.

3. A Multi-Body Synthetic Model

The B-polarization phase response of the *uchida* model confirms that a multi-body anomaly can give the observed local minimum at long periods but the question we now ask is whether this is true in general, i.e. whether the appearance of the minimum necessarily indicates multiple bodies at depth. To investigate this point further, we have undertaken some additional response calculations for the synthetic model illustrated in Fig. 9 which is based on a structure of the NACP anomaly proposed by Jones and Craven (1990) and labelled the *jones-2* model by Jones (1993). It consists of four separate conductive bodies, well-isolated from each other by the resistive (200 Ωm) crust, and overlain at the surface by a uniform sedimentary layer of thickness 2 km and resistivity 2.5 Ωm.

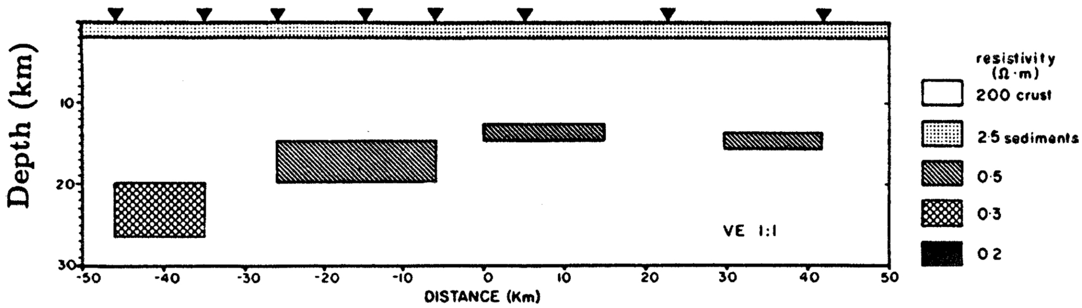

Fig. 9. A multi-body synthetic model based on the *jones-2* model of the NACP anomaly. The crustal resistivity is 200 Ωm.

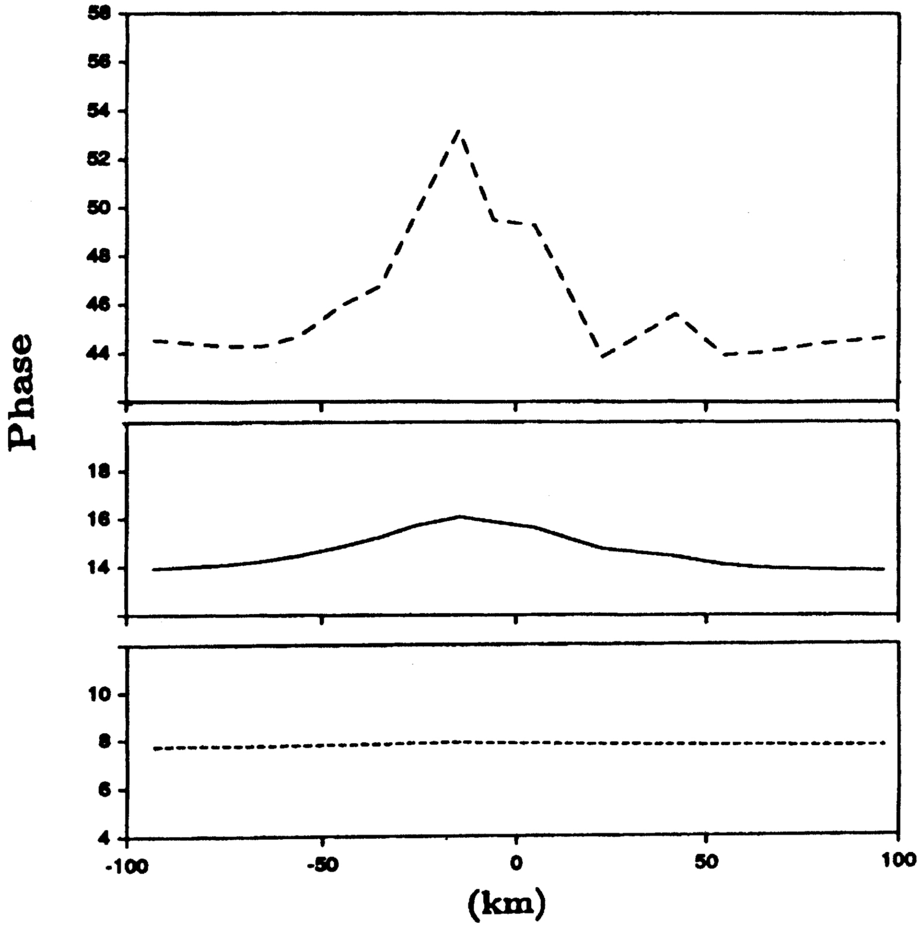

Fig. 10. *B*-polarization phase response curves at the period 56.9 s for the model shown in Fig. 9 (solid line), for the same model with the surface layer removed (broken line), and for the model in Fig. 9 with a crustal resistivity of 2000 Ωm (dotted line).

The B-polarization phase response at the period 56.9 s is plotted in Fig. 10 (the response for the other period, 85.3 s, considered earlier displays a very similar behaviour and conveys no new useful information for our purposes here). The solid line depicts the response of the model portrayed in Fig. 9; it clearly displays a maximum over the anomaly, not a minimum. Two other variants of the model have been considered as well. In the first, the sedimentary layer at the surface was completely removed; its response is plotted as a broken line in Fig. 9. In this case, the resistive gaps between the conducting bodies do become revealed by local minima in the phase response, just as the arguments put forward by Jones (1993) would have predicted. The significance of the shielding effect of the conducting sediments has been demonstrated, however, because there is no evidence of these minima in the solid line curve. Finally, the response of a model in which the resistivity of the host crust is 2000 Ωm, rather than 200 Ωm, is indicated by the dotted line in the same figure. The higher crustal resistivity, which is more akin to the value in the *agarwal* model, strongly inhibits the leakage of current between the deep conducting bodies and the surface layer so that the NACP anomaly is effectively decoupled from the sediments. The resulting effect is that the response curve is completely flattened and it becomes virtually impossible to identify the nature of the deep structure from the B-polarization phases alone—further evidence of the very important role played by the sedimentary layer in determining the nature of the B-polarization phase response.

4. Conclusions

The purpose of this paper has not been to determine whether the NACP anomaly is composed of a single body or multiple bodies, but rather to suggest that the evidence for a multi-body anomaly based solely on the fine structure of the B-polarization phase response may not be as convincing as claimed. Numerical experiments have been conducted to show that resistivity variations in the sedimentary layer which covers the region have an enormous impact on the B-polarization phase response while the NACP anomaly itself exerts very little influence even at the longer periods in question. The critical local minimum in phase on which the arguments in favour of a multi-body seem to depend could be created, modified and repositioned in a model response by suitable adjustments to the resistivity of the surface layer almost independently of the form taken by the deep anomaly. Although the short period responses are affected by such manipulations too, they could be controlled to some extent by allowing vertical as well as lateral structure within the sedimentary layer. It was noted that logging data used by one participant in COPROD2 confirmed the presence of significant structure in the sediments, and that the *uchida* model, which gave a response that fitted the observed local minimum best, also had resistivity variations in the sedimentary layer and upper crust in addition to the split conducting body beneath.

Finally it has been shown that a multi-body anomaly in a resistive host can actually give rise to a local maximum in the B-polarization phase response provided that a conductive surface layer representing the sediments is present. Without this conductive cover, local minima which identify the resistive breaks in the anomaly do appear, but such conditions are unrealistic for the terrain covered by the COPROD2 profile.

We conclude that, despite the persuasive arguments that have been advanced in favour of a multiple body, the precise geometrical form of the NACP anomaly may still be open to question. In his closing remarks Uchida (1993), who found a two-body model for the NACP anomaly, wrote: "Because ... the TM data hardly detect the anomaly, the split conductors are not necessarily required to explain the data." We agree with that statement.

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REFERENCES

Agarwal, A. K. and J. T. Weaver, Inversion of the COPROD2 data by a method of modelling, *J. Geomag. Geoelectr.*, **45**, 969–989, 1993.

Fischer, G., L. Szarka, A. Adam, and J. T. Weaver, The magnetotelluric phase over 2-D structures, *Geophys. J. Int.*, **108**, 778–786, 1992.

Jones, A. G., The COPROD2 dataset: tectonic setting, recorded MT data, and comparison of models, *J. Geomag. Geoelectr.*, **45**, 933–955, 1993.

Jones, A. G. and J. A. Craven, The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow data in Saskatchewan, Canada, *Phys. Earth Planet. Inter.*, **63**, 169–194, 1990.

Takasugi, S., T. Sato, and Y. Honkura, Two-dimensional forward modelling for the COPROD2 MT data, *J. Geomag. Geoelectr.*, **45**, 957–962, 1993.

Uchida, T., 2-D inversion of the COPROD2 magnetotelluric data by use of ABIC minimization method, *J. Geomag. Geoelectr.*, **45**, 1063–1071, 1993.

Wu, N., J. A. Booker, and J. T. Smith, Rapid two-dimensional inversion of COPROD2 data, *J. Geomag. Geoelectr.*, **45**, 1073–1087, 1993.