Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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No. 36

An appraisal of the VLF ground resistivity technique as an aid to mineral exploration

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An appraisal of the VLF ground resistivity technique as an aid to mineral exploration

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36 An appraisal of the VLF ground resistivity technique as an aid to mineral exploration

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SUMMARY

To assist the Department of Industry Mineral Reconnaissance Program (DIMRP) limited research has been undertaken to provide guidelines on new geophysical prospecting systems, field techniques and general exploration methodology.

A short study has been made of the ground VLF resistivity (VLF-R) method to assess its potential for mineral prospecting and geological mapping. Field trials confirm that the method is well suited for mapping broad mineralised zones, flat lying conductors of limited lateral extent, or abrupt changes in conductivity associated with geological contacts. In resistive terrains the method offers distinct operational advantages over galvanic resistivity methods. The principal disadvantages of the technique relate to interpretational ambiguities associated with the complex behaviour of surface impedance at VLF and the fact that the operator has no effective control over the depth of investigation. Theoretical model studies show that too small and too large a penetration can both result in non-detection of a resistive target, but that excessive penetration will not seriously affect the resolution of conductive targets.

INTRODUCTION

It is recognised within the DIMRP that the efficacy of geophysical techniques in the UK suffers from a reliance on overseas exploration practice, with too little cognisance taken of local exploration environments. The high degree of imitation is attributed to a lack of indigenous research into exploration methodology and inadequate opportunities to assess the suitability of "purchased technology". Accordingly provision was made to undertake a limited program of research to provide guidelines on the use of new prospecting systems, or techniques and to assess their relevance to the UK Mineral environment.

This report describes a short study of the Radiohm VLF resistivity technique*. Limited field trials have been made at several sites to assess its applications to mineral exploration and related structural investigations. Theoretical models are used to provide insight on the behaviour of the response parameters to changes in target depth and thickness, and to examine some concepts of target detectability.

*Summarised elsewhere by Ogilvy (1980).

THE RADIOHM METHOD

The Radiohm technique (Collett and Becker, 1968) is not new, but it has received relatively little attention. Some use has been made of the technique for mapping resistive gravel deposits and permafrost (Hoekstra *et al.*, 1975) but its potential for mineral surveys and structural investigations does not appear to have been fully recognised.

The Radiohm equipment is commercially available as the Geonics EM16R, and comes as an attachment to the Geonics EM16 VLF receiver. As with VLF electromagnetic (VLF-EM) surveys, use is made of remote radio stations operating in the VLF band of 15–25 kHz. The apparent resistivity of the earth is determined from the complex surface impedance (E_x/H_y) of the incident VLF wave, viz

$$\rho_a = (E_x/H_y)^2 \, (1/\mu_0 \omega) \qquad [1]$$

where $\mu_0 = 4\pi \times 10^{-7}$ henry/m
ω = frequency, radians/sec
ρ_a = resistivity, ohm-metres

Measurements of the horizontal electric field, E_x, are made using two probes spaced 10 m apart and aligned in the direction of the transmitter; the horizontal magnetic field (H_y) is measured by an integral coil in the receiver handle. The high input impedance ($10^8 \Omega$., 0.5 pF) means that only marginal ground contact is required. A reading is taken by orientating the instrument for an inaudible null so that the coil is maximally coupled to H_y. Apparent resistivity in ohm-metres and phase in degrees, are read directly from calibrated dials. Accuracy depends on the signal to noise ratio which in turn depends primarily on the distance from the transmitter.

For most purposes the depth of exploration of the Radiohm system can be taken as the apparent skin depth (δ_a) where

$$\delta_a = \sqrt{(2\rho_a/\mu_0 \omega)} = 503.3\sqrt{(\rho_a/f)} \text{ m} \qquad [2]$$

where f = frequency, Hz.

A schematic representation of a VLF resistivity survey is shown in Fig. 1.

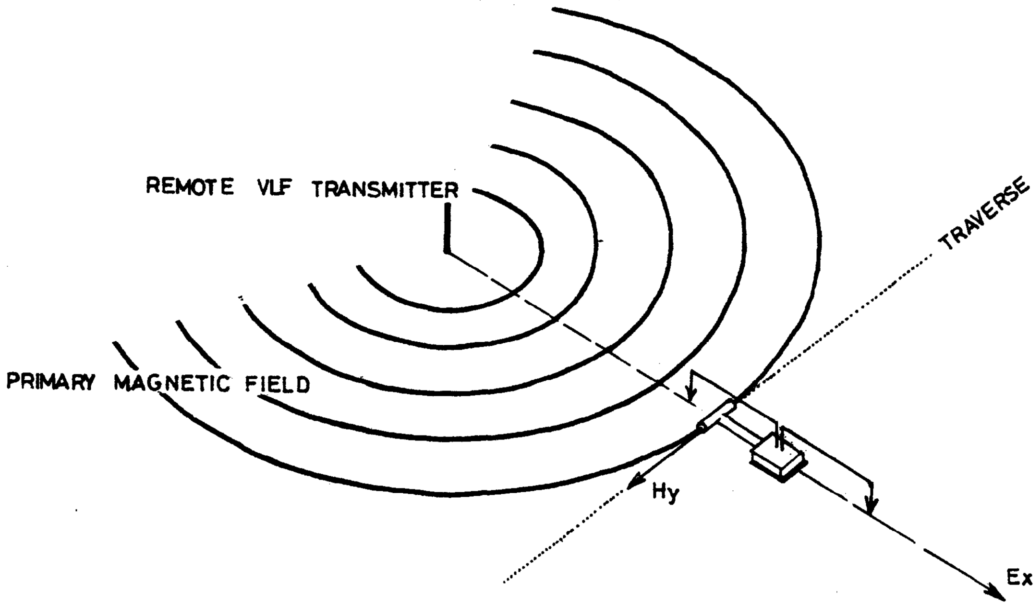


FIG. 1 SCHEMATIC REPRESENTATION OF A VLF RESISTIVITY SURVEY

INTERPRETATION

The behaviour of apparent resistivity based on surface impedance at VLF is particularly sensitive to skin depth and layer sequence. This dependence is illustrated graphically in Fig. 2. It will be noted that a relatively thin conductive surface layer may significantly depress the apparent resistivity obtained over resistive bedrock. Caution is required, therefore, in assessing the areal distribution of a particular rock type or target horizon based on its apparent resistivity value. Similarly the full extent of a buried conductor (e.g. fault zone or sulphides) may not be recognised if the primary field is attenuated by near surface layers of high conductivity.

These operational constraints and interpretational ambiguities can be assessed more readily by modelling the geoelectric section to extract true layer resistivities and thicknesses. To date this has been achieved by published two layer nomograms (McNeil, 1973) but these are necessarily limited to a specific range of earth models. An alternative and more useful approach is to obtain individual solutions in the field by directly inverting the VLF-R data using a pocket calculator. If necessary, solutions can be obtained on a station by station basis. The advantage of this approach is that it provides the operator with instant interpretive feedback, and leads to more careful investigations in anomalous areas.

Where adequate geological control is available, the interpretation may be extended to three layers (Ogilvy, 1979). This may also be done in the field, but requires forward modelling and more time. The theory (Wait, 1962) permits solutions for "n" layers, but as the Geonics EM16R is restricted to one frequency and only two parameters are measured, solutions for more than two layers become increasingly ambiguous. If multifrequency measurements were made over several decades, then "n" layer solutions would of course be possible.

FIELD EVALUATION STUDIES

SOURTON TORS

This site is located on the north-west margin of the Dartmoor granite. A broad zone of iron sulphide mineralisation occurs in northerly dipping Carboniferous slates of the Crackington and Meldon Chert formations. The mineralisation which had been detected by airborne and ground geophysical surveys was shown by subsequent drilling to consist of interlacing veinlets of predominantly pyrrhotite and pyrite (Beer and Fenning, 1976). The mineralisation is widely dispersed throughout the slate but has sufficient continuity to give bulk conductivity anomalies when using galvanic or electromagnetic prospecting techniques.

The results from recent VLF investigations are shown in Figs. 3 and 4. Although several techniques may be necessary to establish the probable source of a geophysical anomaly, it is apparent that the combined VLF-EM and VLF-R data would have provided sufficient information for an accurate siting of exploratory drillholes. The in-phase profile indicates two localised conductors centred beneath 225SE and 160SE respectively. Application of the Karous-Hjelt filter (Karous and Hjelt, 1977) gives reliable estimates of the extent and dip of the more intensely mineralised zones. However, estimates of conductor depth based on the pseudo-section can be misleading. Interpretation of the VLF-R data indicated a two layer geoelectric section, with resistive overburden on a conductive substratum. The interpreted depths between stations 100SE and 250SE agree to within 1—2 m with the depths to mineralised bedrock obtained from drillhole information.

The earlier DC resistivity survey gave a similar broad resistivity low to that obtained with the EM16-R, but it was not possible to derive the depth of the low resistivity horizon from the DC measurements. Further it will be noted that the VLF-R profile gives an anomalous low of 10 ohm-metres compared to 200 ohm-metres for a Wenner "a" spacing of 15.2 m. The apparent skin depth for the Rugby station (GBR, 16 kHz) is of the order of 12 m over the anomalous zone, which corresponds closely to the depth to mineralised bedrock. For a Wenner "a" spacing of 15.2 m, the depth of investigation would be approximately equal to only 5 m (Roy and Apparao, 1971).

The excellent correlation between interpreted depths and drillhole data suggests that the EM16R was able to resolve local variations in thickness, even over distances of 10—20 m. This observation confirmed theoretical expectations that the VLF-R method would be particularly useful for mapping resistive or conductive zones of limited lateral extent — in contrast to galvanic methods where large current spreads would tend to average out such variations.

PEN Y DRUM

At Pen y drum, VLF measurements were made over a known contact between Llanrhychwyn slates and a dolerite sill (Fig. 5). It will be noted that, although the VLF-EM profile clearly indicates the presence of a strong subsurface conductor, it would be difficult to locate the geological boundary with any degree of certainty. In contrast, the resolution of the VLF-R profile is such that a distinct lateral discontinuity occurs at 300E. It is apparent also that the conductive slate lithology extends at least to station 00E. This would not be evident from the VLF-EM method which essentially responds only to the slate margin.

The geoelectric section was obtained for an assumed resistivity value (ρ_1) of 1000 ohm-metres.

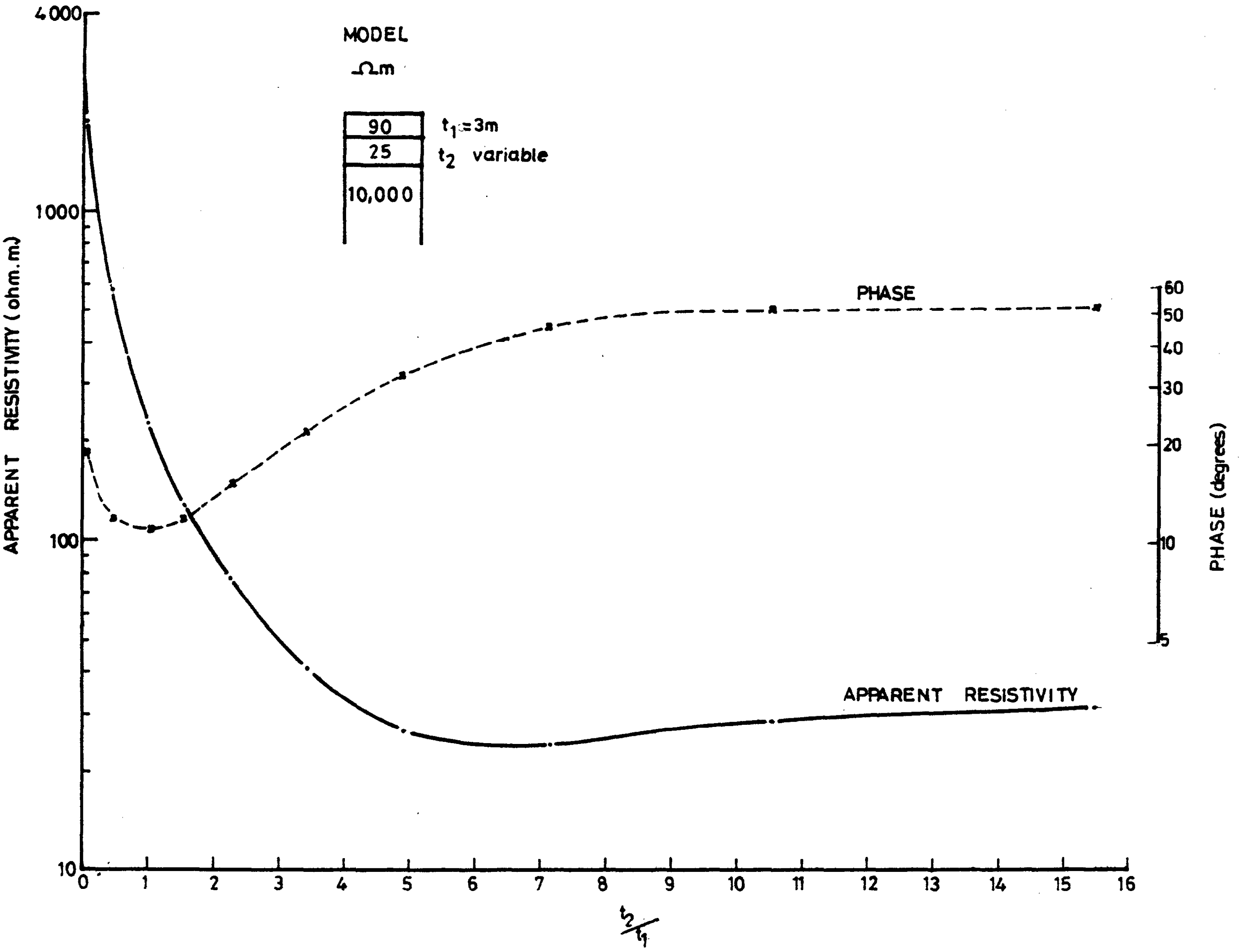
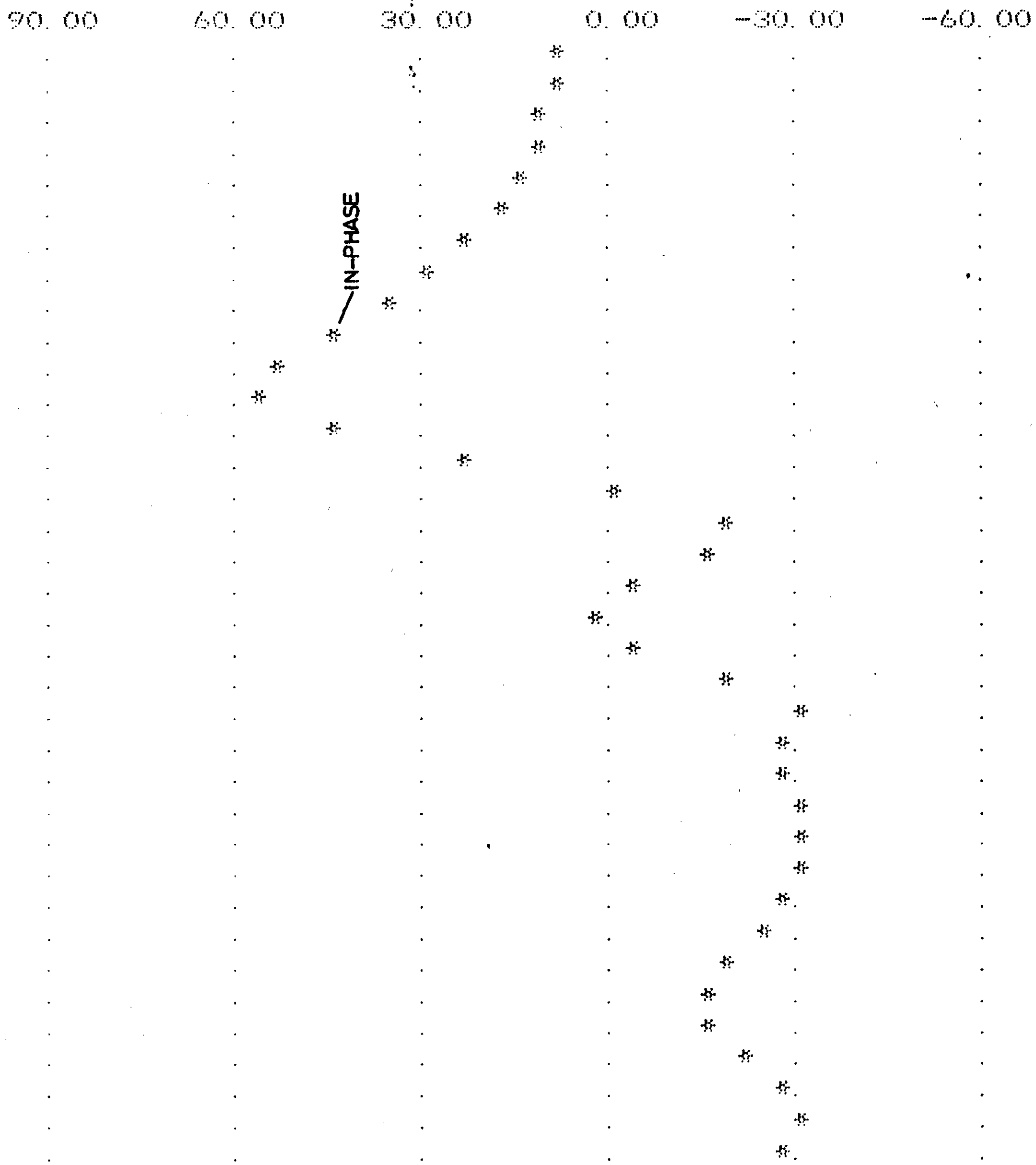


FIG. 2 DEPENDENCE OF VLF RESISTIVITY AND PHASE ON LAYER THICKNESS

SOURTON TORS

CONTOUR INTERVAL = 10.0



360.0SE	8.00
350.0SE	9.00
340.0SE	10.50
330.0SE	13.00
320.0SE	15.00
310.0SE	18.00
300.0SE	23.00
290.0SE	29.00
280.0SE	35.00
270.0SE	45.00
260.0SE	54.00
250.0SE	58.00
240.0SE	46.00
230.0SE	25.00
220.0SE	0.00
210.0SE	-17.00
200.0SE	-14.00
190.0SE	-3.00
180.0SE	1.50
170.0SE	-4.00
160.0SE	-18.00
150.0SE	-29.00
140.0SE	-27.00
130.0SE	-26.00
120.0SE	-29.00
110.0SE	-30.00
100.0SE	-29.00
90.0SE	-28.00
80.0SE	-24.00
70.0SE	-19.00
60.0SE	-14.00
50.0SE	-15.00
40.0SE	-21.00
30.0SE	-26.00
20.0SE	-29.00
10.0SE	-28.00

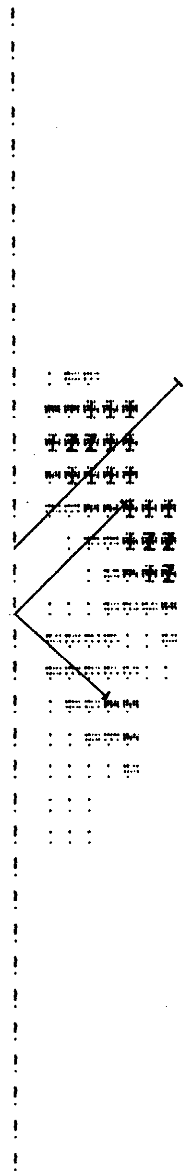


FIG. 3 IN PHASE VLF-EM AND KAROUS-HJELT CURRENT DENSITY PSEUDO-SECTION, L1, SOURTON TORS

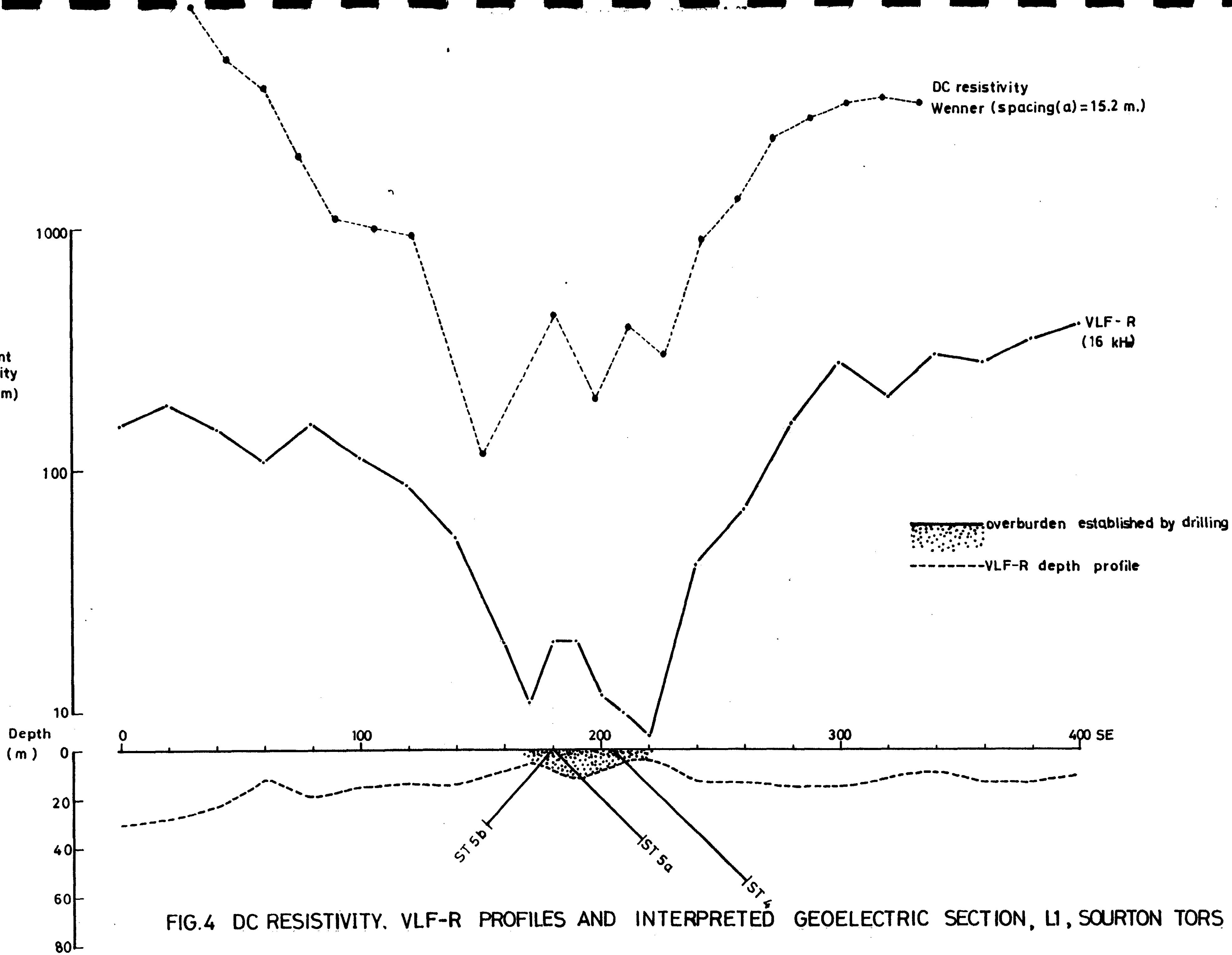


FIG.4 DC RESISTIVITY, VLF-R PROFILES AND INTERPRETED GEOELECTRIC SECTION, L1, SOURTON TORS

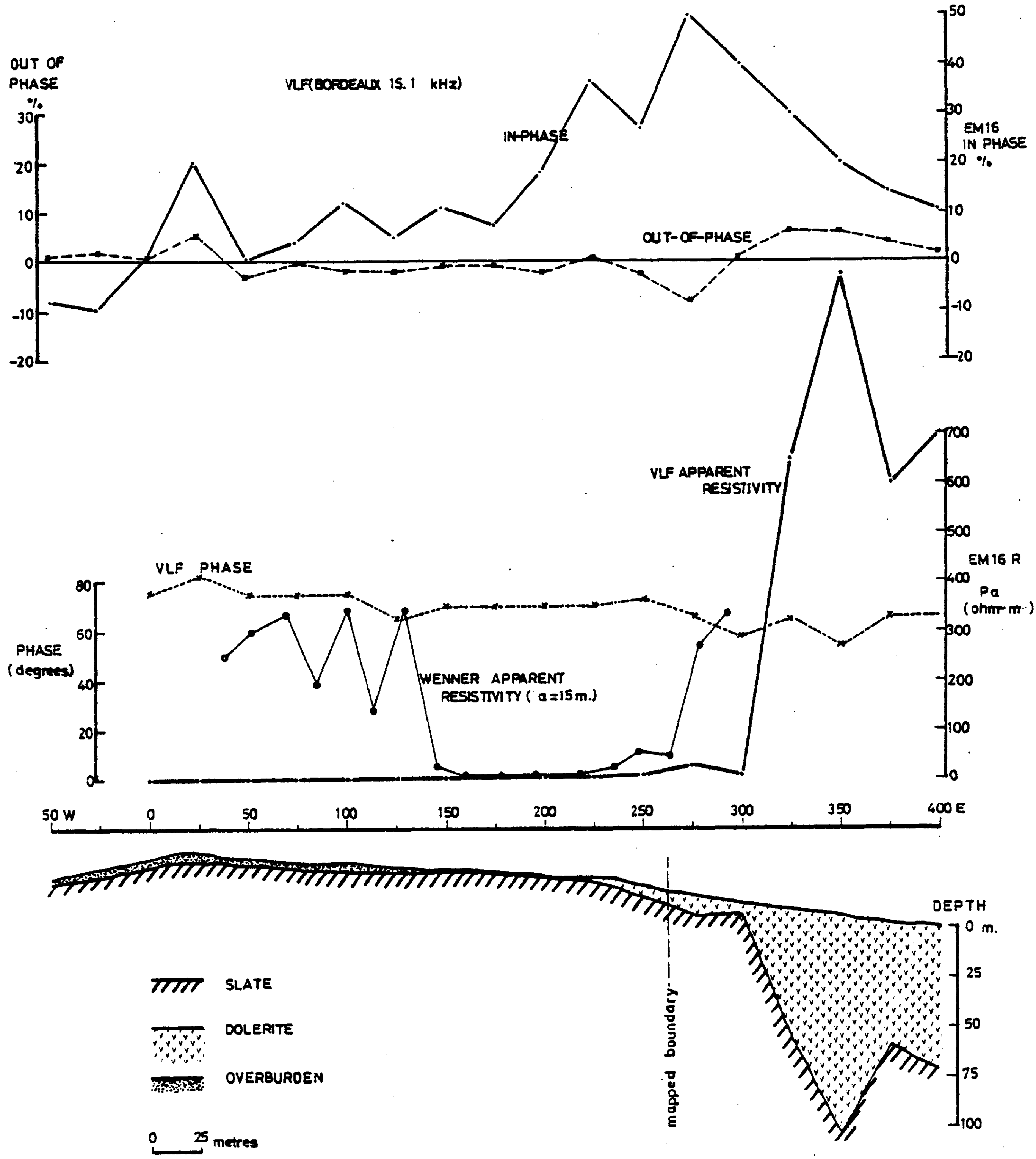


FIG. 5 VLF-EM . VLF-R, DC RESISTIVITY RESULTS, AND INTERPRETED GEOLOGIC SECTION, L 25S, PEN Y DRUM

Without prior knowledge of the geology, the rapid change in thickness east of 300E would suggest either a sudden thickening of drift, or an abrupt lateral change in conductivity. In this case, the change may be attributed to the outcropping dolerite sill. Phase values over the dolerite were greater than 45°, implying the presence of a conductive lower layer. This would be compatible with the sill intrusive overlying the slate. Some ambiguity exists on the thickness of the dolerite, but assuming a resistivity value (ρ_1) of 5000 ohm-metres, the interpreted section indicates a thin dolerite margin of 5 m, thickening rapidly to 70 m towards the east. For that section of the traverse between 300E and 00E, variation of ρ_1 between 100 and 10 000 ohm-metres, produced no significant changes in the interpreted depth due to the high conductivity of the underlying slates.

DC resistivity profiling with a Wenner array gave comparable results to the EM16R but only the near surface slate was detected. From 25 to 125E the high DC apparent resistivity values reflect a thickening of the resistive overburden. It is clear that the selected Wenner spacing of 15 m gave inadequate penetration to resolve the full extent of the slate horizon. The comparison underlines the relative ease with which greater penetration is achieved with radiowave techniques in resistive environments.

LONG RAKE

As part of a larger routine survey, VLF-R measurements were made over a fluorspar deposit at Long Rake, Derbyshire. The aim of the survey was to determine whether geophysical methods could detect the fluorspar mineralisation (in itself, a resistive target) and if so to map extensions to known veins under glacial drift.

No electromagnetic or resistivity anomalies were observed that could be attributed directly to the mineralisation or its host structure — a northerly dipping wrench fault. Nevertheless, it was found possible to map the fluorspar vein indirectly by its association with the subdrift shale/limestone contact, over which strong conductivity anomalies were observed. Some typical VLF-R results are shown in isometric form in Fig. 6. A comparison of VLF-EM and VLF-R data (Fig. 7) again shows that the location of the geological contact is more readily established from the apparent resistivity data than the VLF-EM results, although both methods were successfully used to trace the fluorspar vein some 1.8 km. The disadvantage of VLF-EM in resolving geological contacts is that anomalies tend to be broad, with no clear cross-over position. The ability of the VLF-R technique to resolve subsurface contacts of this type is attributed to the fact that the horizontal magnetic field (H_y) is particularly sensitive to abrupt lateral changes in conductivity (Frischknecht, 1972). A further contributing factor at the Long Rake is that the influence of the underlying limestone to the south has a neglible effect due to skin effect attenuation of the primary field in the conductive shale.

DISCUSSION AND THEORETICAL STUDIES

It is clear from the field examples that the VLF-R technique offers a versatile tool, which is particularly suited for mapping broad mineralised zones, geological contacts, or flat lying conductors. The method does, however, have some important inherent limitations. The most serious of these relate to the ambiguity associated with layered interpretations and to skin depth attenuation which restricts the depth of penetration in conductive terrains.

AMBIGUITY IN INTERPRETATION – EQUIVALENCE

At the Sourton Tors site, the geoelectric section (Fig. 3) was obtained assuming a fixed ρ_1 value of 5000 ohm-metres. Substituting more realistic values of ρ_1 ranging from 300 to 10 000 ohm-metres produced no significant changes in the depth profile, (variations were generally less than 1 per cent). It appeared that the depth determination was, for practical purposes, independent of the resistivity of either layer. Further investigation showed this to be a saturation effect, being a direct consequence of the strong resistivity contrast between layers 1 and 2.

To assess the confidence limits of the two layer model, the inversion program was used to compute the range of equivalent solutions for each station along the profile. Three examples are shown graphically in Fig. 8. By plotting thickness (t_1) against resistivity ratio (ρ_1/ρ_2) it is possible to study the influence of ρ_1 on the interpreted thickness of overburden. It is evident that at 180s, t_1 can vary only between the limits $9.5 < t_1 < 13$ m. Elsewhere the range of equivalence may be large, depending on ρ_1/ρ_2 and the phase (ϕ). It is also seen that saturation occurs for a wide range of ρ_1/ρ_2 and that the choice of ρ_1 has little impact on the depth determination in high contrast situations.

The maximum and minimum depths of overburden consistent with a two layer model are shown graphically in Fig. 9. The result confirms that ambiguity could be expected to increase away from the anomalous zone. In this particular case, however, the result is somewhat misleading as the realistic range of ρ_1/ρ_2 was confined to the lower asymptotic branch of the equivalence curves for each station. Hence the ambiguity in "t", is very much less than indicated. Nevertheless, it is clear from this example that depth determinations

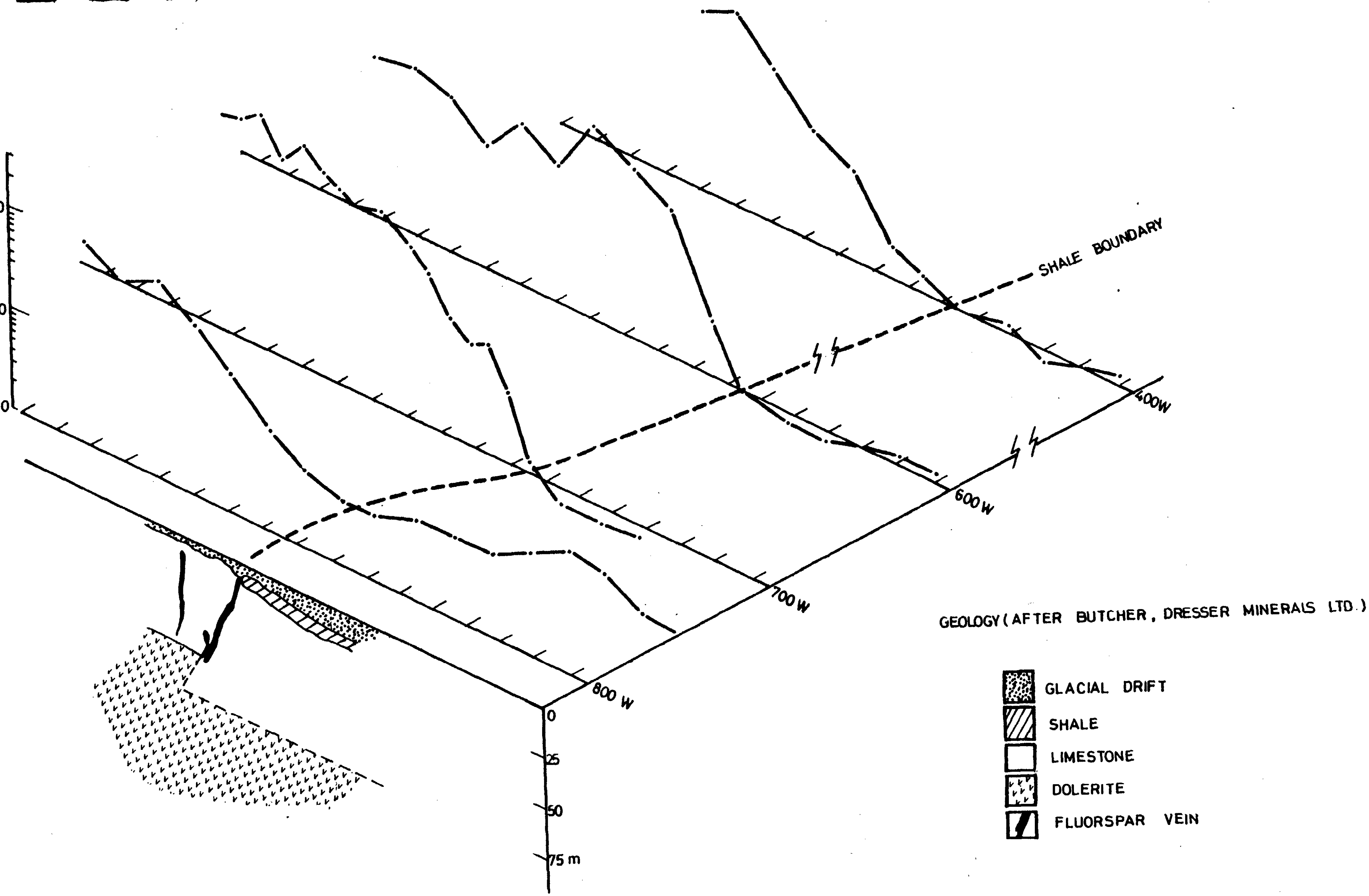


FIG.6 VLF-R SURVEYS, AS AN AID TO STRUCTURAL AND STRATIGRAPHIC MAPPING

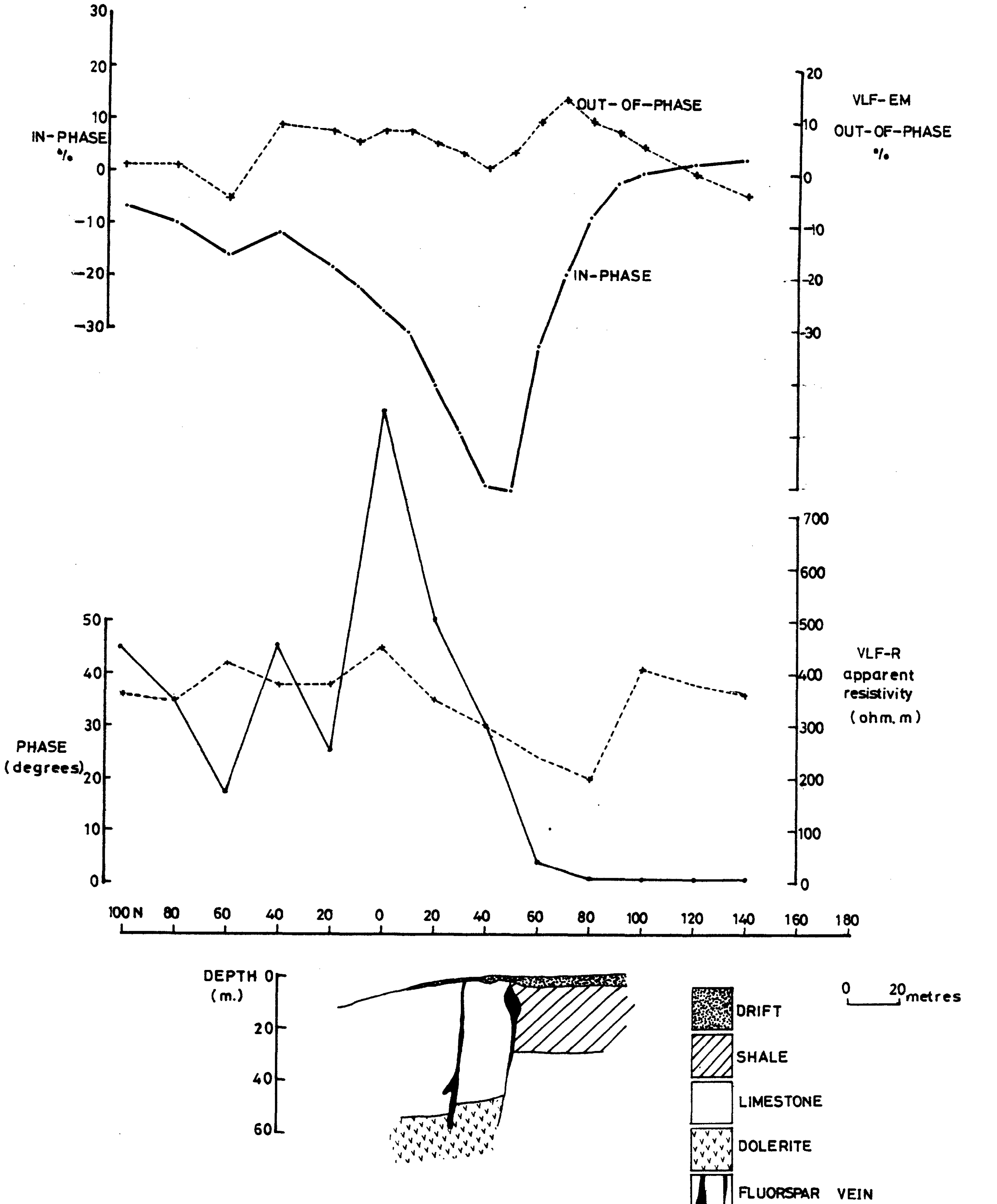


FIG. 7 COMPARISON OF VLF-EM AND VLF-R RESULTS, L 600W, LONG RAKE

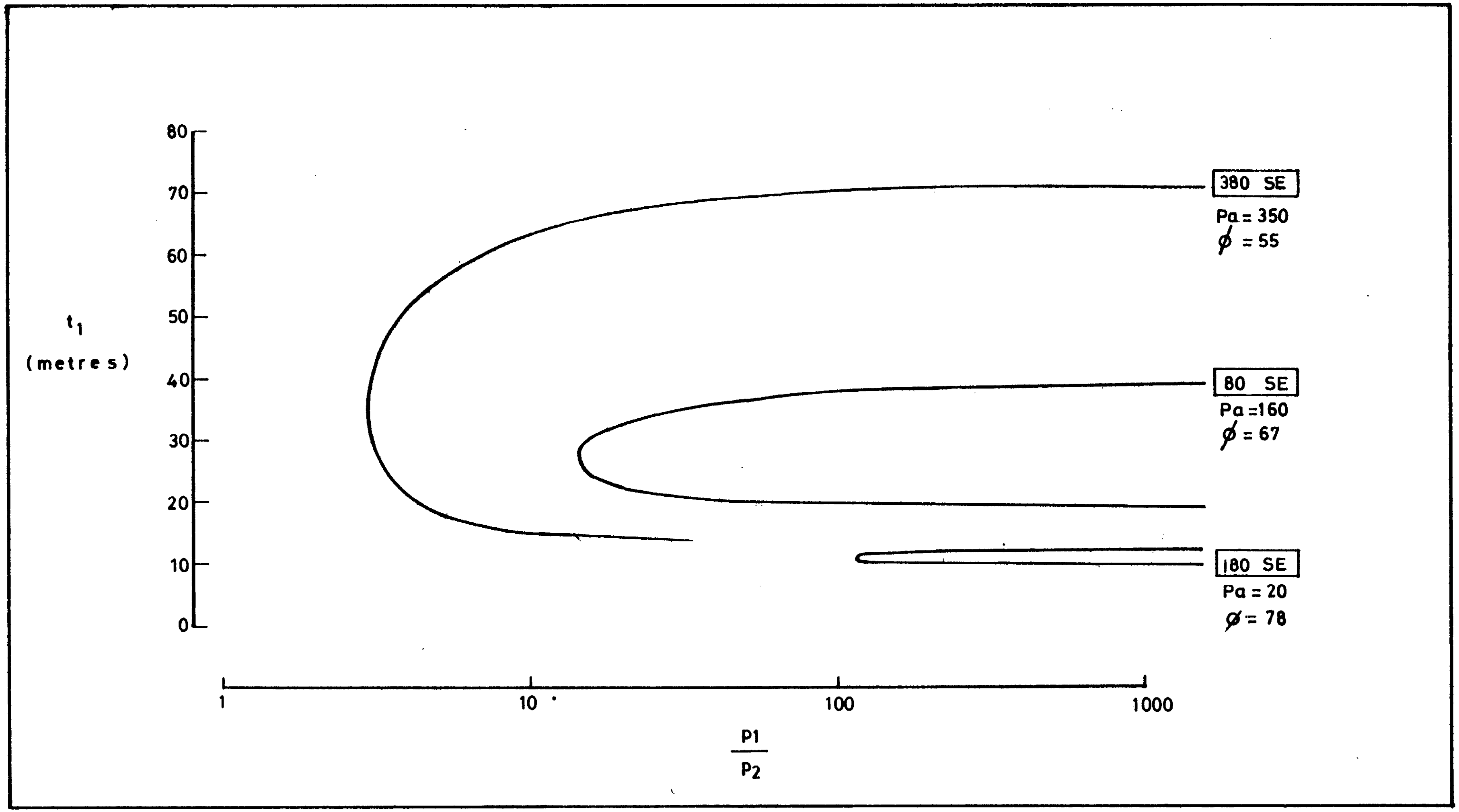


FIG. 8 RANGE OF EQUIVALENCE AT STATIONS 80, 180, 380 SE SOURTON TORS

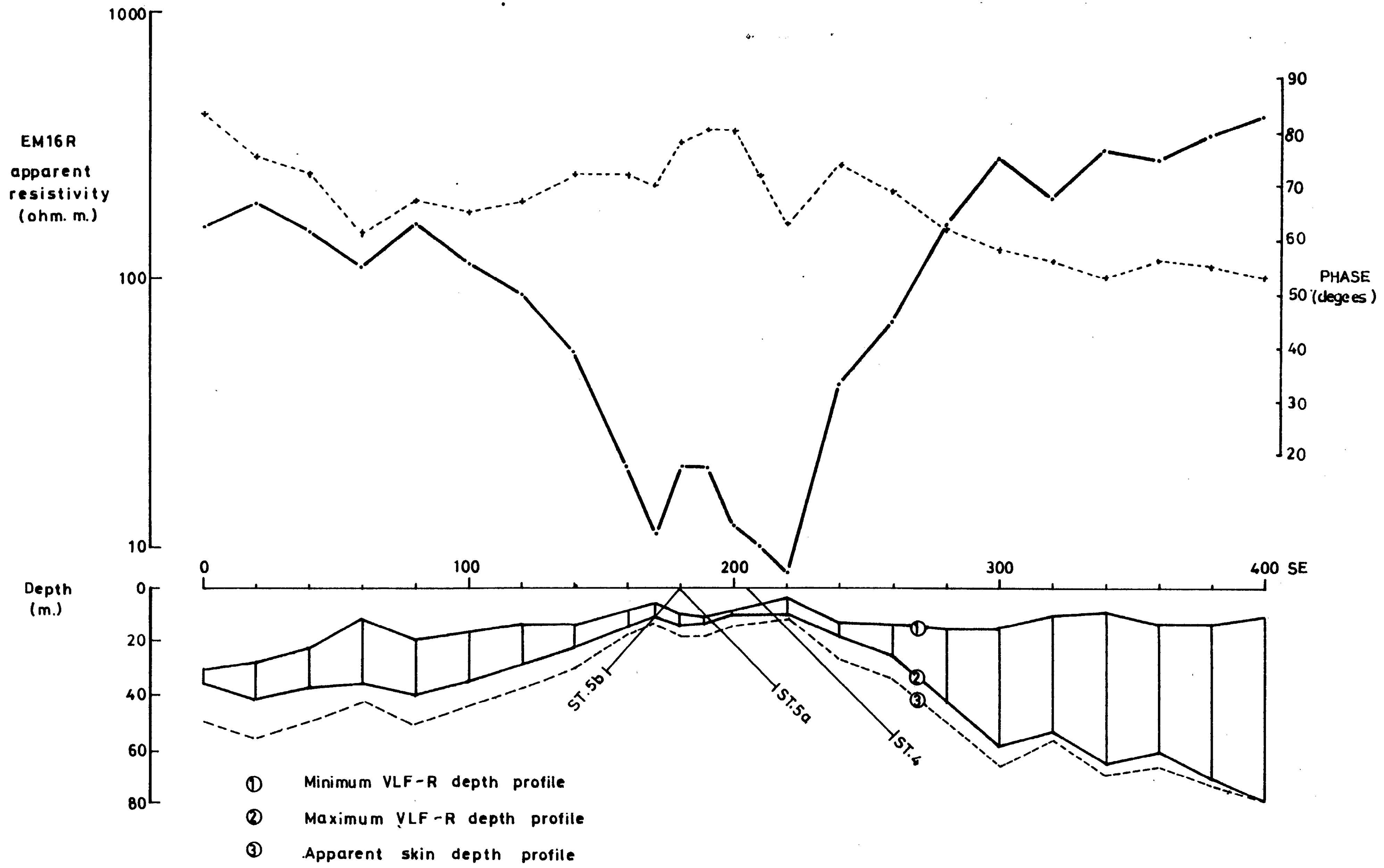


FIG. 9 MAXIMUM AND MINIMUM DEPTH LIMITS BASED ON A 2-LAYER INVERSION OF THE VLF-R DATA, L1, SOURTON TORS

should be treated with some reservations, particularly in areas of low to moderate resistivity contrast. For reconnaissance work it would be advisable to have control from DC vertical soundings to monitor departures from the two layer assumption, and to obtain reliable estimates of layer resistivity.

In multilayer cases, the ambiguity in layered interpretation is such that the EM16R is effectively reduced to a profiling tool to delineate lateral variations in conductivity that occur within a skin depth of the surface.

THE INFLUENCE OF SKIN DEPTH ON DETECTABILITY

Detectability of a target requires that it give rise to a certain level of response at the surface. With the VLF-R method it is generally assumed that this can occur only if the target lies within a skin depth of the surface. Unfortunately, skin depth, or more appropriately apparent skin depth (δ_a) can vary considerably within a given area, as it is dependent upon both subsurface conductivities and layer sequence. In areas of high surficial conductivity, penetration will be low, which may render the technique ineffective. In resistive environments, an excessively large depth of penetration could result in a large background contribution to the measured signal which may adversely affect target resolution and hence detectability.

An illustration of how effective penetration (i.e δ_a) may vary along a traverse is shown in Fig. 9. The plot shows a mirror resemblance to the ρ_a profile, as ρ_a is proportional to δ_a (eq. 2). A consequence of this behaviour is that, for bulk conductivity targets at least, what may seem to be an excessive penetration depth in background rocks is automatically adjusted upwards over the target. Intuitively this self-adjustment could be expected to improve resolution as the influence of background resistivities will be reduced. Similarly over a comparable resistive target, detectability will be downgraded, as δ_a will be increased.

As the EM16-R is a fixed frequency instrument, it was considered important to assess what relationship, if any, existed between skin depth and detectability. Theoretical computations of apparent resistivity (ρ_a) and phase (ϕ) where made for two flat lying targets, one resistive and one conductive. The results are shown in Figs. 10—12. One dimensionality has been assumed in the calculations but the results would be equally valid for profiling applications provided the targets had lateral dimensions several times their depth of burial.

For Model 1, the range of t_1/δ_1, over which an anomalous ρ_a response is recorded is wide for shallow targets but narrows with increasing depth. The ability to detect deep targets therefore would normally depend upon the operator being able to "tune" for the peak amplitude response. This is not possible with the EM16R but it will be noted that for a VLF of 16 kHz (GBR, Rugby) the observed ρ_a response migrates towards the peak response with decreasing depth of burial of the target. The impact of too large a depth of penetration (δ_1) in background rocks is offset by the decrease in apparent skin depth, as the target becomes shallower. For each case modelled the frequency would need to be very low before excessive penetration seriously affected target resolution. The consequences of too small a penetration require little elaboration. For t_1 = 0.79 δ_1, virtually no ρ_a anomaly at all is observed. For deeper targets between 0.79 and 2 δ_1 an interesting paradox would occur as a result of the response overshoot. At these depths, a higher ρ_a would be observed over the conductive target than over the resistive half-space.

Fig. 11 shows the corresponding phase data for the same model. It will be noted that not only is the response more complex but that the peak responses are shifted towards higher values of t_1/δ_1, thereby increasing the depth of investigation, and the range of t_1/t_2 over which an anomalous response is observed. Hence a target which may not be evident from the apparent resistivity data could, in fact, be inferred from anomalous phase values. Phase data should not therefore be merely regarded as providing conductivity information. This advantage is offset to some extent by the fact that the phase parameter responds to the target over a narrower range of t_1/δ_1 than the apparent resistivity parameter. For $t_1/\delta_1 < 1.13 \times 10^2$, the influence of layer 3 becomes dominant and phase values of less than 45° are observed. Further, in multilayer cases a phase value of 45° does not necessarily imply the presence of a homogeneous half-space. Where cross-over values of ϕ = 45° occur, equating the apparent resistivity with the true resistivity of layer 1 could clearly lead to an erroneous interpretation.

For Model 2 (Fig. 12) similar conclusions can be drawn concerning the behaviour of the ρ_a and ϕ responses. As expected, smaller peak amplitude responses were recorded, resulting in a smaller depth of investigation. Another significant difference in the resistive target case is that for VLF = 16 kHz, the ρ_a amplitude response migrates away from its peak value with decreasing depth. This may be attributed directly to the apparent skin depth increasing as the resistive target becomes shallower, with a subsequent loss of target resolution.

These theoretical observations support the earlier contention concerning the self adjustment of δ_a and its "tuning" and "de-tuning" influence on the detectability of conductive and resistive targets. The results also indicate that the VLF resistivity technique is more suited for detecting conductive targets (e.g. sulphides) of indeterminate depth than resistive targets — subject to the common restriction that both must occur within

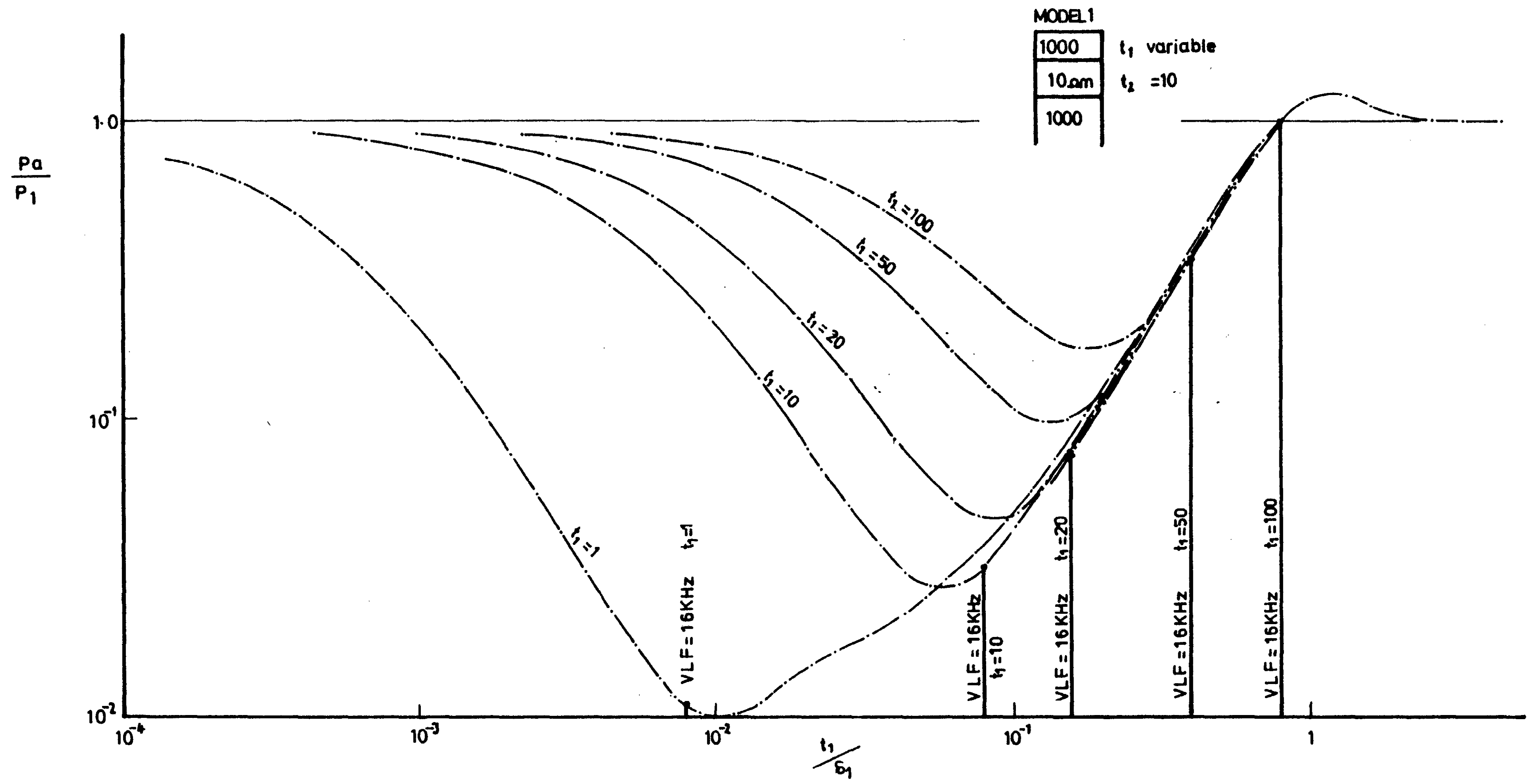


FIG 10 DEPENDENCE OF APPARENT RESISTIVITY ON SKIN DEPTH – CONDUCTIVE TARGET

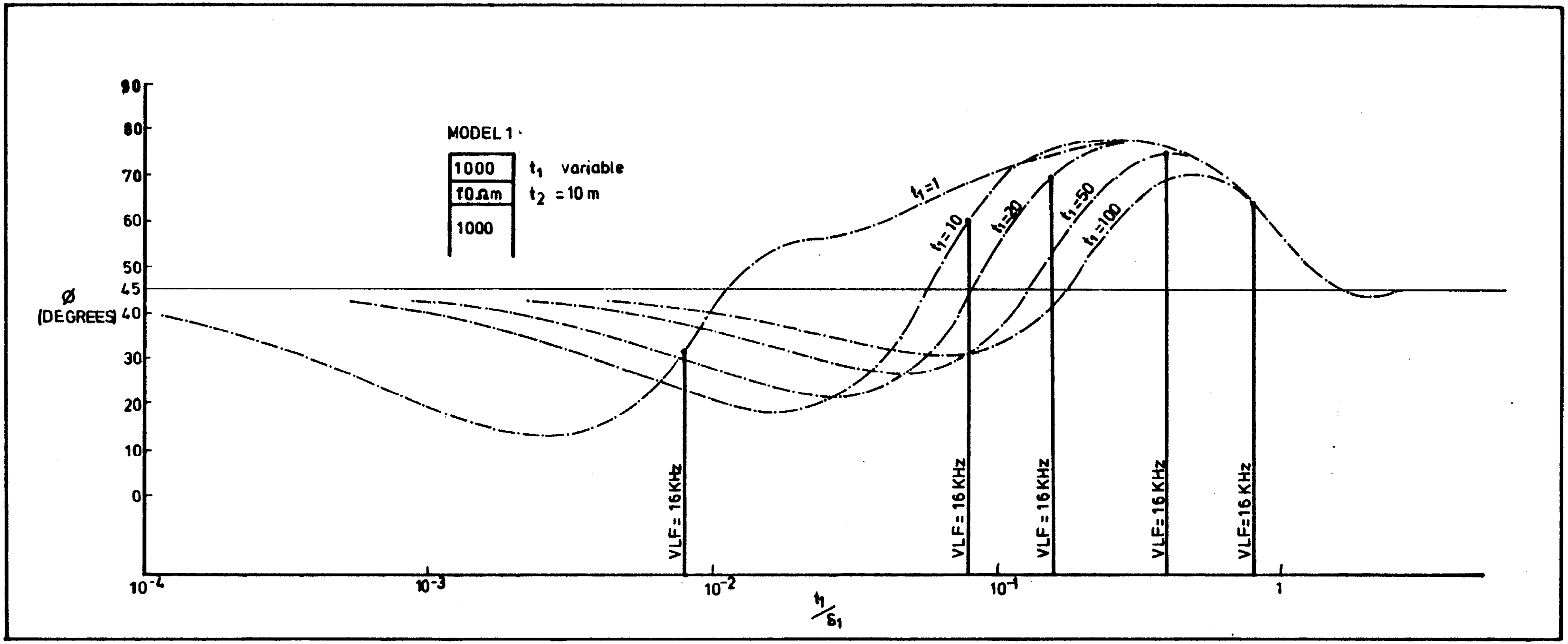


FIG.11 DEPENDENCE OF PHASE ON SKIN DEPTH - CONDUCTIVE TARGET

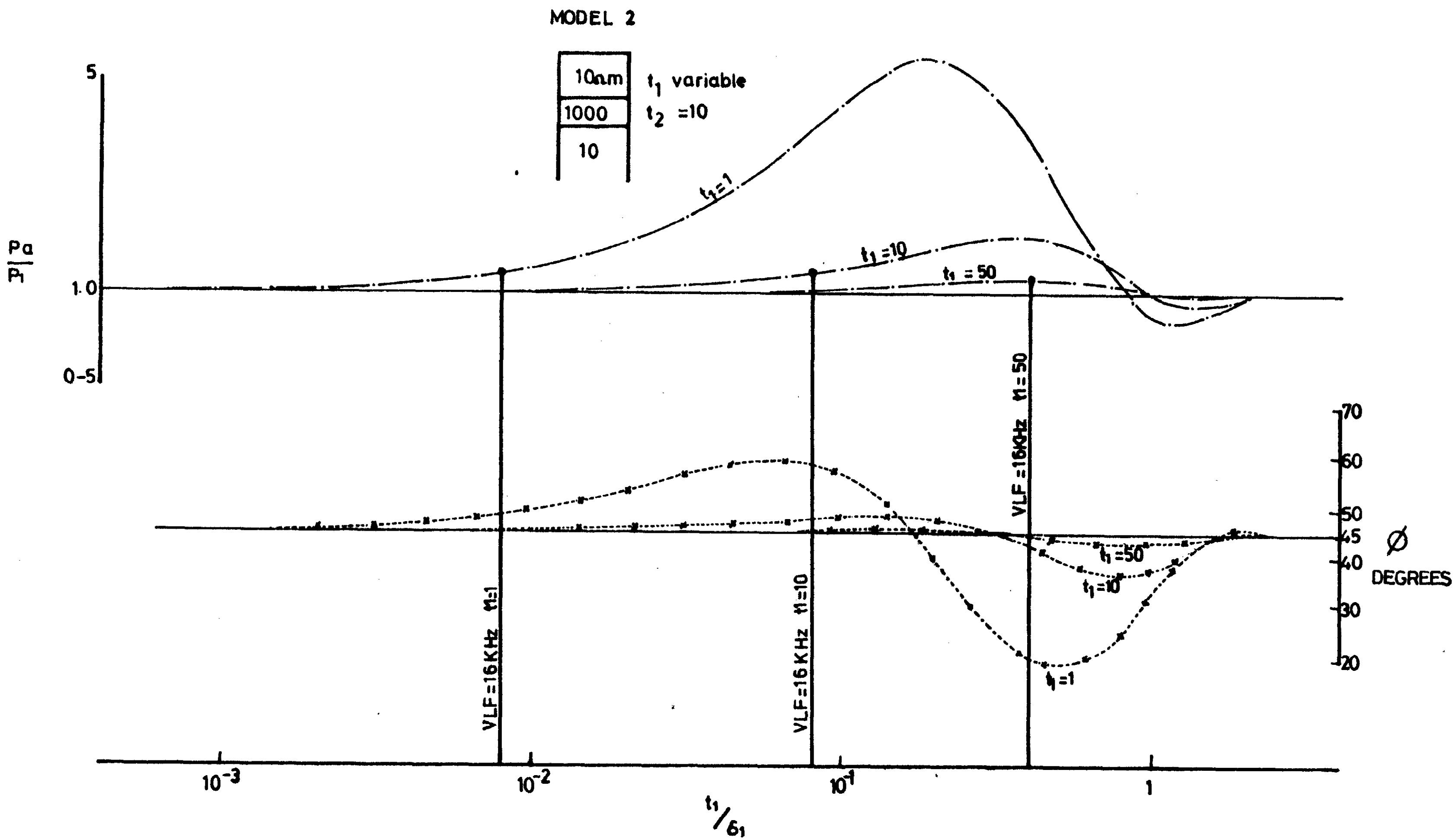


FIG. 12 DEPENDENCE OF APPARENT RESISTIVITY AND PHASE ON SKIN DEPTH
– RESISTIVE TARGET

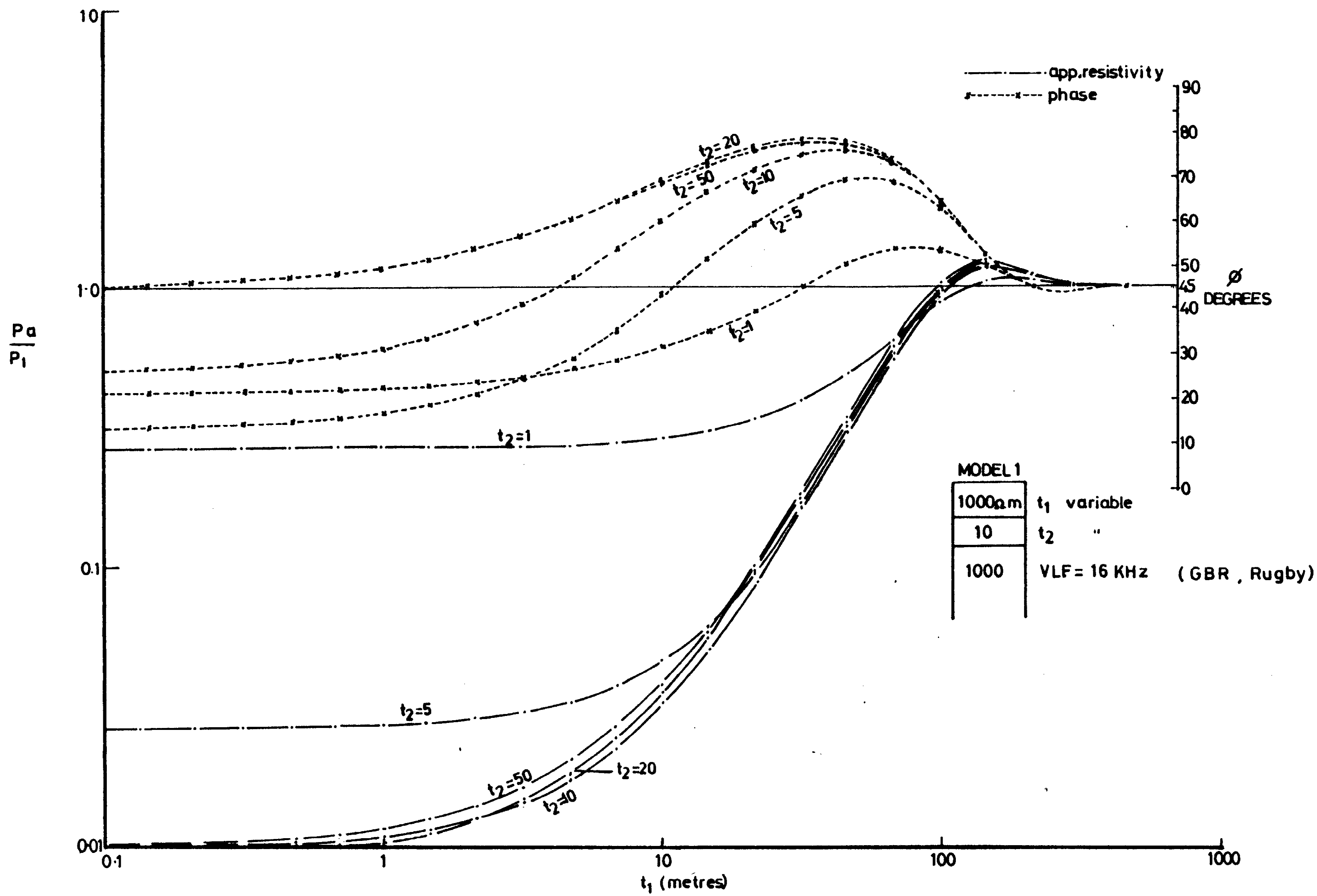


FIG.13 THE INFLUENCE OF DEPTH AND THICKNESS ON THE RESPONSE OF A CONDUCTIVE TARGET

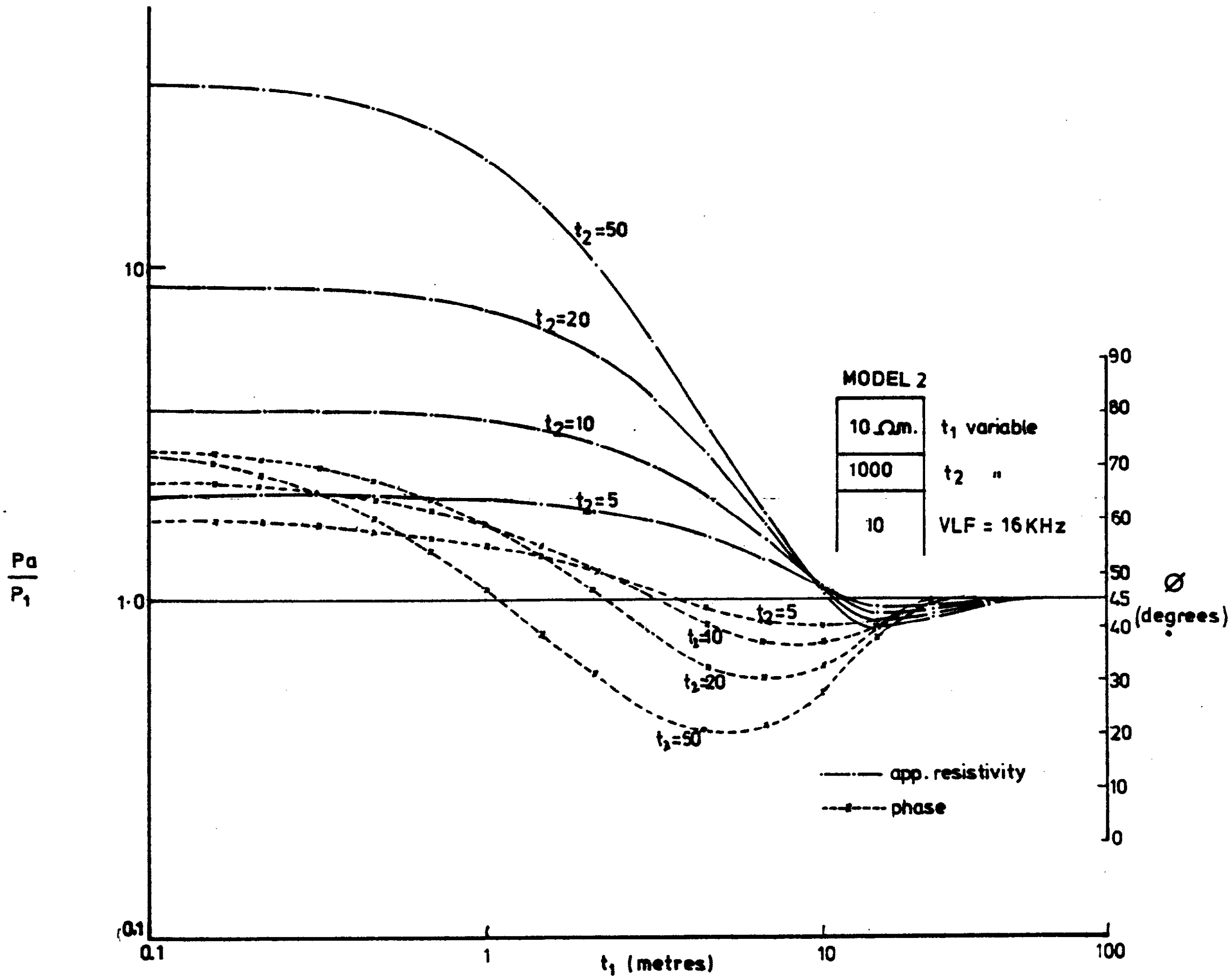


FIG 14 THE INFLUENCE OF DEPTH AND THICKNESS ON THE RESPONSE OF A RESISTIVE TARGET

the skin depth of the enclosing host rocks. In this respect the fixed frequency of the EM16R is a severe limitation, as it is not possible to vary the penetration or optimise the target response by adjusting the frequency. In the case of Model 1 at a depth of 100 m, the optimum frequency would be 900 Hz not 16 kHz. However, it is possible at the pre-survey stage to determine over what range of target depth (t_1) and thickness (t_2) an anomalous response can be expected, bearing in mind that a 1-D model will give an optimistic estimate of the detection limits. This can be done by studying the variation of apparent resistivity and phase as a function of target depth and thickness for a fixed VLF operating frequency (see Figs. 13, 14).

For Model 1, it is apparent that in each case, the maximum depth of detection is of the order of 80 m. This assumes that anomalous values of both ρ_a and phase are required, and that noise is not in excess of 10% of background values. The phase response is more sensitive to target depth and thickness than apparent resistivity but saturation effects occur in both responses for the larger values of t_2. This effect is a major disadvantage, as it detracts from the reliability of large target thickness determinations. However, the sensitivity of the method to thin conductive layers at depth should be noted.

It is clear from these theoretical considerations that the behaviour of apparent resistivity and phase at VLF, is complex and that only broad guidelines can be drawn on the relationship between skin depth and detectability. The results confirm that too small or too large a skin depth can both result in non-detection of a resistive target, but that excessive penetration is unlikely to have a serious effect on the detection of conductive targets.

CONCLUSIONS

Although the VLF-EM technique in mineral exploration is well established, the VLF resistivity method has received less attention. Field evaluation studies have shown that the technique enjoys the same operational advantages concerning speed and portability, and is more suited than VLF-EM for mapping broad flat lying conductors, and abrupt changes in conductivity associated with geological contacts.

By combining VLF-R and VLF-EM measurements, the electromagnetic field is more adequately sampled, and the scope of detectable targets is widened. Further, the additional information provided by VLF-R data on the geoelectric section can aid the interpretation of VLF-EM surveys.

The potential for mapping resistive ores has not been established except in an indirect sense. Nevertheless when compared with conventional DC methods, the VLF-R technique can offer some important advantages:

(1) Sampling is localised ($\sim 20\ m^2$); conductivity and thickness variations of limited lateral extent can be successfully resolved.

(2) In simple overburden situations reliable estimates of layer conductivities and thickness can be derived from a single data set. To obtain the equivalent information from a DC sounding would require a series of measurements and might take upwards of ½–1 hour.

(3) Large depths of investigation can be achieved in resistive environments, without the operational inconvenience normally associated with DC methods.

(4) The productivity of measurements is extremely high; between 100–200 stations a day can be occupied by a two man crew using tape and compass surveying.

The principal disadvantages of the technique relate to interpretational ambiguities associated with the complex behaviour of surface impedance at VLF, and the fact that the operator has no effective control over the depth of investigation. In areas of high surficial conductivity skin depth attenuation may render the method unsuitable. In resistive environments the penetration may be excessively large. Theoretical model considerations have confirmed that both conditions can result in non-detection of resistive targets, but that excessive penetration should not seriously affect the resolution of conductive targets, due to the compensating decrease that occurs in apparent skin depth. The inability to optimise target response by varying the operating frequency is a major disadvantage of the method. It seems unlikely that any improvement could be made in this direction without the use of a portable controlled source and major changes in instrument design and operating procedure.

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