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Novel regularized inversion of VLF(R) data and coincident radar sections over a probable fault affecting carboniferous sedimentary rocks in the Saar region, Germany

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Abstract. Coal mining induced subsidence along the surface trace of faults has caused extensive damage and consequent expense in parts of the Saar, Germany. An ongoing CEC assisted project was established to determine an efficient strategy for the detection of fault traces, prior to undermining, involving geological mapping, lineament analysis and surface and borehole geophysics. We present VLF(R) and GPR (multi-frequency) results from three traverses, 10 m apart, crossing a suspected fault that was subsequently proved by inclined core drilling. The modelled resistivity distribution (VLF) indicates a dipping, blind conductive zone of limited depth extent, while the radar sections reveal a well defined anomalous zone separating contrasting lithologies on either side of the fault. Additional geophysical data (EM conductivity and DC gradient array mapping and sounding) provide supportive evidence of the faulting.

Extensive and costly damage to buildings and roads is being caused in several coal producing areas of the Saar, southwest Germany, following undermining and subsequent subsidence that propagates to the surface principally along pre-existing fault planes. The British Geological Survey and Saarberg, together with several German collaborative organizations, are engaged in part CEC funded research to determine an efficient procedure for accurately locating the fault traces and other weakness zones at the surface prior to undermining so that early remedial action may be taken.

Available techniques include the underground mapping of faults and their projection to surface, airborne optical scanning for lineament detection and a wide range of surface and borehole geophysical techniques. In this paper we compare the responses to a suspected fault zone of two of the geophysical techniques that have proved most successful to date: very low frequency resistivity measurements (VLF(R)) and ground probing radar (GPR). Brief reference is also made to supportive evidence provided by other geophysical techniques.

The present site was chosen for geophysical investigations because it is traversed by a clearly defined lineament that is almost coincident with a projected fault plane. Reconnaissance VLF(R) traversing, conducted by one of our German collaborators, indicated the presence of a linear conductive zone and this was considered worthy of detailed follow-up work.

Geology

The survey area is a generally flat lying grass meadow with a uniform gentle downslope to the northwest, perpendicular to the traverse direction. It has a variable soil cover, up to 50 cm thick. The rocks of the area comprise a sedimentary sequence of Stefanian B (Upper Carboniferous) age. Red, green and grey shales are predominant (about 70%) and may attain thicknesses up to nearly 100 m. Sandstone layers up to 30 m thick are interspersed throughout; these, occasionally forming packages, are mostly fine to medium grained but may become coarse grained and even conglomeratic. Intermittent coal seams (up to 2 m thick) and tonstein (thin layers of volcanic ashes) display remarkable uniformity and persistence across large distances and are used as marker horizons (Klinkhammer & Konzan 1967/1970; Bintz *et al.* 1979). Structurally the area lies within the Saar–Nahe Basin, on the northern limb of the NE–SW trending Saarbrücker Hauptsattel (Central Anticline), an overthrust formed during the Variscan orogeny (Schneider 1991). The strata dip to the NW at between 25° and 30°. Block faulting has formed a system of small horst and graben structures that are restricted by cross and oblique faults. One of the major cross faults in the present area is known as the Hahnwies; this displays downthrow to the west of some 60 m. The block faulting of strata dipping at low angles results in large horizontal displacements of their subcrop; hence the fault zones may be detected both directly (usually as a conductive feature) and indirectly (by the abrupt along-strike termination of a particular horizon).

The area has twice been undermined. In 1969 working of a 1.87 m seam of coal (the Lummerschied) at approximately 270 m depth, caused reactivation of the Hahnwies Fault with severe damage to a house (resulting in subequent demolition) approximately 500 m north of the present site. Mining of a deeper seam (the Wahlschied) commenced last year.

Detailed geophysical work

Three parallel survey lines were prepared, ten metres apart (0, 10S and 20S) and extending between 125 m and 175 m west of the grid origin (Fig. 1). These traverse lines are centred approximately on the projected trace of the Hahnwies Fault. The following data sets were acquired, generally at either 2.5 m or 5 m observation interval: shallow conductivity (Geonics EM31), two Schlumberger array vertical electrical soundings (VES), gradient array resistivity (60 m current electrode separation), total field and vertical gradient magnetics, VLF (both magnetic field and resistivity measurements) and GPR. The Scintrex IGS-2 equipment was used for the magnetic and VLF observations, the latter utilizing the Rugby, UK, 16kHz transmitter on a bearing of 320°. The VLF(R) data were collected with 5m dipoles aligned on this same bearing.

The Pulse Ekko IV system was used for the GPR work, employing antennae frequencies of 25, 50 and 100 MHz, with antennae separations of 3, 2 and 1 m respectively, in the perpendicular-broadside array (i.e. the long axis of both antennae is perpendicular to the traverse line). An observation interval of 0.5 m was used with the 25 MHz system and 0.25 m for the other frequencies. The anticipated vertical reflector resolution was between about 2 m (25 MHz) and 0.5 m (100 MHz). While features of smaller dimensions can produce diffraction and interference patterns recognizable in the GPR sections, they will not be uniquely identifiable.

The conversion from time to depth in the radar sections is based on the velocity of 0.07 m/ns. This represents the average vertical speed of electromagnetic transmission through the rocks investigated and this value was derived from four constant midpoint stacks at sites along Line 0. Data processing has been confined to routine corrections for time zero drift, for signal dewow and simple two-point horizontal and vertical filtering. Topographic corrections were not necessary.

Numerous high-voltage transmission lines, microwave repeater stations and radio transmitters occupy the immediate vicinity and it was predicted that interference would prove troublesome with some of the geophysical techniques.

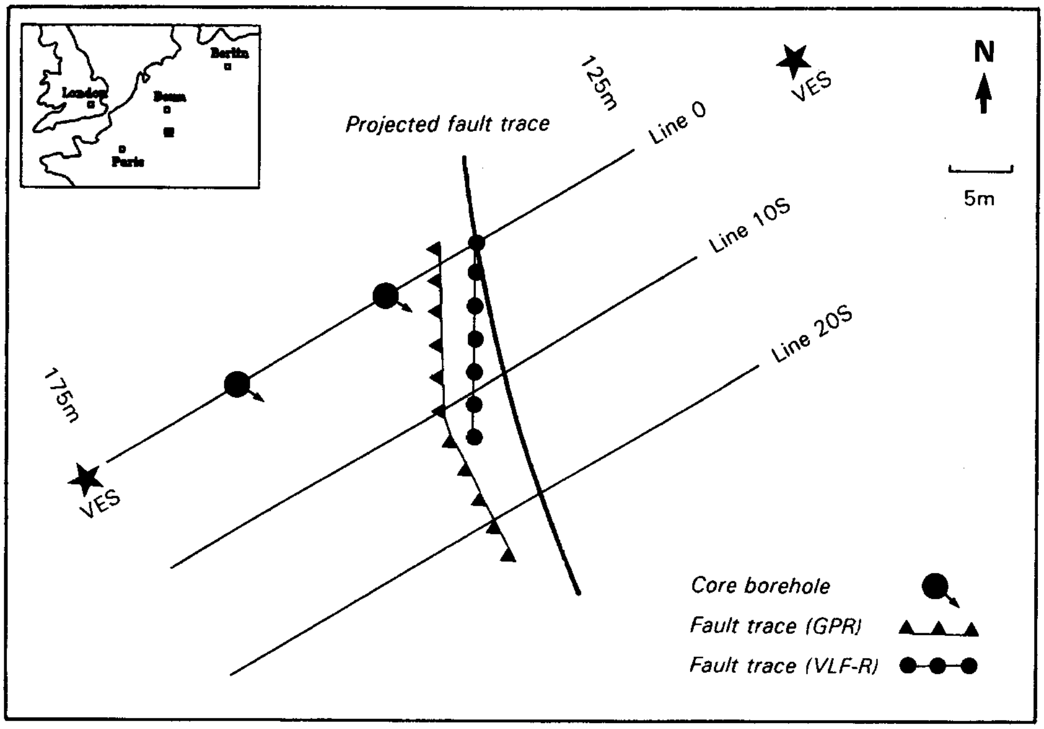

Fig. 1. Location diagram.

Modelling of VLF(R) profiles

VLF(R) profiles are normally used for qualitative assessments of subsurface resistivity variations for integration with other geophysical studies. The VLF data, particularly the VLF-R measurements however, contain potentially detailed information on the resistivity cross-section. In order to extract such information it is necessary to consider two-dimensional modelling and inversion of VLF (plane-wave) fields. This subject has recently been investigated by Beamish (1994) and only a brief outline is given here.

VLF-R profiling is a single frequency plane-wave EM method. The use of a single frequency provides only a limited vertical resolution while the high observational density provides the potential for high lateral resolution. In a two-dimensional assessment of the problem, it is the *overall* (both vertical and lateral) configuration of resistivity variations that control the resolution that can be achieved. Such resolution is, of course, case-specific.

The VLF technique has a directional limitation and the difficulties of interpretation that ensue have been extensively discussed by Tabbagh *et al.* (1991). In order to be consistent with a two-dimensional assessment, the profile data must conform to one of the two modes of induction which are referred to as TE (electric field parallel to strike) and TM (magnetic field parallel to strike). In the present case the data characteristics indicated that the appropriate two-dimensional mode was TM (Beamish 1994).

In two-dimensional modelling we seek a resistivity cross-section that fits the measured data. Inverse methods allow us to automate such procedures. Regularized inversion schemes have been developed to overcome the problem of equivalence (lack of uniqueness) inherent to *all* EM sounding methods (Constable *et al.* 1987). Such schemes provide us with a smoothly varying resistivity cross-section. The smooth cross-section will be the resistivity distribution *with the minimum amount of structure* that fits the observations. Such minimum structure models, although they cannot contain

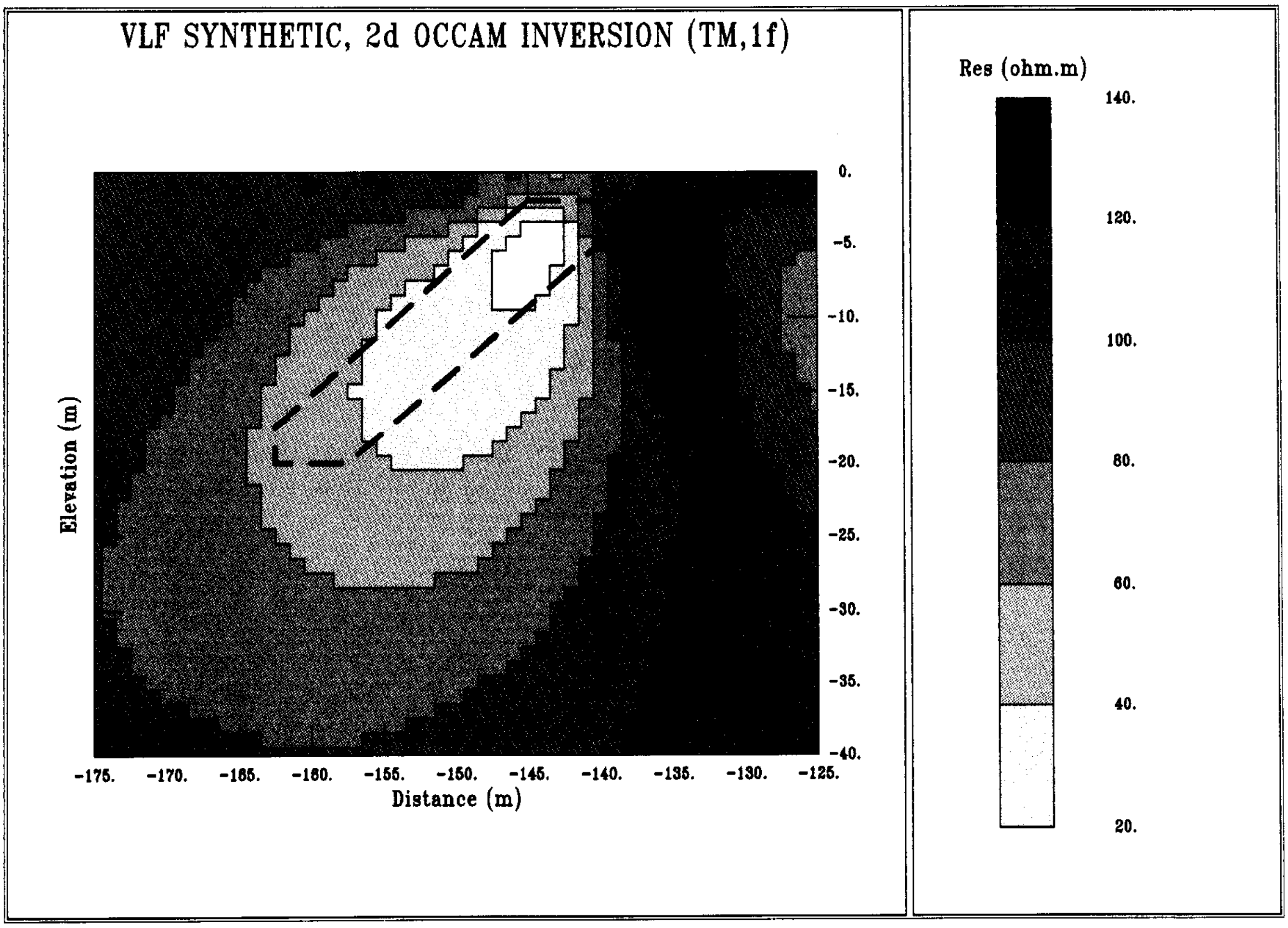

Fig. 2. Conductive zone (heavy dashed line) and resulting resistivity distribution.

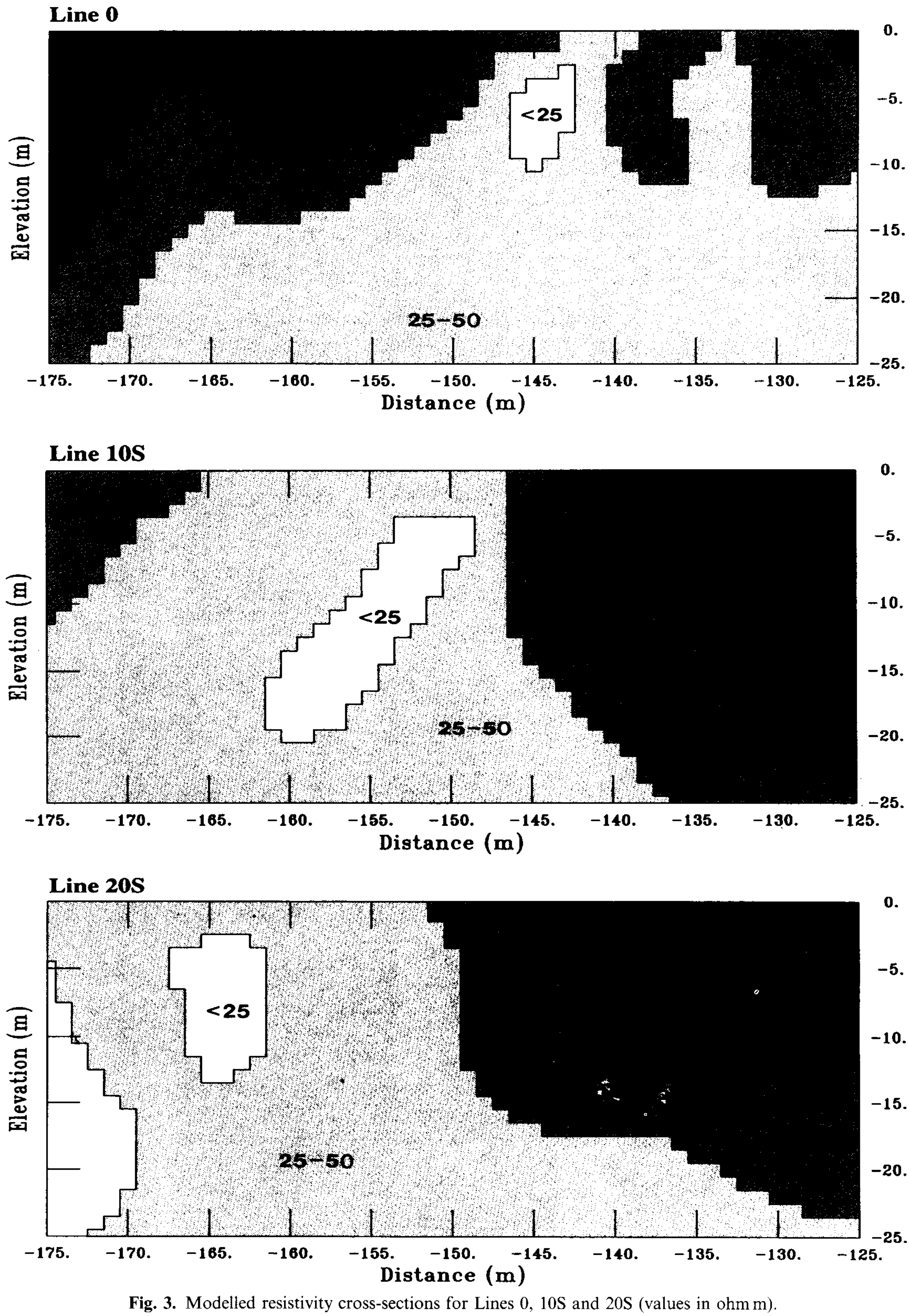

Fig. 3. Modelled resistivity cross-sections for Lines 0, 10S and 20S (values in ohm m).

interfaces, define features (resistivity gradients) that have a high likelihood of being representative of the 'true' resistivity distribution.

A synthetic example consisting of a concealed, dipping conductive zone can be used to illustrate the type of resolution achieved by a limited profile of VLF-R data. The conductive body (5 ohm m), shown as the heavy dashed line in Fig. 2 is immersed in 100 ohm m material. Forward 2D modelling was used to obtain the surface VLF-R response (16 kHz) along the 50 m traverse. Nominal data errors of 1% were assigned to the data. Starting with a uniform region of 30 ohm m, the inversion algorithm returned the resistivity distribution contoured in Fig. 2. The r.m.s. misfit between model and data is unity. As can be seen in Fig. 2 single-frequency data cannot be expected to fully resolve *all* the features of the dipping anomalous region. The white zone contoured in Fig. 2 represents the minimum resistivities returned by the inversion (< 20 ohm m). This zone is seen to correlate with the 'upper-edge' of the anomaly at a depth of 2.5 m. Elsewhere, the gradients indicate an asymmetrical conductive zone 'attempting' to return to a uniform background of 100 ohm m. The upper surface of the anomaly (which corresponds to first wavefield contact) is well resolved and the dipping zone is imaged by a gradient dipping at about 50° to the southwest. Below this conductive zone resolution decreases and the 'true' depth extent of the zone is difficult to establish. This synthetic data example can be used to good effect in the interpretation of the inverse models returned by the field data.

In order to process the survey data, nominal errors of 2.5% (representing conservative error bounds) were assigned. The inverse models obtained across each of the three lines are shown together in Fig. 3. In each case the starting model was a half-space of 30 ohm m and the models shown provide an r.m.s. misfit of 0.25. Thus the inversions provided models with excellent fits to the observed data. The cross-sections are true scale and use a contour interval of 25 ohm.m. The lowest resistivity material (<25 ohm m) is shown in white. An asymmetric (dipping) conductive zone is indicated on all three cross-sections. Resolution of the conductive feature on Line 20S is more limited due to the fact that it occurs closer to the end of the observational profile.

It is stressed that interpretation of minimum-structure (smooth) resistivity cross-sections must be 'weighted' in accordance with the limited resolution of single-frequency data. We initially associate the lowest-resistivity zone (<25 ohm m) with the near-surface expression of a conductive fault-zone (e.g. Fig. 2). From the behaviour observed on all three lines, the upper surface of this conductive zone appears to lie in the depth range 2 to 3 m. The dip of the zone (using resistivity gradients) is estimated to lie between 45° (Line 0) and about 60° (Line 10S). There is evidence (Lines 10S and 20S) that the conductive feature extends to a considerable depth (>25 m).

The models (Fig. 3) also indicate that the at- and near-surface resistivities which abut the fault-zone are transposed between Lines 0 and 10S. It seems clear from Fig. 3 that the strike of the fault is not linear and there are significant lateral variations in the configuration of the rock units (primarily across the 10 m separating Lines 0 and 10S).

Ground probing radar sections

The variable penetration and resolution afforded by the three different frequencies is clearly shown in Fig. 4. Taking account of the variable depth scales used, we see a weak but coherent reflector at about 8 m on the 25 MHz section compared with a lower limit of about 3.5 m for 100 MHz. The projected location of the Hahnwies Fault on Line 0 is at 146 m and all three frequencies display a strongly anomalous feature in this vicinity. The 50 MHz section appears to give the best overall definition and this images a low angle (*c.* 35°) fault plane dipping towards the southwest at this location. The character of the reflections for all frequencies also show a distinct change about this point; to the southwest the layering appears to dip and is rather complex whereas conditions to the northeast seem far more uniform and possibly more conductive (as suggested by the more rapid signal attenuation here). Figure 5 shows the 50 MHz sections for all three surveyed lines. Again the location of the probable fault, apparently trending somewhat west of south, is clearly defined on Line 20S (at about 152 m) and less well on Line 10S. It is also clear that the indications of more complex layering (and resistive conditions) on these southerly lines occurs to the northeast of the fault.

Comparison of VLF(R) and GPR results

Both the techniques have detected an anomalous dipping zone in the vicinity of the projected fault plane. The geophysical indications are almost laterally coincident on Lines 0 and 10S but appear to diverge at 20S; this, however, may reflect the poorer resolution of the VLF(R) inversion towards the end of the traverse. Both techniques reveal the presence of contrasting lithologies about the fault plane and the apparent transposition of these between Lines 0 and 10S. VES interpretations suggest the presence of shallow strata on Line 0 of high (850 ohm m) and intermediate (290 ohm m) resistivities to the southwest and northeast respectively of the projected fault. By analogy with our observations in an adjacent test site we conclude that on Line 0 a low porosity, coarse grained to conglomeratic sandstone/arkose occurs to the southwest of the presumed fault and a fissile, finer grained sandstone to the northeast.

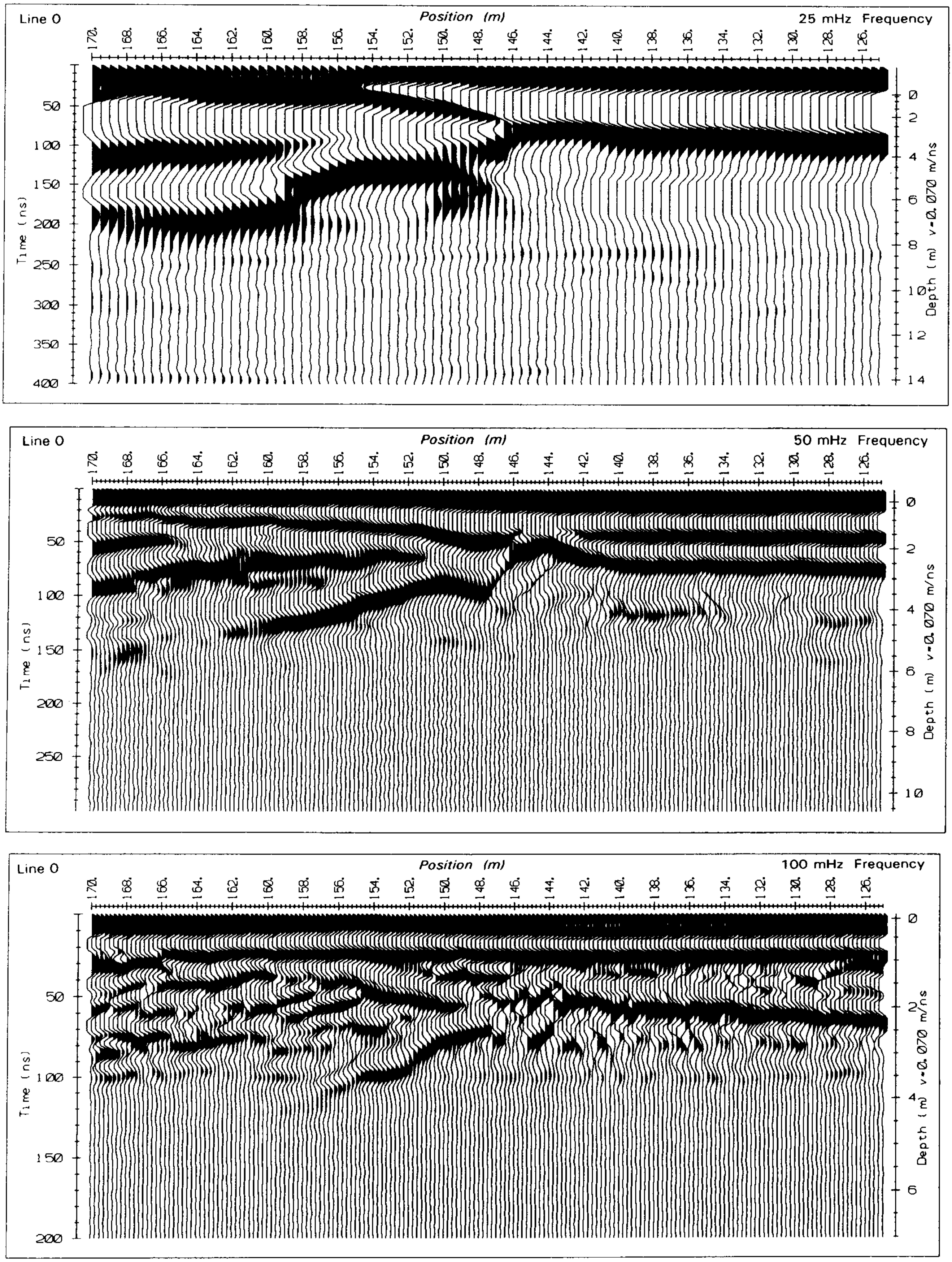

Fig. 4. Comparison of 25-, 50- and 100 MHz GPR frequencies (Line 0).

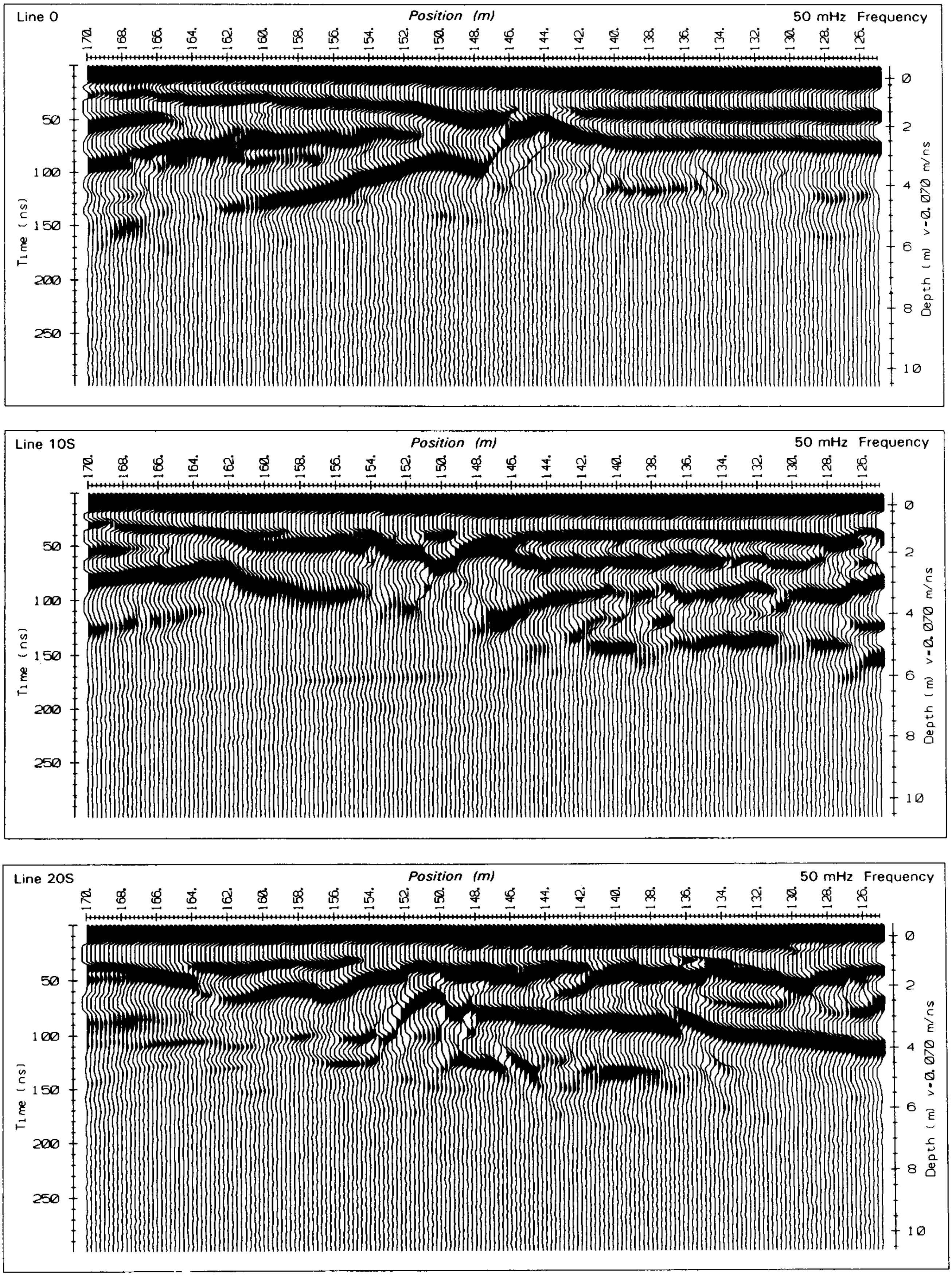

Fig. 5. The 50 MHz GPR section for Lines 0, 10S and 20S.

The apparent transposition of these units is not easy to explain, given that the expected horizontal displacement of shallow dipping layers by a 60 m downthrow (as measured underground) is some 130 m. One possible explanation is that the fault we have detected does not suffer such a large throw.

The shallow conductivity and gradient array resistivity mapping largely support the lateral resistivity distribution (including the transposition between Lines 0 and 10S) indicated by the VLF(R) modelling. The magnetic data suggests the presence of a magnetic horizon within the fine-grained (fissile?) sandstone to the northeast of the fault.

Results of inclined core drilling

Two inclined core boreholes were subsequently completed on Line 0 (see Fig. 1). These proved the presence of a fault zone (comprising largely 'fat' clays), subcropping between 143m and 146m and dipping to the southwest at about 60°. A coarse grained (partly conglomeratic) sandstone was proved to the southwest and a medium to fine grained sandstone with shaley intercalations to the northeast.

Conclusions

Inverse modelling of a limited VLF(R) data set has yielded a coherent resistivity distribution that suggests the presence of a dipping conductive fault zone separating two contrasting lithologies. These strata are apparently transposed within a distance of 10 m and the indicated structure is complex. GPR sections show anomalous features that are laterally almost coincident with the VLF(R) conductive zone and largely support the apparent transposition of shallow strata. The interpreted fault location and the juxtaposition of contrasting lithologies on Line 0 has been confirmed by inclined core drilling; however, the dip of the fault was underestimated, particularly with the GPR data. Both geophysical techniques have performed well in an environment that was predicted to be troublesome. It is suggested that VLF(R) and GPR are largely complementary techniques in the current application, with GPR yielding fine detail of the top 5 m and VLF(R) allowing very rapid mapping of the resistivity distribution down to about 30 m.

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References

BEAMISH, D. 1994. Two-dimensional regularised inversion of VLF data. *Journal of Applied Geophysics*, **32**, 357–374.

BINTZ, J., KLINKHAMMER, B. & VINCENT, P. L. 1979. Geologische Übersichtskarte 1:200 000 Blatt Nr CC 7102 Saarbrcken, Herausgeber BGR (Hannover 1979).

CONSTABLE, S. C., PARKER, R. L. & CONSTABLE, C. G. 1987 Occam's inversion: a practical algorithm for generating smooth models from EM sounding data. *Geophysics*, **92**, 289–300.

KLINKHAMMER, B. & KONZAN, H. P. 1967/1970. Geologische Karte des Saarlandes 1 : 25 000, Blatt Nr 6607 Heusweiler (1967) und Erläuterungen (1970), Herausgeber GLA (Saarbrcken).

SCHNEIDER, H. 1991. Saarland, Sammlung Geologischer Führer Nr 84, Verlag Gebr. Borntraeger, Berlin.

TABBAGH, A., BENDERITTER, Y., ANDRIEUX, P., DECRIAUD, J. P. & GUERIN, R. 1991. VLF resistivity mapping and verticalisation of the electric field. *Geophysical Prospecting*, **39**, 1083–1097.