Transactions of the Royal Society of Edinburgh: Earth Sciences, **84**, 197–202, 1994 (for 1993)

Geophysical surveys of the East Kirkton Limestone, Viséan, West Lothian, Scotland

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ABSTRACT: Magnetic and resistivity geophysical surveys conducted across the only known exposure of the East Kirkton Limestone have produced new information upon its extent. This is important to determine because of its unique faunal assemblage and possible hot spring deposition, suggesting a potential for precious metal mineralisation. Magnetic anomalies are attributed to basalts within the Bathgate Hills Volcanic Formation. Modelling of the magnetic data demonstrates a general dip to the west of about 25°, and the presence of significant local faulting. Modelling of vertical electrical sounding data shows the East Kirkton sequence (the limestone and associated beds) to be a low resistivity layer within the more highly resistive volcanic sequence. The East Kirkton sequence is seen to deepen to the west, and also to the north probably by faulting. Therefore the present exposure is the only near surface occurrence of the East Kirkton Limestone locally, but within the area of the survey no lateral limits to the formation are observed.

KEY WORDS: Geophysics, hot springs, magnetic surveys, mineralisation, resistivity surveys, Lower Carboniferous.

The East Kirkton quarry at Bathgate (Fig. 1) is the only known exposure of the Lower Carboniferous East Kirkton Limestone, which occurs within the Bathgate Hills Volcanic Formation as part of a *c.* 15 m thick largely sedimentary sequence observed within the quarry. Lithostratigraphically the East Kirkton sequence (EKS) can be divided broadly into three beds: the East Kirkton Limestone, forming over 50% of the sequence, overlain by the Little Cliff Shale and Geikie Tuff. Full details of the stratigraphy and location of the East Kirkton Limestone are given by Rolfe *et al.* (this volume). Overall, the sequence is a varied succession of thin, interbedded, lacustrine limestones, shales, sandstones, ironstones and tuffs, thought to have formed in a hot spring environment (e.g. Hibbert 1836; Muir & Walton 1957). Current opinion is divided regarding the amount of geothermal input to the East Kirkton water body (McGill *et al.*, this volume; Walkden *et al.*, this volume).

Bedding planes seen at outcrop dip at 15–25° to the W. Various hypotheses exist regarding the extent of the East Kirkton Limestone beyond the quarry: (1) it continues N beneath a thin glacial cover as shown on the one-inch geological map (Scotland Sheet 31); (2) subcrop to the N is limited due to faulting at the N end of the known exposure (Stephenson & Monro 1986); or (3) the sequence was deposited in an isolated lagoon forming only a small lens of sediment (Geikie 1861).

Magnetic and resistivity surveys were undertaken to determine the structure and extent of the EKS in the vicinity of the quarry. Exploration was undertaken mostly W (down dip) and to the N. Housing development prevented work to the S. The results are of use in future prospecting of the East Kirkton Limestone for precious metal mineralisation (Stephenson *et al.* 1983), or with regard to its rare fossil assemblage (Rolfe *et al.* 1990).

1. Geophysical approach

Our aim was to determine the subsurface structure of the EKS using the East Kirkton quarry as a reference point. Given the presence of basaltic lavas and clastic volcanics above and below the sedimentary sequence, it was anticipated that there would be a strong contrast of magnetic and electrical resistivity properties between the EKS and volcanics. Borehole information was made available by the National Museums of Scotland, permitting calibration of the geophysical results but only to rather limited depths (typically 10 m, maximum 33 m).

2. Magnetometer survey

The total magnetic field intensity was measured along 12 E–W traverses across the quarry and its projected continuation along strike to the N. The contoured results are plotted in Figure 2. Large magnetic anomalies in the W of the survey area can be correlated with basalts at outcrop, and in the NE with a quartz dolerite sill. Low anomaly values are obtained within the East Kirkton quarry and to the N of the quarry, where the anomaly trend coincides with the N–S strike of the strata. Although this suggests that the EKS may continue to the N at very shallow depth, it is absent from the line of boreholes GC3-6 (Fig. 3). A localised, high anomaly occurs immediately W of the quarry. This correlates with the basalt seen immediately above the EKS, but the limited extent of the anomaly suggests that there is local structure affecting the basalt.

Magnetic susceptibility measurements of borehole samples (Fig. 4) indicate that the largest susceptibility contrast is between basalt and other lithologies. Thus the distribution of basalts is the major control upon the local magnetic field.

Remanent magnetisation of the highly magnetic basalts was measured; it showed a very low angle inclination. This would be expected for Lower Carboniferous lavas extruded in equatorial latitudes.

Using these values, a model profile across the East Kirkton quarry was determined using the GRAVMAG computer program. The model was constructed along line Z, a dip line crossing the anomaly immediately W of the quarry (Fig. 2) and passing near to BH1 (Fig. 3). The model (Fig. 5) shows two basaltic horizons. The upper one is the unit seen at outcrop W of the road. The lower one (7 m thick) immediately overlies the EKS and is downfaulted by at least 7 m near to the W side of the quarry. Other horizons cannot be distinguished magnetically. These results clearly demonstrate a general dip to the W of about 25°, and the presence of significant local faulting.

The one-inch geological map shows the EKS to be underlain by basalts (Fig. 1), which would be expected to generate a significant anomaly near to the subcrop of their contact with the EKS to the E of the quarry. This anomaly is clearly absent from our magnetic data (Fig. 2). We conclude that either the rocks beneath the EKS are not basalts but perhaps clastic volcanics, or that these basalts have lost their magnetic properties perhaps due to hydrothermal alteration. Our dataset does not permit us to distinguish between such models.

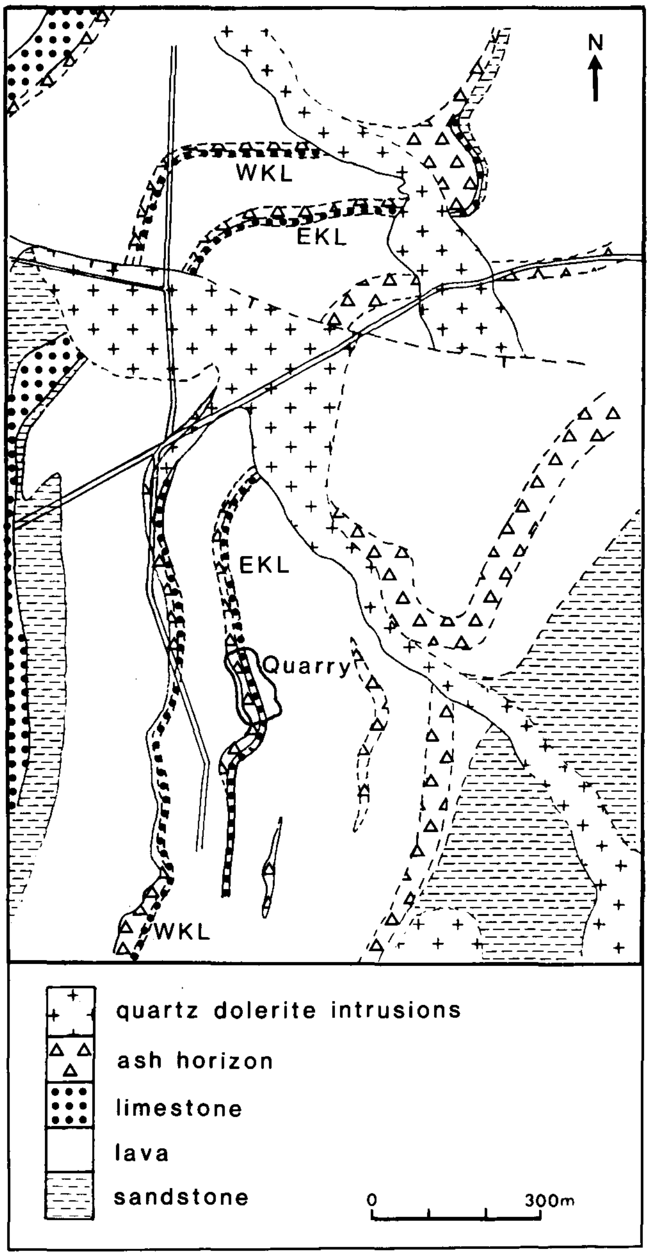

Figure 1 Geological map of the East Kirkton quarry locality based on Scotland Sheet 31. EKL = non-marine East Kirkton Limestone; WKL = marine West Kirkton Limestone.

3. Resistivity survey

Four electrical resistivity vertical soundings were conducted using expanding Wenner arrays (VES1–VES3 of Fig. 3) and an Offset Wenner array (VES4). Maximum electrode spacings were 40, 100, 64 and 64 m respectively. Computer modelling was undertaken for each sounding, assuming a one-dimensional variation of ground electrical properties. Each model is attributed to the centre point of the array. The field data and results of VES1 are shown in Figure 6 to illustrate our data and the goodness of fit obtained in the modelling procedures. The models of all four soundings are shown in Figure 7. A constant separation traverse (points 1–6 on Fig. 3) was carried out to determine changes in depth to the N of the quarry.

Resistivity of rock ranges over several orders of magnitude and is one of the most variable of rock physical properties. Most rock-forming minerals are insulators and electrical current is mainly carried through rock by the passage of ions in pore waters. Therefore porosity is the main control of resistivity, which generally increases as porosity decreases. Crystalline rocks may be conductive to some extent due to water-filled cracks and fissures. Identification of lithology is not possible on the basis of resistivity data alone, correlation with outcrop and/or boreholes is required.

At East Kirkton we attribute generally low, but highly variable, resistivities modelled at surface to soils and/or boulder clay. At depth the main resistivity contrast was expected to be between the highly resistive volcanics of the Bathgate Hills Volcanic Formation and the low resistivity of the mixed sedimentary EKS. Resistivities of much less than 100 ohm-m modelled at depth can be correlated with the EKS. High resistivities (480 ohm-m) above the EKS on VES1 and VES2 are correlated with the lower of two basalts of the magnetic model. High resistivities (typically over 400 ohm-m) beneath the EKS are consistent with the presence of volcanic rocks. Figure 7 is an attempt to correlate the results of VES1 to VES4. The lithological interpretations are based on modelled resistivity values and correlation with boreholes and the magnetic results. The correlation of units is entirely reasonable, particularly the contrast of the EKS and adjacent volcanic units. However, the assignment of lithologies to near surface layers and within the volcanics above the EKS must be treated with caution given the variability of resistivity values (see above).

The following points arise from the resistivity results:

(1) Comparison of VES1 and VES2 confirms the significant westward deepening of the EKS shown by the magnetic interpretation.

(2) VES1, VES3 and VES4 are located broadly along strike from each other, but show the sub-EKS volcanics to deepen northwards. This was confirmed by the constant separation traverse. Thus the EKS may thicken. The resolution of the resistivity data does not permit us to distinguish between a northward deepening due to folding or faulting.

4. Discussion

The geophysical techniques used have produced models of subsurface structure at East Kirkton based upon different rock physical properties. The resistivity survey has shown the EKS to be a low resistivity unit between volcanic units of higher resistivity. The magnetometer survey has provided a model of basalts within the overall sequence. Both techniques show the EKS to deepen to the SW. The magnetic model (Fig. 5) shows this deepening to be a function of dip. However, significant local structure is superimposed on this general trend.

The modelled E–W magnetic profile crosses the local anomaly immediately W of the quarry. A fault is modelled near to the W edge of this anomaly and it is suggested that the N edge of the anomaly is also associated with faulting, especially since the EKL also appears to be displaced at this point. Borehole BH2, drilled close to the NW edge of the quarry (Fig. 3), does not penetrate basalt. Good exposure of the base of the quarry sequence, at its northern end, indicates no displacement although it is possible that quarrying has assisted natural erosion processes and

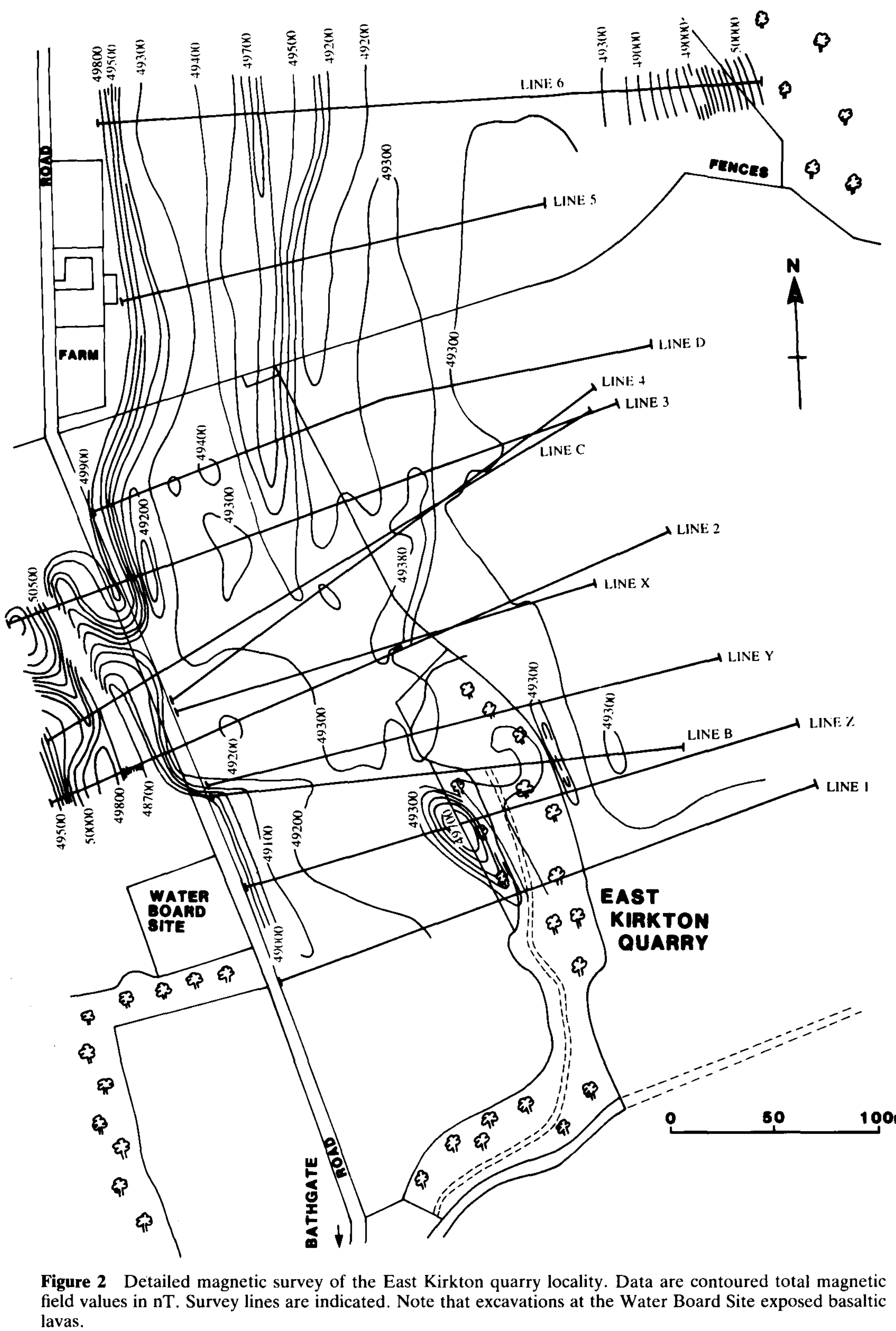

Figure 2 Detailed magnetic survey of the East Kirkton quarry locality. Data are contoured total magnetic field values in nT. Survey lines are indicated. Note that excavations at the Water Board Site exposed basaltic lavas.

removed the basalt capping the succession; backfilling obscures these exposures.

Comparison of the magnetic and resistivity results regarding units below the EKS is revealing. High resistivity values are consistent with the basalt lavas shown on the one-inch geological map to underlie the EKS and subcrop to the E of the quarry. However, the absence of an associated magnetic signature indicates that either these lavas are no longer magnetic or that clastic volcanics underlie the EKS. Therefore we use the general term 'volcanics' for this unit on Figure 7.

The resistivity modelling of the sub-EKS unit is also significant since it not only shows the top of the unit to deepen SW as expected, but also that its top (and so the base of the EKS) becomes deeper towards the N. The presence of local faulting seen at outcrop and in the magnetic model suggest that this deepening may be due to faulting.

No lateral limits to the EKS were identified within the area of the survey. It is seen to continue to the W and N, deepening and possibly thickening in both directions. Therefore, regarding the hypotheses outlined in our introduction, it would appear that locally the EKS occurs at surface only at the quarry, that Geikie's localised model is refuted at the scale of the survey, and that deepening to the N of the EKS could be fault controlled. The presence of such faults could be an important factor in any precious metal mineralisation.

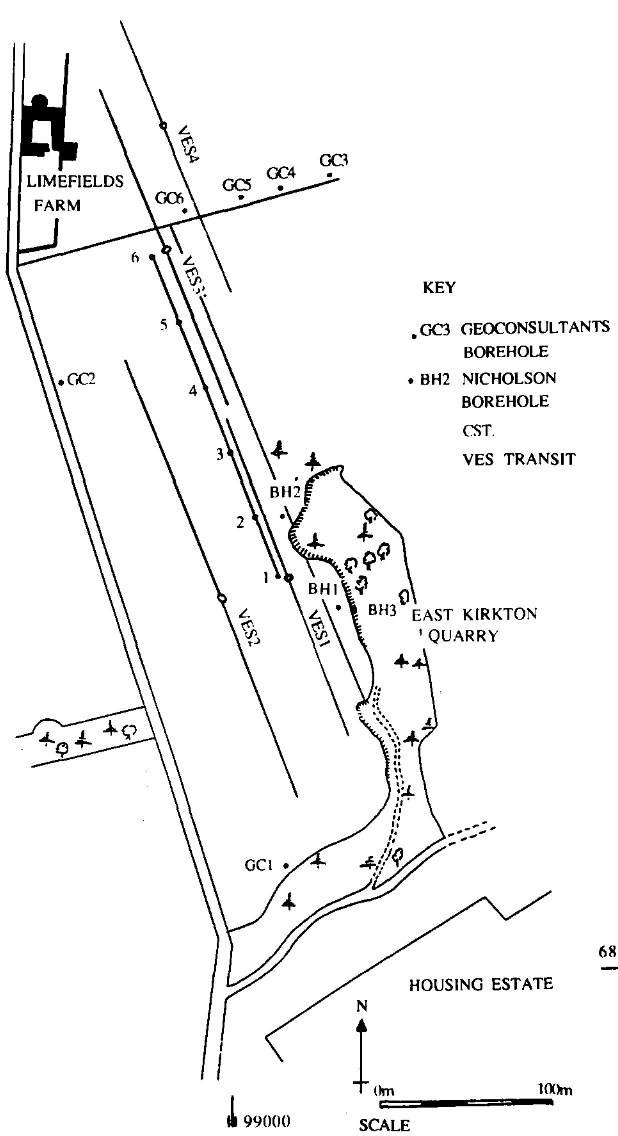

Figure 3 Map of the resistivity profiles and boreholes used in this survey. VES1–4 are vertical electrical sounding profiles; the line marked 1–6 is a constant separation traverse profile. Boreholes are shown by labelled dots.

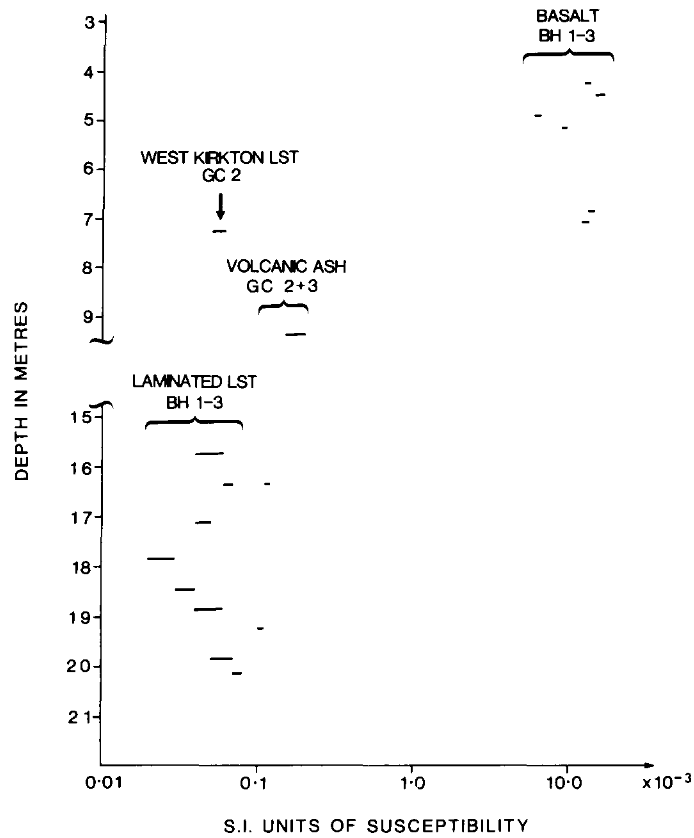

Figure 4 Magnetic susceptibility results for local lithologies determined form indicated boreholes. Note the logarithmic horizontal scale which is in SI units of susceptibility. LST = Limestone. See Figure 3 for location of boreholes.

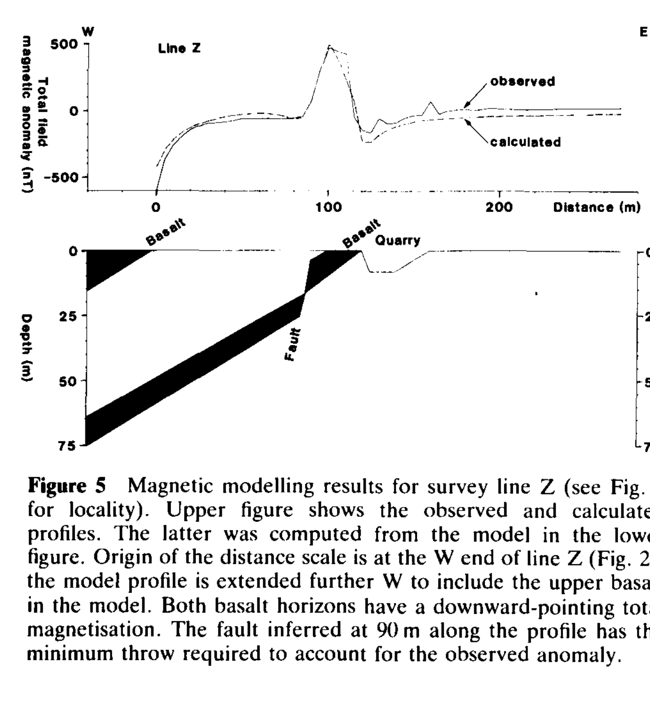

Figure 5 Magnetic modelling results for survey line Z (see Fig. 2 for locality). Upper figure shows the observed and calculated profiles. The latter was computed from the model in the lower figure. Origin of the distance scale is at the W end of line Z (Fig. 2); the model profile is extended further W to include the upper basalt in the model. Both basalt horizons have a downward-pointing total magnetisation. The fault inferred at 90 m along the profile has the minimum throw required to account for the observed anomaly.

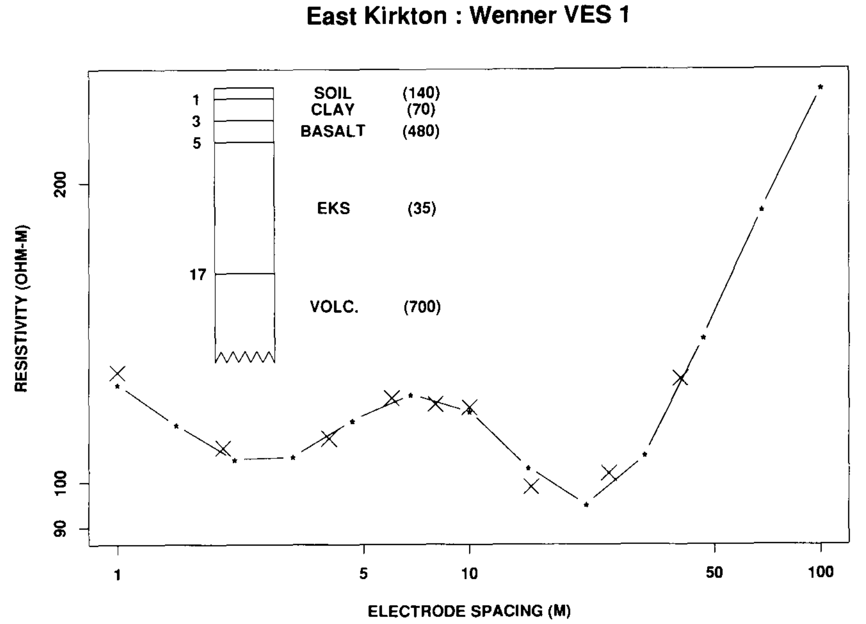

Figure 6 Comparison of the field data (crosses) of vertical electrical sounding profile VES1 (see Fig. 3) and final computed model curve (asterisks). The model is shown in the inset: depth in m, resistivities in ohm-m. EKS = East Kirkton sequence; VOLC = Volcanics.

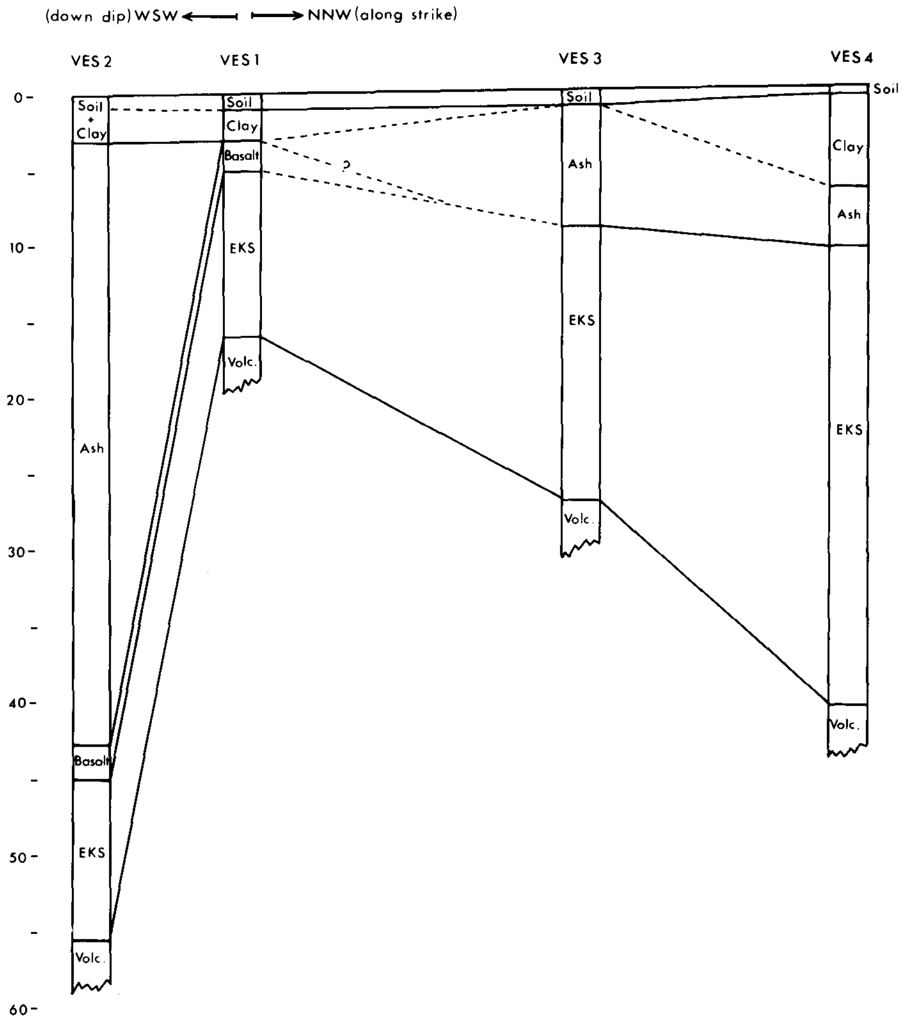

Figure 7 Correlation of the 1-dimensional depth models derived from the vertical electrical sounding profiles. Note: VES1 was sited immediately west of the East Kirkton quarry (see Fig. 3); boreholes GC5 and GC6, both located in the vicinity of VES3 and VES4, show a clay to weathered ash/tuff transition at depths of 5–10 m. EKS = East Kirkton sequence; Volc = volcanics.

5. Acknowledgements

This survey formed part of RARM's PhD research on the geochemistry and petrography of the East Kirkton Limestone, supervised by Dr Allan Hall and Dr Ian Rolfe. Both are thanked for discussions of these surveys. We are grateful for field assistance by a number of people including Peter Chung, Joe Crummy, Roger Hall, Chris McKeown and Susan Waldron. West Lothian District Council is thanked for access to the East Kirkton quarry. The staff from the National Museums of Scotland were most helpful with the provision of core samples and logged data from boreholes BH1-3 and GC1-6. Doyle Watts is thanked for assistance with magnetic susceptibility and remanent magnetisation measurements and for valuable discussion. We also thank Bob Cumberland and Sheila Hall for help with the figures.

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(*Published* 9 *February* 1994)