J. Geomag. Geoelectr., **32**, Suppl. I, SI 141–SI 150, 1980

Magnetovariational and Magnetotelluric Investigations in S. Scotland

V. R. S. HUTTON and A. G. JONES*

Department of Geophysics, University of Edinburgh, Edinburgh, U. K.

(Received November 22, 1977; Revised January 23, 1978)

A two-dimensional array of 20 Gough-Reitzel magnetometers was operated over S. Scotland in 1973 and in 1974–5 magnetotelluric and magnetovariational observations in the period range 10–10,000 s were made in the same region. In this paper, the analyses of the magnetic data from both studies are presented in the form of induction vectors and hypothetical event contours. They suggest that the lateral variations in electrical conductivity structure associated with the Eskdalemuir anomaly are more complex than suggested by earlier studies. A marked discontinuity in electrical structure is apparent in a narrow belt parallel to and south of the S. Uplands fault. This belt is associated with a major gravity anomaly and with steep gradients in the seismic profile at crustal depths. Another discontinuity is indicated near the Northumberland Basin. Representative examples of the magnetotelluric analysis and of one-dimensional Monte Carlo inversion of the M-T data are presented for the three regions separated by these discontinuities. They show that the conducting zone associated with the Eskdalemuir anomaly is at a depth greater than 24 km, while on either side of this region, there are good conductors within crustal depths.

1. Introduction

The tectonic history of S. Scotland is currently a subject of much interest. The existence of an ocean—the Iapetus—in this region during early Palaeozoic times is now generally accepted on geological grounds (DEWEY, 1974; PHILLIPS *et al.*, 1976) and there is convincing palaeomagnetic evidence (BRIDEN *et al.*, 1973) that the separation between the continental masses of Scotland and England was eliminated by the end of the Caledonian orogeny. The plate tectonic processes associated with the Iapetus closure are, however, still uncertain and many tectonic models have been postulated to explain the surface geology (MOSELEY, 1977).

Some knowledge about the deep structure in this region has resulted from recent geophysical studies. For example, the Lithospheric Seismic Profile in Britain (LISPB) has indicated that the Moho discontinuity changes in character from a well-defined transition under the northern part of the Midland Valley to an ill-defined one under the Southern Uplands (BAMFORD *et al.*, 1976, 1978). The seismic section published by

* Present address: Institut fur Geophysik der Westfalischen Wilhelms Universitat, D-4400 Munster/Westf., West Germany.

these authors also shows that the top of the 6.4 km s^{-1} refractor dips sharply from about 7 km to more than 14 km under the S. Uplands fault, where LAGIOS and HIPKIN (1979) have found a tectonically significant gravity anomaly.

Prior to the studies reported in this paper, electromagnetic induction techniques had been used in this area by several workers. JAIN and WILSON (1967) interpreted their magnetotelluric observations from Eskdalemuir using curve fitting techniques. This yielded a three-layer geo-electric section in which there was a middle conducting layer with its upper interface at a depth of about 10 km. Interpretation of similar observations across the Irish Sea from Stranraer also gave a conductive zone at lower crustal depths. Magnetovariational observations, by EDWARDS *et al.* (1971) and others, have been interpreted in terms of an anomalous Southern Uplands conductor at either lower crustal or upper mantle depths. BAILEY and EDWARDS (1976) have more recently used Bailey's hypothetical event technique to suggest that this anomaly may be caused by "unusually low resistivity in rocks presently *in the lower crust* which formed part of a 'Proto-Atlantic' oceanic crust in the late Palaeozoic".

A two-dimensional array of Gough-Reitzel magnetometers has now been operated over southern Scotland and magnetotelluric soundings have been made at 13 locations across and along the region of the anomaly, referred to by previous workers as the Eskdalemuir Anomaly.

2. Data Acquisition and Analysis

The locations, at which the Gough-Reitzel 3-component variometers were installed and operated simultaneously for approximately three months between 1973–4, are shown on the map of S. Scotland—Fig. 1. The magnetotelluric sites are indicated by crosses on the same map—in this case, single station observations were made, a typical recording

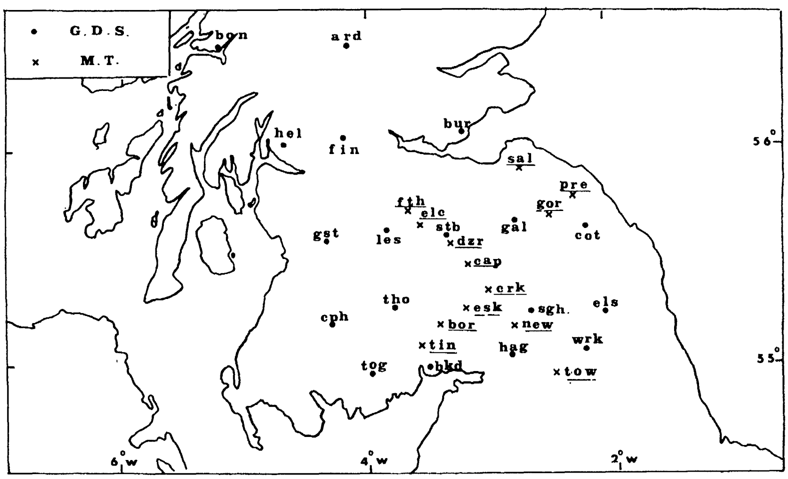


Fig. 1. Map of southern Scotland showing the location of: (a) the Gough-Reitzel magnetometer sites ●. (b) the magnetotelluric sites ×, names underlined.

interval at any one site being approximately 20 days for observations of periods in the 10 s to 24 hr range. Variations of the vertical component of the magnetic field, as well as the horizontal magnetic and electric field variations required for the magnetotelluric analysis, were recorded at these 13 M-T sites.

As the Gough-Reitzel magnetometers have a sensitivity of about 1 nT (Gough and Reitzel, 1967) and a digitisation interval of 20 s was used in this study, useful magnetovariational data was obtained from the array sites for periods $T>200$ s. Both fluxgate and Jolivet (1966) magnetic sensors were employed in the magnetotelluric system which has been described by Jones (1977). A circuit diagram has been published by Hutton (1976, Fig. 13).

Several techniques have been applied to the interpretation of data from these two investigations. In this paper emphasis is placed on the presentation and interpretation of the magnetovariational data using techniques which could be applied to both studies and by which a unified interpretation could be made of observations in the overlapping period range. The mapping of induction vectors and of hypothetical event contours suitably satisfy these objectives. A full account of the magnetotelluric study is published elsewhere (Jones and Hutton, 1979 a, b). Examples of the results of the M-T data anal-

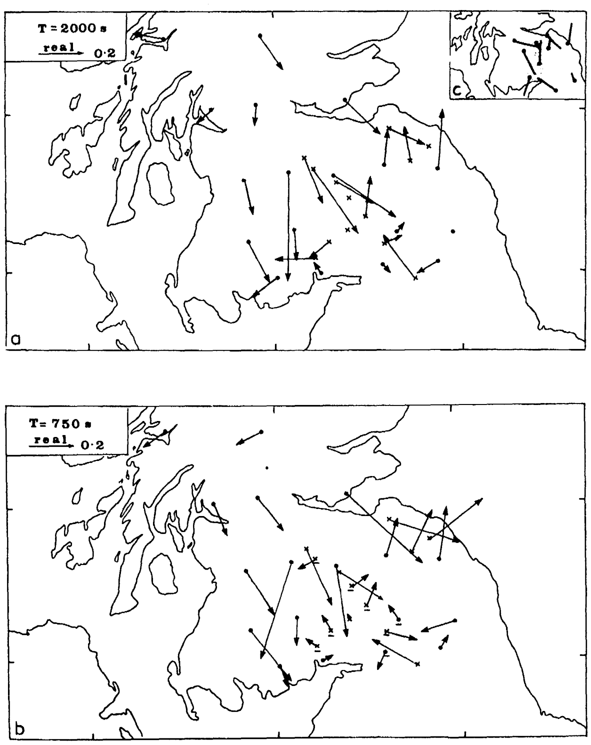
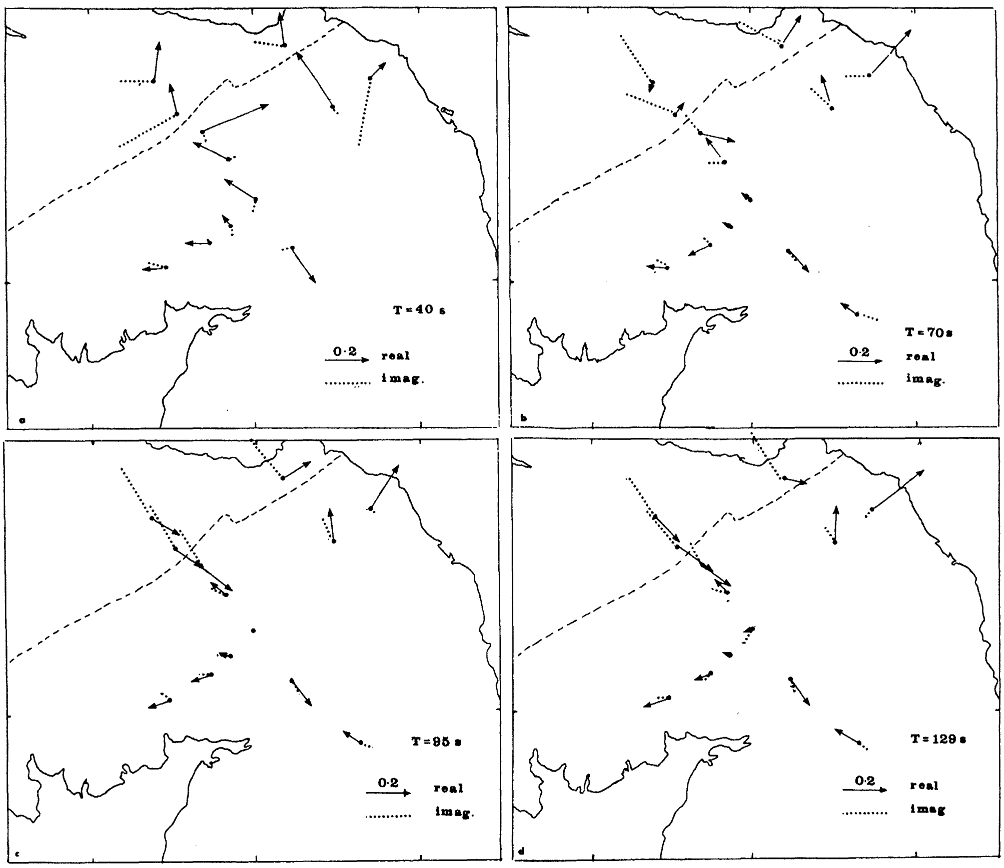


Fig. 2. The real 'Parkinson' vectors for (a) T=2,000 s and (b) T=750 s. The inserted Fig. 2 (c) has been redrawn from Edwards *et al.* (1971). It shows (a) their real 'Parkinson' vectors for T=40 min and (b) their proposed conductivity anomaly—dotted region.

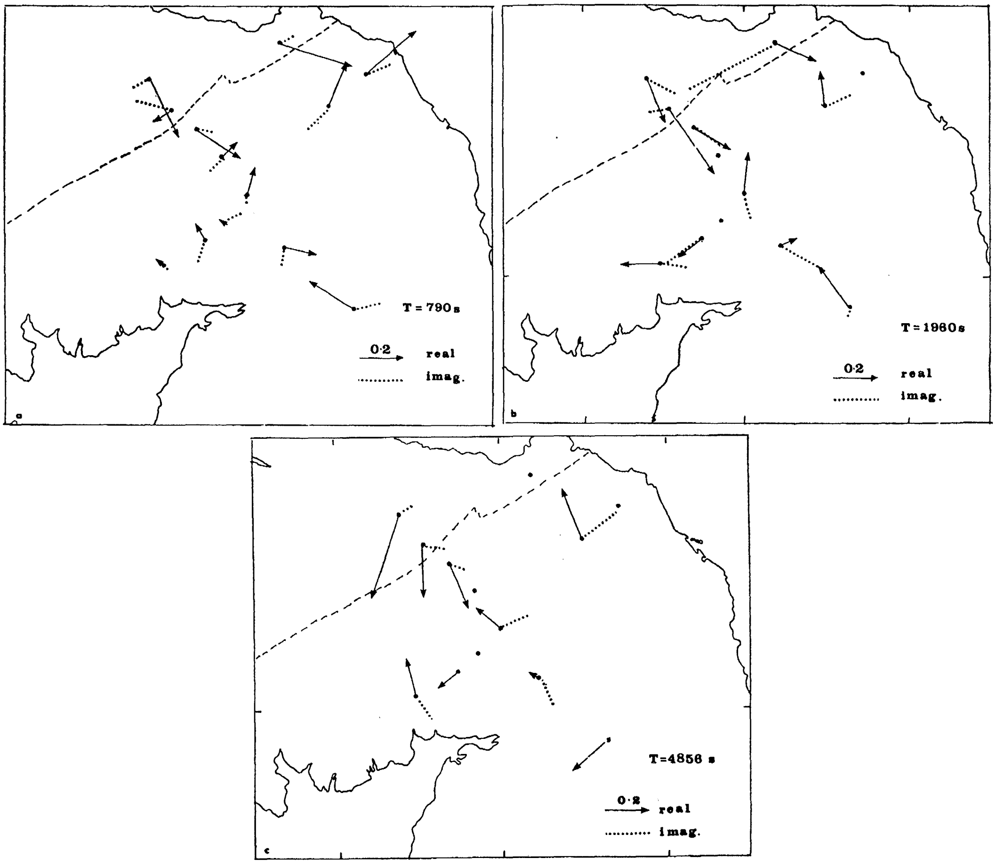


(a)
Fig. 3

ysis and of one-dimensional Monte Carlo inversion are presented here to illustrate the complementary nature of the two types of study and as an aid to the understanding of the magnetovariational results. A full account of the data analysis procedures is given by JONES (1977), who applied rigorous acceptance criteria to all the single station data from the M-T sites.

3. Magnetovariational Data

The real induction vectors from both studies are presented in Fig. 2(a) for T=2,000 s, and Fig. 2(b) for T=750 s. Following the Parkinson convention, their directions have been reversed so that they point towards current concentrations. The insert in Fig. 2(a)—Fig. 2(c)—has been redrawn from EDWARDS *et al.* (1971) and shows their real induction vectors for T=40 min and also a dotted region to indicate the strike of their proposed anomalous conducting layer. While, in general, the interpretation of our induction vectors for 2,000 s does not differ greatly from those of the earlier study, our map for



(b)

Fig. 3. Real and imaginary 'Parkinson' vectors for (a) T=40–129 s and (b) T=790–4,856 s. The location of the Southern Uplands Fault is denoted on each map by the dashed line.

the shorter period—Fig. 2(b)—includes a number of sites, denoted by underlined dots and crosses, at which the behaviour of the induction vectors is not compatible with a single conducting region as indicated in Fig. 2(c). Instead there is some suggestion at this period that there may be two regions of current concentration. Some insight into the complex structure responsible for the behaviour of these induction vectors can be obtained by following the change in pattern of the vectors as the period increases from the shortest period for which reliable data are available. The real induction vectors obtained at the M-T sites for periods in the range T=40 s to T=4,856 s are shown in Figs. 3(a) and (b). The location of the Southern Uplands Fault (S.U.F.) is also marked on each of the maps presented in these figures. At a period of 40 s, the vectors indicate current concentrations both to the north of the S.U.F. and to the south of Scotland. As the period increases, the vectors near the S.U.F. rotate until for periods of 95 s and 129 s, there are well-defined reversals in the directions of the vectors in (a) a narrow belt parallel to and south of the S.U.F. and (b) between the two most southern stations. The maps of vectors for periods of 790 s, 1,960 s, and 4,856 s also show changes in both the amplitude and direction of the real induction vectors at most sites. A current concentration near the S.U.F. appears to exist at all periods but that in the region of the Scottish border appears to be replaced at the longer periods by one further south, as indicated by the behaviour of the most southern vector. The existence of at least two anomalous regions is also suggested by the hypothetical event contours shown in Figs. 4(a)–(c). Using the technique first suggested by BAILEY *et al.* (1974), contours of equal vertical magnetic field amplitude have been drawn—for each figure—for a hypothetical uniform horizontal inducing field in a direction perpendicular to the strike of the major geological features of the region. In each map, large negative gradients in Z amplitude occur (a) near the S.U.F. and (b) near the Scottish-English border, and are compatible with lateral discontinuities in electrical conductivity structure in these two regions.

4. Magnetotelluric Data

Plots of apparent resistivity amplitude and phase as a function of period for 9 of the 13 sites could be classified into three distinct types, such as shown in the examples in Fig. 5. Data from the other 4 were rejected. Reference to Fig. 5 shows that stations FTH and SAL lie north of the S.U.F. and stations NEW, BOR, and PRE are in the Southern Uplands. Station TOW is in the Northumberland Basin. The errors associated with the estimates plotted in these figures are omitted in this presentation for the sake of clarity. It should also be noted that some of the average values plotted in Fig. 5, e.g. the 3 shortest period averages at SAL, are averages of 3 or less estimates. These values were not considered in the subsequent data inversion. For one station in each group, the results of a one-dimensional 3-layered Monte Carlo inversion (JONES and HUTTON, 1979 b) of the acceptable 'rotated major' apparent resistivity and phase data are shown schematically in Fig. 6. The method of rotation used in this study follows closely that suggested by REDDY and RANKIN (1974). The 'rotated major' direction can be regarded as equivalent to that of E-polarisation at stations on the conductive side of a vertical interface and of H-polarisation on the resistive side. The differences between the profiles presented in this figure indicate that there are major lateral variations in electrical conductivity structure in this region.

5. Conclusions

1) North of the Southern Uplands Fault there is conducting layer ($\sigma \sim 2\text{–}5 \times 10^{-2}$ S m^{-1}) extending from a depth of about 10 km to 45–65 km.

2) In the Southern Uplands, the whole of the crust is resistive and there is a good conductor *at upper mantle depths.*

3) A very good conducting layer $\sigma \sim 5 \times 10^{-1}$ S m^{-1} exists at TOW in the upper crust.

4) Lateral variations in electrical conductivity structure, as indicated by the magnetovariational data, are most marked in the narrow belts separating the three regions described in 1)–3) above. The possibility that this may be indicative of sharply dipping conductors connecting the three regions is now being examined by further mathematical

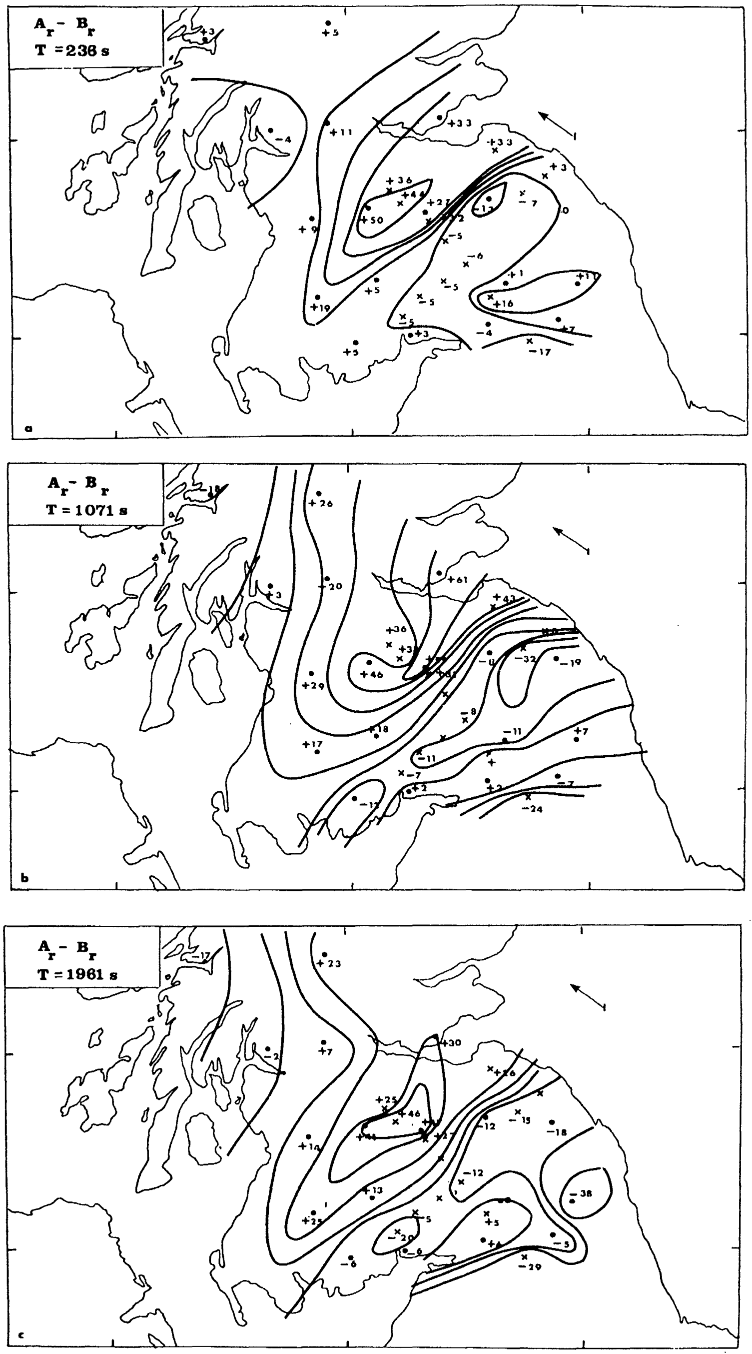


Fig. 4. *Z* contours for a unit regional horizontal inducing field directed as shown by the arrow drawn in the North Sea, i.e. approximately perpendicular to the strike of the major geological features of the area. (a) T=236 s, (b) T=1,071 s, and (c) T=1,961 s. The contour interval is 0.10 nT.

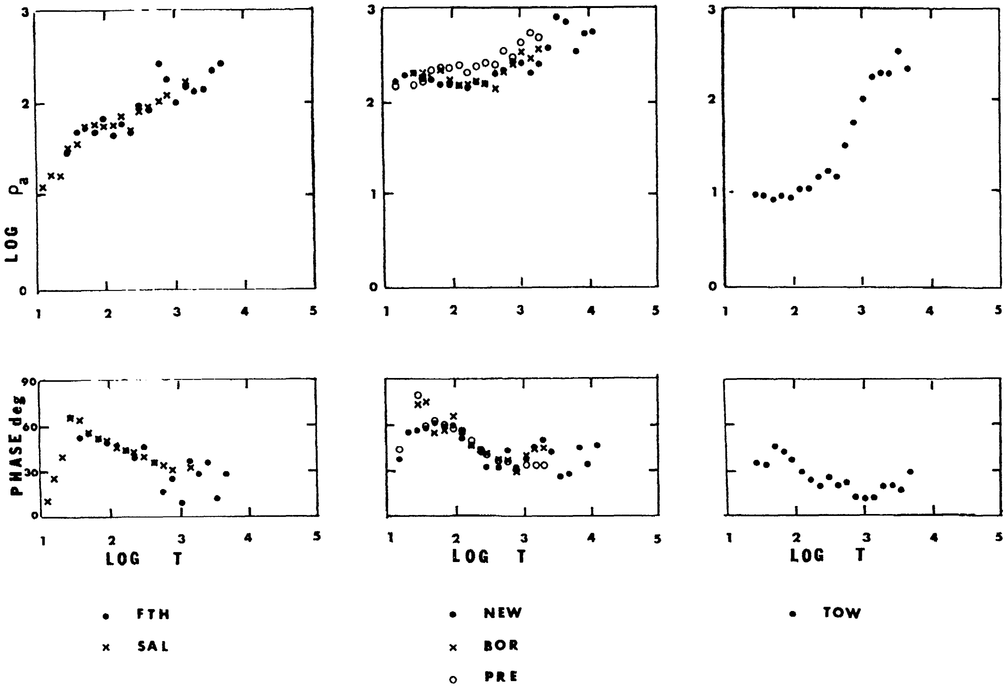


Fig. 5. Variation of log (apparent resistivity) and of phase with log (period) for several sites. FTH and SAL are north of the Southern Uplands Fault. NEW, BOR, and PRE are in the Southern Uplands and TOW is in the Northumberland Basin. ρ_a: Ωm, T: sec.

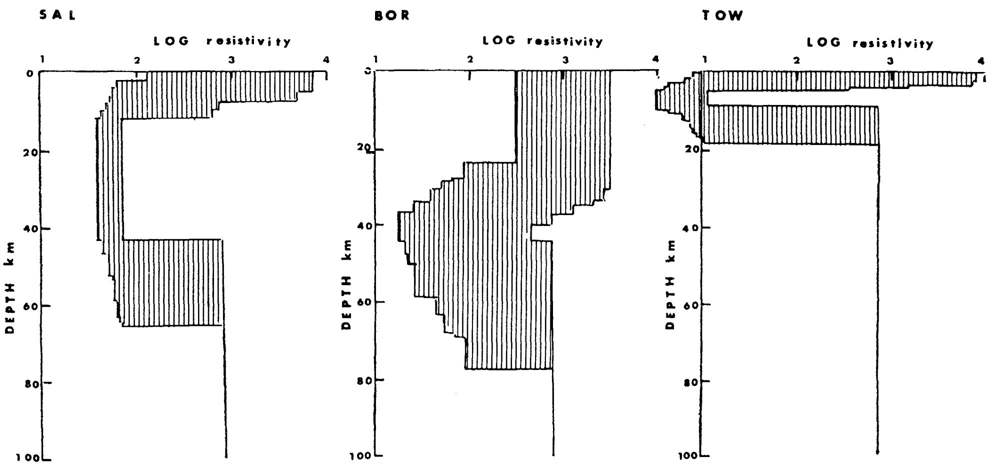


Fig. 6. A schematic representation of the resistivity-depth profiles obtained by one-dimensional Monte Carlo inversions of the apparent resistivity and phase data for SAL, BOR, and TOW. Note that the inversion of the BOR data demands a low resistivity middle layer (σ<90 Ωm). Resistivity: Ωm.

modelling of the data.

5) The marked lateral variation in electrical conductivity structure a few kilometers south of the Southern Uplands Fault occurs in a region where the top of the 6.4 km s^{-1} seismic refractor dips sharply and where there is a well-defined gravity low. The geophysical significance of these associations and also of the interpretation of the conductivity estimates which have been obtained will be discussed in a subsequent paper.

The authors acknowledge the support for this project of the Natural Environment Research Council, both in the form of research grants and of a studentship to one of us (A. G. J.). They are also indebted to Dr. D. I. Gough for the loan of his magnetometers, to Dr. J. Sik, Mr. S. Chita, and many others who participated in the fieldwork programme and to Dr. D. Rooney for assistance with the processing of the array data. The project could not have been undertaken without the willing cooperation of the many people who provided facilities for our observations.

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