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Localized Source Effects on Magnetotelluric Apparent Resistivities

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Abstract. There is a reawakening of interest in 'source effects' in magnetotellurics, because of the very precise data now being acquired in regions where such effects might be anticipated.

Dipoles at ionospheric heights were taken to be worst-case localized sources. Theoretical apparent resistivities were calculated for horizontal and vertical electric and magnetic dipoles. The earth model was a simple conductive sedimentary basin, where minimal source effects might be anticipated. These results were compared with the usual plane wave apparent resistivities, and with the Price-Wait source models. We found that, with this model, the short period magnetic dipole results were indistinguishable from those due to a planar field, but significant differences occurred at periods greater than 50 s. Horizontal electric dipole sources in particular gave apparent resistivities which differ completely from those due to magnetic dipoles. A more general range of sources and models was also studied.

Key words: Magnetotellurics – Source effects – Three-dimensional modelling.

Historical

For 10 years, from 1955–1965, a great debate was carried on, in and out of the literature, regarding source effects in *MT*. Was Cagniard's assumption, that the source was a plane wave, true or false? Price in 1962 showed that one critical factor was the lateral uniformity of the source field. If it is not uniform, as was assumed by Cagniard, then impedances and apparent resistivities increasingly depart from the plane wave prediction as the period increases. These departures were called 'source effects'.

The geomagnetics discipline viewed the sources of magnetic pulsations in terms of large horizontal loop current sheets, like that responsible for Sq, together with other discrete current systems. These have horizontal scales of 10^4 km or so. They flow at an elevation of 100 km, and Price showed that their

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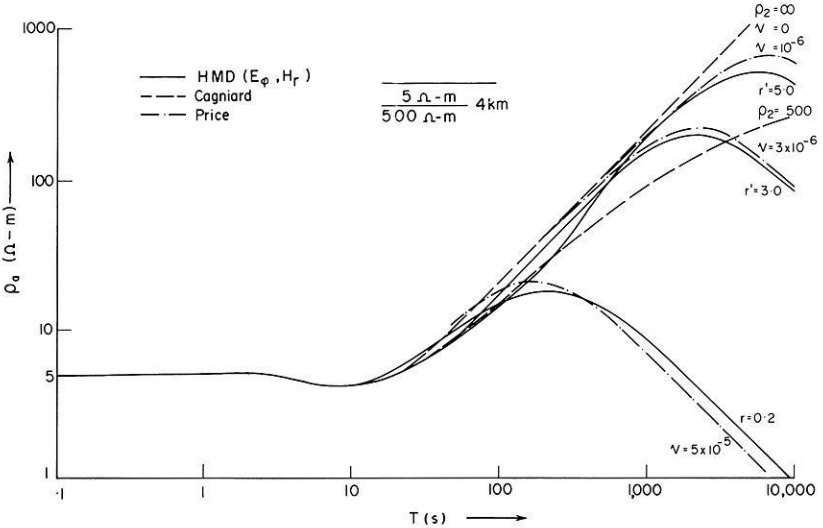

Fig. 1. Summary of results over two-layer models using Cagniard plane wave ($\rho_2 = \infty$ and 500), Price's variable horizontal wavenumber ν when $\rho_2 = \infty$, and Quon's computations for HMD at various r when $\rho_2 = 500$. Radial magnetic (H_r) and tangential electric (E_ϕ) components were used to compute dipole ρ_a. The upper layer represents sediments overlying a fixed resistivity basement, r' is r/dipole height, ν is in units of m^{-1}, and ρ is in $\Omega\cdot\mathrm{m}$

source effects should be considerable for one particular earth model at least. This, plus the fact that *MT* apparent resistivities obtained at long periods differed from those predicted by purely magnetic observations, cast considerable doubt on Cagniard's approach.

To review this question further, Quon, in 1963, assumed a simplified model of the Alberta sedimentary basin (Fig. 1) and computed the apparent resistivities due to electric and magnetic dipole sources in the ionosphere, at 100 km elevation. These were then compared with the plane wave prediction, and with Price's prediction for a range of horizontal wavelengths. Quon used dipoles at that height since they represented extreme cases of source concentration and hence worst possible concentration of short spatial wavelengths. At periods up to about 100 s, Quon found that with one exception, (which now appears to have been an error) it made little difference whether the source was a plane wave or a dipole. At longer periods the magnetic dipole curves decreased in much the same way as Price's. Also, at any given horizontal distance r from the dipole, ρ_a was nearly the same as if the source field had horizontal wavelength $= r$. That is, horizontal offset and horizontal wavelength play nearly identical roles, as had been anticipated (Fig. 1). Note that r' in all figures is the ratio of radial distance to dipole elevation, ν has the units of $(\mathrm{meters})^{-1}$ and resistivities are given in ohm · m.

When the source was a vertical electric dipole (VED) (Fig. 2), apparent resistivities increased monotonically with increasing period, rather than approaching ρ_2 (as Cagniard predicted) or decreasing (as for the Price and HMD models).

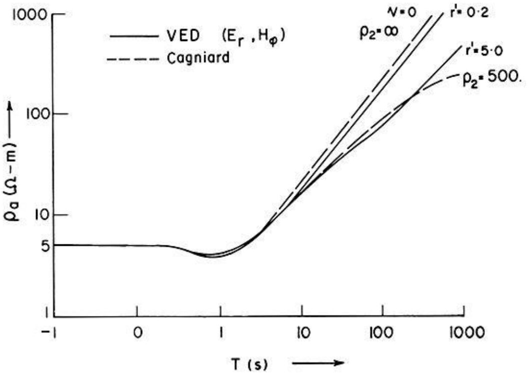

Fig. 2. Comparison of Cagniard $\rho_a(\rho_2 = \infty, 500)$ with those of Quon for VED ($\rho_2 = 500$)

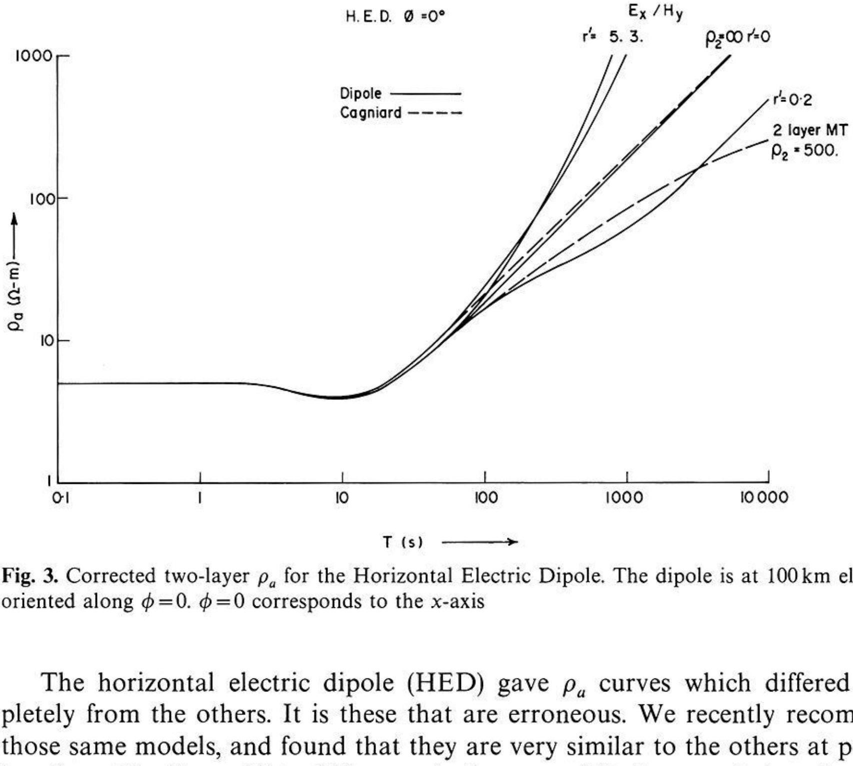

Fig. 3. Corrected two-layer ρ_a for the Horizontal Electric Dipole. The dipole is at 100 km elevation oriented along $\phi = 0$. $\phi = 0$ corresponds to the x-axis

The horizontal electric dipole (HED) gave ρ_a curves which differed completely from the others. It is these that are erroneous. We recently recomputed those same models, and found that they are very similar to the others at periods less than 10 s. From 10 to 100 seconds they may fall above or below the plane wave response curve, depending on position and component. Beyond 1,000 s ρ_a invariably sloped upward at 45° (Fig. 3). $\phi = 0$ corresponds to the x-axis.

Two works appearing in the early 1960's shed more light on the topic. Cantwell's (1960) thesis showed that at least one major addition to Cagniard's model was required. That is, lateral conductivity changes in the earth had to be treated much more seriously. Whereas Cagniard wrote

$$E = zH \tag{1}$$

as a scalar equation relating E and the (perpendicular) H component at each frequency at a site, Cantwell showed that a tensor equation was necessary

$$\begin{aligned} E_x &= Z_{xx} H_x + Z_{xy} H_y \\ E_y &= Z_{yx} H_x + Z_{yy} H_y . \end{aligned} \tag{2}$$

Neglecting this fact, especially near coastlines and other major tectonic features, gave apparent resistivities which were orders of magnitude different from true resistivities, and which varied in time. These were sometimes attributed to source effects.

In 1964 Madden and Nelson issued their classical report 'A defense of Cagniard's magnetotelluric method'. There they showed that, in a laterally uniform earth, the important factor is the ratio of horizontal (source field) wavelength, λ, to skin depth δ

$$\frac{\lambda}{\delta} \approx \frac{(\omega\mu\sigma)^{\frac{1}{2}}}{v} \quad \begin{cases} \gg 1 \text{ no source effects} \\ \leqq 1 \text{ large source effects.} \end{cases} \tag{3}$$

Source effects are important only when this is the order of unity or less. In sedimentary basins, where much of the *MT* work is done, resistivities are low, skin depths are small, and source effects are negligible over the entire range of frequencies used.

These developments, and the usual data scatter resulting from artificial noise and inadequate instrumentation, put an end to the debate at that time.

Very recently, Gamble et al. (1979) showed that, by use of their remote reference technique, apparent resistivity scatter can be reduced to 1% or less. Whereas the method is new, it has since been applied in other surveys in complex areas. It consistently improves the repeatability of results, and makes possible useful measurements in areas so noisy that good data cannot otherwise be obtained.

In another very recent work, Dmitriev and Berdichewsky (1978) showed that the source field over a horizontally layered medium could vary linearly with distance and still give correct values of apparent resistivitiy.

It has therefore become important to reexamine the source effect. The emergence of 3D model programs and of improved, inexpensive 2D model programs, makes this task practicable.

New Computations – Extended Quon Model

The extensive modelling capabilities at Berkeley and Macquarie were used to verify and extend Quon's calculations and to consider other simple models as well.

As mentioned earlier, we verified most of Quon's results except for the HED, which we corrected. Deviation from the plane wave response in the Alberta model was found only at periods >100 s or so. Since this deviation would be expected to diminish for higher conductivities, and since one commonly sees a conductivity increase in the upper mantle, we extended Quon's model by adding

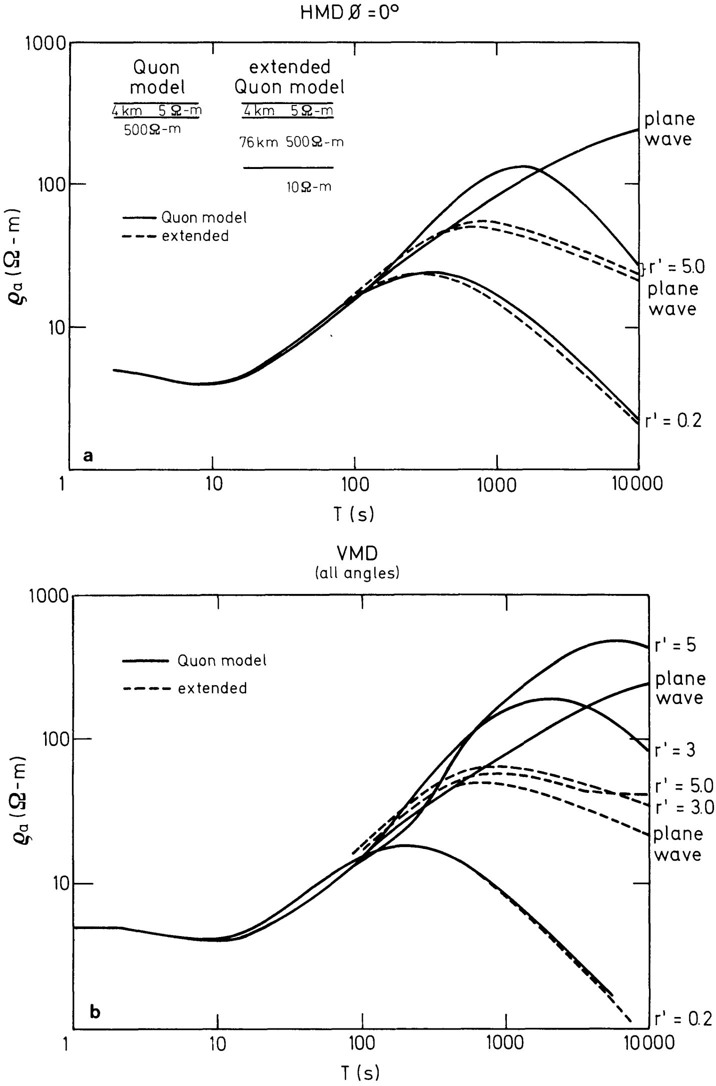

Fig. 4a and b. Plane wave and dipole results over the extended Quon model **a** Horizontal Magnetic Dipole along $\phi = 0°$ using H_x, E_y. **b** Vertical Magnetic Dipole using H_r, E_ϕ

a 10Ω-m mantle at 80 km depth. We found that it has considerable influence on VMD and VED results beyond 300 s period for large spacing, but makes much less difference to either horizontal dipole (Fig. 4). Therefore we cannot always count on being 'saved' by the mantle from source effects at low frequencies. We note in passing that the field strength due to a dipolar source falls off rapidly with horizontal distance. If source effects are to occur in the presence of plane waves, they must be most evident at small distances from their source.

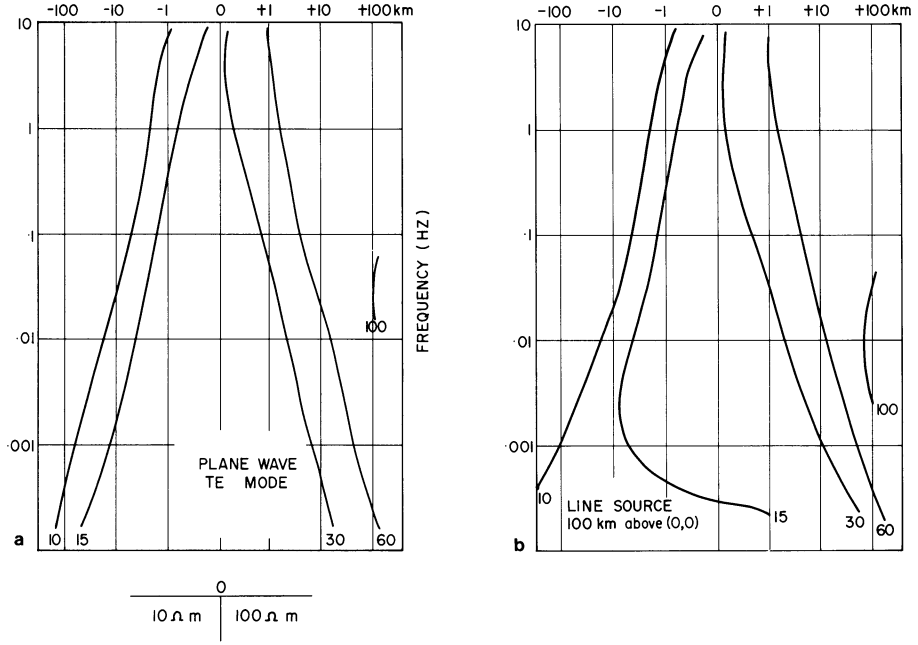

Fig. 5a and b. Apparent resistivity pseudosections for **a** plane wave, *E* parallel to strike, and **b** line current source parallel to strike at 100 km elevation, over the Swift model. Contours are in ohm-meters

New Calculations – Swift Model

While there has been some speculation, there have been no published computations of source effects in more complicated conductivity structures. The simplest of these structures is the vertical exposed fault, and the model shown (bottom, Fig. 5a) is that used by Swift in his early 2D modelling (1967). The question to be examined is whether lateral conductivity variations make much difference in the importance of source effects.

Calculations were carried out for a line source parallel to strike and for horizontal and vertical magnetic dipoles at 100 km above the fault. When the plane wave and the line source apparent resistivities were compared, we found that there were 50% differences at periods of 3000 s, and very little difference at periods less than 100 s (Fig. 5). We also saw that the differences were greatest directly beneath the source. These should diminish as the source moves laterally away from the fault since effective wavelengths at the fault would increase. (The plane wave has the *TE* polarization, and the currents flow parallel to strike in both cases.)

When the line source is replaced by a magnetic dipole, then the result depends on two horizontal coordinates, as did Quon's. It is also evident that, depending on position and dipole orientation, *E* fields can be at any angle to strike. Hence both the smooth transition of the *TE* polarization, and the overshoot-undershoot of the *TM* polarization, should be expected in the various

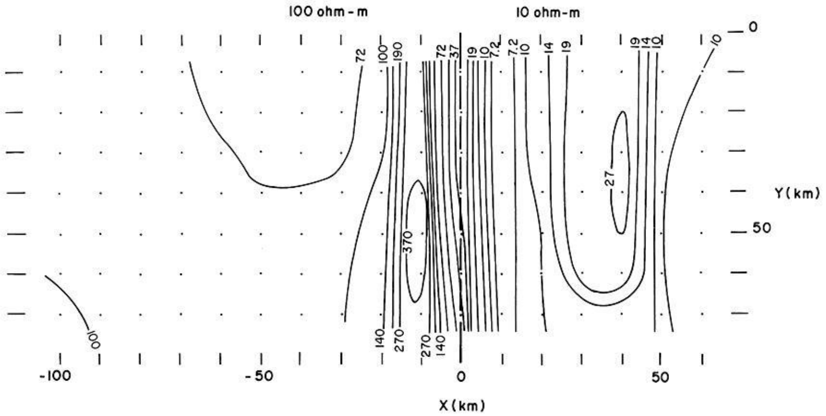

Fig. 6. Plan view of ρ_a due to an x-oriented magnetic dipole above the Swift model. $T = 100$ s, dipole is located at 100 km above (0,0) and ρ_a is calculated from E_x and H_y. Contours are in ohm-meters

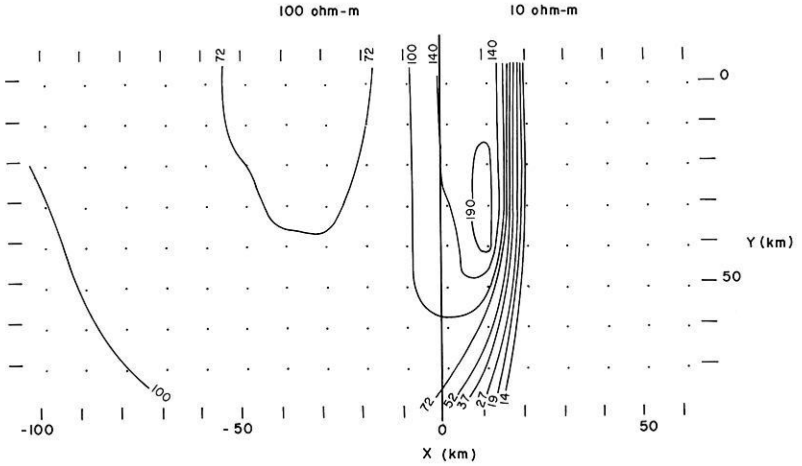

Fig. 7. As Fig. 6, except that the dipole is vertical, and ρ_a is calculated from E_y and H_x. Contours are in ohm-meters

situations. Calculations were done for $T = 100$ s. Larger effects would be expected at longer periods. ρ_{xy} for the x-directed magnetic dipole (Fig. 6; y is strike direction) most clearly shows both overshoot and undershoot. The ratio of extremes (403:6.3) does not quite reach the (100:1) ratio of the TM case, but the values continue to oscillate on the conductive side. The undershoot 10 km on the conductive side is succeeded by a large overshoot at 35 km. The other component, ρ_{yx}, has an overshoot at -80 to -100 km because of the geometric null in the primary magnetic field.

Vertical magnetic dipole results (Fig. 7) at this period are smoother. They show an overshoot (242) but no undershoot. However the overshoot now lies on the conductive side of the contact.

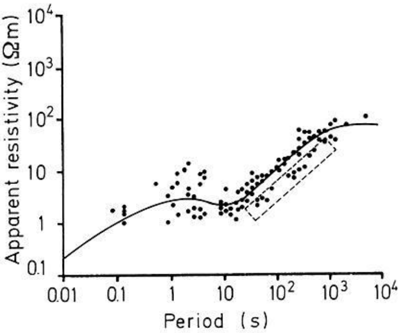

Fig. 8. Rotated tensor ρ_a from a remote site in a simple sedimentary basin. The values in the box appear to be affected by a local source

The Search for Source Effects

Although geomagneticians claim that discrete current or charge systems are unlikely at 100 km elevation, the question of the sources of scatter in good, well smoothed *MT* results remains to be answered. In the result of Fig. 8 the scatter in the 1–10 s period region is due to weak signal. However the lower cluster at 30–700 s was obtained in a single recording at a time of large signal. It differs from the other data only in the time at which it was recorded. The site, in central Australia, is remote from artificial interference, over a sedimentary section of 1.5–4 Ω-m, 2.3 km thick.

Beahn (1976) looking with high precision at small differences between two closely-spaced sites, detected occasional events that had the characteristic of source effects. Large source effects at 500–1,000 s period should be expected at auroral latitudes, where Gokhberg (personal communication, 1976) describes large differences between sites 50 km apart, and several studies of the induction effects associated with the equatorial electrojet can be found (Ducruix et al., 1977). The localized nature of the source currents is central to those results.

Some of the induction effects now ascribed to current channelling, i.e., by 3D conductivity structures – could be caused by combinations of local sources. Consider two discrete, partly coherent sources which are responsible for the *E* and *H* fields at an observing site, and assume that the impedances have different source effects. Then, as the field components add vectorially, the net impedances will vary with the component, and with the relative contribution from each source. If the sources are transitory, then part of the time some components may even cancel, so that null or infinite impedances could be observed for short intervals.

It seems that *MT* could in fact become a valuable technique for studying local heterogeneities in the lower ionosphere, and plans are under way to carry out such an experiment in the auroral zone. An obvious way to approach the subject is with the aid of field intensity and phase distribution measurements at the surface.

As regards the exploration applications of *MT*, if we are fortunate then source effects will remain a curiosity which can be removed, except possibly very near the magnetic equator and the auroral zones. However if we are unfortunate, source effects could be as disruptive to *MT* surveys as magnetic storms are to magnetic surveys.

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