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Application of ground penetrating radar to geological investigations

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Application of ground penetrating radar to geological investigations

J P Busby, R J Cuss, M G Raines, and D Beamish

Key words

Ground penetrating radar, geological investigations, void detection, fissures, aggregate assessments.

Front cover

The Noggin 250 MHz GPR being used in combination with the Dual EM ground conductivity meter (long yellow boom) on the Holme Pierrepont sand and gravel deposit.

Bibliographical reference

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Keyworth, Nottingham NG12 5GG

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Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report present the results of a study by the British Geological Survey (BGS) into the applications for ground penetrating radar (GPR) within the BGS Core Programme. Previous experience of GPR during the 1990's was mainly directed at investigations of the Quaternary sequences. Developments in GPR field equipment, software and new horizons of the BGS Programme have all combined to present new fields to which GPR can contribute. Hence, through the presentation of examples, a number of applications are shown that are relevant for the current and future Programme.

Acknowledgements

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Summary

Ground penetrating radar data have been collected from a number of sites in order to investigate the shallow sub-surface. The purpose was to investigate, through active participation, the benefit that GPR can have to elements of the BGS Core Programme and to explore ways that GPR can be used more widely in the future. Field data were collected mainly with a 250 MHz Noggin GPR system manufactured by Sensors and Software Limited, but some additional data were also collected using frequencies of 50 and 100 MHz. Good results were achieved for mapping fractures, characterising an aggregate deposit and for locating infrastructure including, tunnels, voids, steel reinforcing bars and capping for a mineshaft. The use of new equipment that collects data rapidly was found to be especially useful for creating three-dimensional blocks of data. Three-dimensional displays enable artefacts in the data to be identified and for the true dip of structures to be measured. Surveys were less successful when characterising chalk and estimating the thickness of buried channels where the depth of the channels was found to be too deep for high frequency GPR.

GPR is a powerful tool for investigating the shallow sub-surface when used in the appropriate environment. It is therefore important that BGS Programme Managers and project leaders should be aware of the potential of GPR and be prepared to utilise it when devising new projects. This is most likely to be achieved through active consultation with geophysicists during the planning phase of a project.

1 Introduction

This is the final report from the project “Application of ground penetrating radar to geological investigations” which was a three-year project initiated in April 2001. Ground penetrating radar (GPR) is a pulsed electromagnetic technique that generates a two-dimensional section of the sub-surface in a manner very similar to reflection seismics. Reflections occur due to contrasts in dielectric properties that enable structures in the near surface to be resolved on the decimetre scale. Unlike reflection seismics, however, GPR is easy to operate and involves only a single transmitter/receiver coil pair that can be towed over the ground surface. Recent developments in GPR technology and software are opening up new areas within the earth sciences where GPR can make a significant contribution. The objectives of the project were to:

i. Develop BGS's capability in the application and interpretation of GPR.

ii. Demonstrate, through active participation, the benefit that GPR can have to elements of the BGS Core Programme.

iii. Explore new applications for GPR, particularly in the area of climate change research, that may lead to new initiatives.

The project was funded as a Development of Capability project within the Geophysics and Marine Geoscience Discipline. Funding was moderate for the first two years and was reduced by approximately half for the final year. Funding for field surveys was extremely limited. The motivation for the project was the purchase by the BGS in 2001 of a 250 MHz Noggin GPR system manufactured by Sensors and Software Limited of Canada. This is a single frequency system deployed from a “Smart Cart” that is easy to assemble and operate, and can record data very rapidly. The Noggin was used on all field surveys. In addition, a Pulse Ekko 100 system, also manufactured by Sensors and Software Limited that operates over the frequency range 25 – 200 MHz, was hired for use on one survey. Software comprises Sensors and Software data transfer programs (v 2.1) and REFLEXW, written by K J Sandmeier of Karlsruhe, for the processing and interpretation of reflection and transmission data.

This report proceeds with a description of GPR, an account of the previous use of GPR within the BGS and then illustrates potential applications with a series of demonstration surveys. The overall potential for GPR is summarised within the conclusions section and recommendations are made for the future.

2 Background

GPR is an easy-to-deploy geophysical technique that produces high-resolution images of the shallow subsurface in a manner analogous to reflection seismics. It is usually used as a surface technique although borehole radar is used in specialist applications (only surface GPR is considered in this report). Like many geophysical techniques, GPR can provide very useful data if applied in the appropriate context and this is discussed in the sections below. Hence, any sub-surface investigation that requires shallow, high-resolution imaging may benefit from the inclusion of GPR.

2.1 GPR METHODOLOGY

The GPR technique is similar in principle to sonar methods. The radar transmitter produces a short pulse of high frequency (25 - 1000 MHz) electromagnetic energy, which is transmitted into the ground through an antenna. Variations in the electrical impedance within the ground generate reflections that are detected at the ground surface by the same or another antenna attached to a receiver unit. Variations in electrical impedance are largely due to variations in the relative permittivity or dielectric constant of the ground. The reflection coefficient for a normal incident signal is

$$R = \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}}$$

where K_1 is the dielectric constant of medium 1 and K_2 is the dielectric constant of medium 2. The power reflected is $|R|^2$. Water has a dielectric constant of 80 (compared, for example, to 5 for dry soil and 8 for rock) and hence there are high reflection coefficients between dry and wet materials. In addition, the water table is a strong reflector.

The mode of GPR surveying deployed here was common-offset, single-fold reflection profiling. In such a reflection survey, a system with fixed antennae geometry is moved along a survey line to map reflections versus position. The radar section is built up from successive traces that are either recorded with the radar stationary at each point or moved continuously in a walking mode. All radar traces are accumulated by stacking traces in order to improve the signal to noise ratio. In walking mode, a slight smearing of the data will occur, but it is minimal due to the very high propagation velocities of electromagnetic waves.

There are seven parameters to define for a common-offset, single-fold GPR reflection survey. These are the frequency, the time window, the time sampling interval, the station spacing, the antennae spacing, the line location and spacing and the antennae orientation. These are selected from a consideration of:

- What is the target depth?
- What is the target geometry?
- What are the target electrical properties?
- What is the host material?
- What is the survey environment like?

2.1.1 Expected resolution and depth of investigation

The resolvable thickness of a geological layer depends on the radar wavelength. If the maximum resolution is taken as ¼ of a radar wavelength, then for a GPR system operating at 50 MHz, in a medium having a velocity range of 0.07 (till) – 0.11 (sand and gravel) m ns^{-1}, the maximum spatial resolution will be between 0.35 – 0.56 m. Vertical definition is mainly affected by attenuation and scattering of the signal. It should be noted that thin layers, i.e. very much less than one wavelength, can generate strong reflections if they are associated with a high reflection coefficient, although the thickness of the layer will not be resolvable. The attenuation of the radar signal in the ground is largely controlled by the conductivity of the materials through which the signal passes. A rough guide to penetration depth is:

$$d_{max} < 35/\sigma$$

where σ is the conductivity in mS m^{-1} (milliSiemens per metre).

2.1.2 Acquisition parameters

Selecting the optimum GPR frequency for geological investigations is the most critical decision for a GPR survey since it has to be an acceptable compromise between resolution and depth of penetration. Clearly, the frequency must be high enough to resolve the target size and geometry. However, as the frequency increases small-scale features such as fine scale bedding, cracks and joints become radar targets that reflect and scatter the signal. This results in clutter within the recorded data and reduces the amount of energy penetrating to depth. In addition, as the radar frequency increases the signal attenuation within the ground increases. A rough guide for frequency selection is to assume that the spatial resolution required is about 25% of the target depth. Thus a frequency of 250 MHz is suitable for shallow investigations in the top two metres, but deeper investigations to 10 m or more will require frequencies of 100 or 50 MHz .

The time window in which data are recorded is determined by the depth of penetration of the radar energy and the radar propagation velocity. If the desired depth of penetration is 20 m at a velocity of 0.1 m ns^{-1}, then the twtt (two way travel time) would be 400 ns. The time window needs to be longer than this to allow for noise monitoring before the first arrival of the received pulse. Hence, 500 ns is the preferred initial time window. In practice a pre-survey check is always made of the received data so that if a coherent signal is present at the end of the time window, that window is extended. Similarly, if the data are attenuated due to absorption, then the time window is reduced to speed up data collection. The sampling interval of the radar signal is selected to avoid aliasing. The recommended sampling intervals are 1600, 800 and 300 ps for frequencies of 50, 100 and 250 MHz. Stacking the data improves the signal to noise ratio, although the number of stacks must be reasonably small when working in walking mode in order to reduce smearing of the data.

To avoid spatial aliasing of the data the station (trace) separation must not exceed the Nyquist sampling interval. Flat lying reflectors will be defined if the Nyquist sampling interval is exceeded, but steeply dipping reflectors will not. In general, station spacings of 5, 25 and 50 cm should be used for frequencies of 250, 100 and 50 MHz respectively. Data taken with the Pulse EKKO 100 used antennae separations of 1.0 and 2.0 m for frequencies of 100 and 50 MHz. The antennae were orientated perpendicular to the survey direction in order to minimise sideswipe from targets outside of the survey line.

2.1.3 Data processing

Initial data processing is to “dewow” each trace, whereby a time domain filter is applied to remove very low frequency components. These can be associated with either inductive phenomena or possible instrumentation dynamic range limitations. An automatic time zero shift correction is applied to each radar section to compensate for time zero drift. This correction should bring time zero to the start of each trace and align each trace in the section. Sections were generally plotted using an AGC (Automatic Gain Control) gain. This gain attempts to equalise all signals by applying a gain that is inversely proportional to the signal strength. Hence, all parts of the signal, including noise, are amplified and relative amplitude information is not preserved. Where appropriate the data were filtered with spatial and time averaging filters.

2.1.4 Interpretation

Interpretation is largely empirical and relies upon the identification of GPR reflector configurations and patterns within a GPR section. Ground truthing as a result of boreholes and excavations provides valuable case histories upon which experience is built.

2.1.5 Survey outputs

Results are plotted in section form as two way travel time against traverse position. A time to depth conversion can be applied to the data by adopting an electromagnetic propagation velocity. Typical values are 0.08 m ns^{-1} for profiles over till and 0.1 m ns^{-1} for profiles over sand and gravel. It is possible to estimate radar velocity directly and there are two procedures. In the first, known as CMP (Common Mid-Point) the receiver and transmitter antennae are positioned over a horizontal reflector and then moved apart. The radar signal is thus reflected from the same point on the reflector (common mid-point), but with increasing signal travel time. The increased reflection arrival time with antennae separation (move-out) has a hyperbolic dependence from which radar velocity can be estimated. In the second procedure, hyperbolic reflections within a radar section (often referred to as diffractions) are utilised. These occur at point sources whose dimensions are much smaller than the radar wavelength, such as boulders and vertical contacts. Non-vertical reflections are created that are picked up by the radar for a considerable length of profile as the antennae pass over the point source. Since all recorded data are assumed to be reflected from directly below the data recorder they plot as hyperbolae. Processing software, such as REFLEXW, allows the processor to identify two points along the hyperbola and outputs a corresponding velocity at that point. Changes in lithology and water saturation levels will lead to both horizontal and vertical velocity gradients within the GPR section. The data are plotted in radar section form as wiggle traces, colour images or a combination of the two. An example of a wiggle trace is shown in Figure 1.

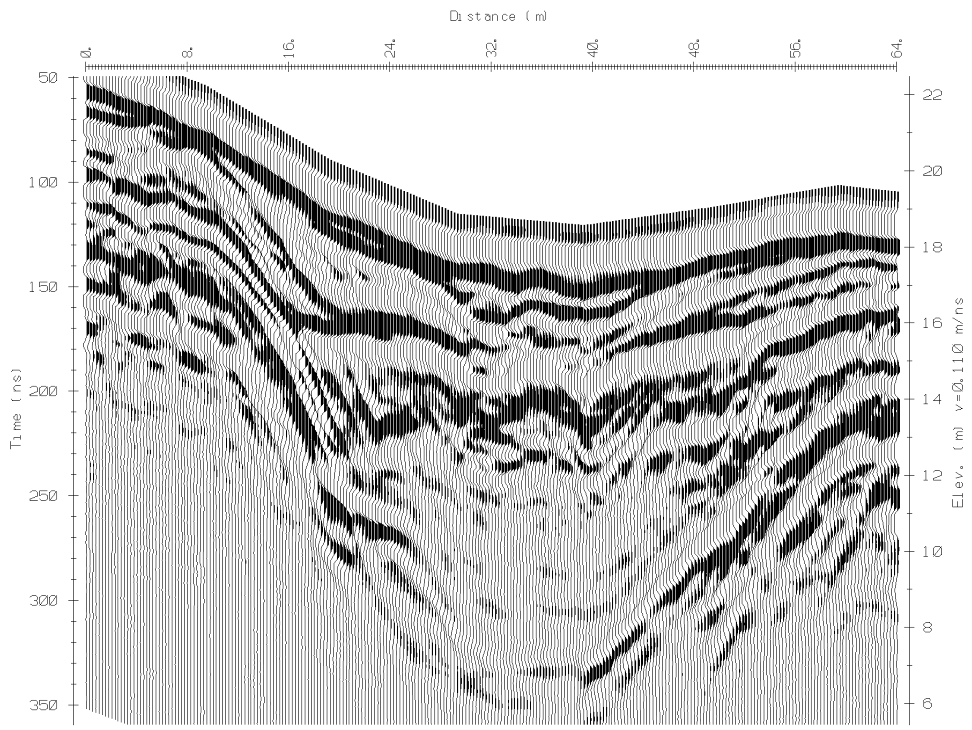

Figure 1. Example of a wiggle trace radargram. The reflections are interpreted as a kettle hole infilled with flat-lying onlapping sediments (after Busby and Merritt, 1999).

2.2 PREVIOUS INVESTIGATIONS BY THE BGS WITH GPR

Much of the background to the development of GPR as a tool for investigating geological problems can be attributed to Annan and Davis (1976), Olhoeft (1984) and Davis and Annan (1989). The BGS established a GPR capability in 1990 with the purchase of a GSSI SIR 3 analogue radar system with 100, 500 and 900 MHz antennae. The SIR 3 generated a permanent record of each radar profile on a graphic analogue recorder, although it was possible via an analogue to digital converter to record the data on a digital tape recorder. Processing of the digital data was cumbersome and much of the interpretation was carried out manually on the paper records from the analogue recorder. Early surveys were orientated towards archaeology with encouraging results obtained at Culross Palace, Fife (Greenwood and Raines, 1991) and evidence for voiding found at the Cathedral Church of St Martin, Leicester during a GPR survey to locate a crypt (Greenwood and Raines, 1993). In addition, GPR was included amongst the methods used on a number of site investigations, one example being a survey to locate former toxic waste pits at a horticultural institute (Raines and Rippin, 1995). GPR was also included in surveys to locate mine shafts and ventilation shafts in the urban environment (Busby, 1994 a, b).

In 1992 The Quaternary Mapping Methods Project was established by Dr P Allen, the Assistant Director in charge of the Thematic Maps and Onshore Surveys Directorate. This project aimed to produce a greater range of Quaternary maps with enhanced content that were of better quality. A number of initiatives were pursued including the greater use of geophysics and in particular GPR. The report of the Quaternary Mapping Methods Project (Browne and Morigi, 1993) led to the commissioning of GPR surveys in the Grampian region of Scotland and in East Anglia. Study areas were chosen where there was reasonably detailed mapping of the Quaternary geology, but the sequences presented a distinctive set of problems that could not be addressed by conventional geological mapping alone. Four surveys were conducted in the Grampian Region at Houff of Ury, Moss of Cruden, Windyhills and Deb of Boddam, and three in East Anglia at Dunwich Forest, Dunwich Heath and Holkham. Unlike all the previous surveys, a digital acquisition system, comprising the Pulse Ekko IV manufactured by Sensors and Software Ltd, was hired. The results (Greenwood et al., 1995; Greenwood and Raines, 1994) demonstrated that GPR could distinguish lithological units in the Quaternary environment based on characteristic reflection patterns. Flat lying and dipping reflections were interpreted in terms of bedding from which depositional sequences could be discerned. For the measurements in the Grampian region an average penetration depth of 8 m was achieved, whilst for East Anglia it was 6 m.

The experiences gained from the Quaternary Mapping Methods Project enabled BGS to bid successfully to UK Nirex Ltd. Nirex were establishing the safety case for an underground nuclear waste repository at Sellafield, Cumbria. GPR surveys were included as part of the Quaternary Phase II Studies Programme within the Sellafield District. The surveys were done in conjunction with numerous linked investigations in order to gain a thorough understanding of all aspects of the Quaternary sequences. GPR was very successful in distinguishing between the major lithological types (clays, sands and gravels of various grade) based on characteristic reflection patterns and occasionally defined discrete bedding planes (Busby et al., 1994; 1995). The Quaternary of the Sellafield District is mainly glacial in origin and has been subjected to glacitectonics. GPR was also found to be especially applicable in mapping glacitectonic structures. A number of GPR anomalies took the form of dipping reflectors, assumed to be thrust planes, offsets in reflectors and characteristic V shaped anomalies taken to be linear collapse structures where glacitectonically emplaced slices of ice had melted out causing sediments to founder and slump (Busby and Raines, 1995). All of the GPR data collected were subjected to a more detailed geological investigation from which it was possible to identify six radar facies (Busby and Eaton, 1995). These were intended to aid in the initial interpretation of subsequent data. Many of the results obtained were presented in two peer-reviewed papers (Busby, 1997; Busby and Merritt, 1999). The expertise gained from the Sellafield investigations enabled the BGS to write a Position Statement for UK Nirex Ltd. on the applicability of GPR as part of the geological investigations of the Sellafield area (Busby, 1995).

GPR was also used for the detection and mapping of reactivated faulting resulting from mining subsidence (Greenwood et al., 1994; Beamish et al., 1994). All suspected faults were mapped, although the radar response varied between an offset of reflectors, a change in reflection character (facies) across the fault and diffraction patterns associated with the fault itself.

3 Demonstration GPR surveys

The surveys described within this section have been chosen because they show a range of applications that GPR has been applied to during the lifetime of the project. Not all of the surveys were successful. GPR is by its very nature a technique that only investigates the shallow sub-surface and penetration depth is limited by the electrical conductivity of the ground. A more general use of GPR by the BGS is dependent on a greater understanding by non-geophysicists of when and where GPR can be successfully deployed.

Sufficient details are presented in order to demonstrate the GPR application. Some information that would normally be included in the account of a survey, such as detailed location maps, is omitted.

3.1 GEOHAZARDS FROM FISSURING: THE A690 AT HOUGHTON-LE-SPRING

Serious cracking to the wearing surface of the A690 Sunderland-Durham road at Houghton Cut, Houghton-le-Spring has been reported from April 2000. The presence of prominent open fissures within dolomitic limestones of the Upper Permian Magnesian Limestone of the Houghton-le-Spring area, and their likely association with coal extraction from the underlying Coal Measures has long been known (Goulty and Kragh, 1989; Young and Culshaw, 2001). This fissuring is widespread in the area and is typically most abundant within the hangingwall zone of known faults mainly, though not exclusively, those with a roughly east to west orientation. Fissuring is actively occurring both in areas with a known history of such ground movement and in areas where such instability has not hitherto been reported. It is associated with damage to land, buildings and structures, including the A690 road. Fissures may appear suddenly and may present significant safety hazards. Study of the existing geological mapping, together with an examination of the abandonment plans of coal workings beneath the area, indicate a close spatial relationship between the occurrence of surface collapse and structural damage, and the position of faults, in both the Magnesian Limestone and underlying Coal Measures. Processes such as land sliding, cambering and limestone dissolution do not appear to play a significant role in the phenomena observed. The field and other evidence gathered are consistent with ground movement resulting from reactivation of pre-existing faults that cut areas of extensive abandonment underground coal workings.

The A690 at Houghton Cut is a dual carriageway and the cracking was only observed in the northern carriageway. GPR surveys to investigate the cracking were undertaken in May 2002 and were reported on by Cuss and Beamish (2002). The Sensors and Software 250 MHz Noggin was used with data collected as follows.

- On the northern carriageway, 19 parallel lines, separated by 0.5 m, were set out parallel to the direction of the road at an angle to the target fissure.
- On the southbound carriageway, 23 lines were conducted perpendicular to the extended trace of the target fissure, at an angle to the road direction. This meant that some lines were very short.
- A GPR dataset of 16 lines was recorded in Houghton Hill Farm fields adjacent to the A690, on the top of the limestone escarpment.

Line lengths varied between 30 and 100 m.

Twelve of the 19 radar profiles from the northern carriageway are shown in Figure 2, progressing from west (1) to east (12). A series of flat reflections, seen most prominently in profile 3 are associated with the section of road that has been resurfaced. The fissure is clearly identifiable on almost all of the profiles. On some profiles, it is only just visible, whereas on others it has created a clear radar reflection. This may indicate sections of the fissure that are open (good reflection) or closed (poor reflection). Radar reflections are created where a discontinuity of electrical properties are encountered. The difference between limestone and air is significantly greater than the difference between intact Magnesian limestone in the bedrock and deformed limestone within a closed fissure. A feature that is seen at approximately 23 m along profile is thought to be due to an underground utility, such as a pipe, as a strong ground conductivity anomaly was also measured over this feature.

From the 2D profiles, a 3D block of data has been constructed that allows maps to be produced at successively increasing time slices, to a depth of approximately 1 m (see Figure 3). The fissure is a continuous linear feature striking at an angle across the survey site. In the top few layers, this strong signal is related to the resurfaced section of the road, but from time-slice 8 onwards, is related to the fissure itself. With increased time (~depth), the fissure feature is seen to gradually move to the south. This shows that the fissure dips towards the south, as observed in the exposures surrounding the A690.

The results from the southbound carriageway were disappointing. The resurfaced section of the road generated strong reflections probably due to the contact between fresh Tarmac and older material. However, there was no evidence of the fissure, this being the case for all of the survey lines in this area. It is likely that the difference in road construction between the north and south carriageways contributed to a difference in reflection character.

Data recorded at Houghton Hill farm showed increased depth penetration, compared with the surveys conducted on the A690. This was due to the lack of a layered road cover. Depth penetration of the radar was in excess of 7m (assuming a velocity of 0.0715 m ns^{-1}). Figure 4 summarises the general features observed on the escarpment. The fissure is an obvious feature, central along line. Due to the open nature of the fissure at this point, it is seen as a 'shadow' zone as the radar data is not transmitted to depth at this point. Other shadow zones may be indicative of smaller fissures. There is considerable structure within the Magnesian Limestone, as seen by the continuous reflections that generally dip to the north on the northern side of the site.

The conclusions from the Houghton Cut survey are as follows:

- Radar penetration was only 6.5m on the northbound carriageway, with only the top 3m generating useful data.
- The known fissure shows up as a strong GPR feature on the northbound carriageway of the A690.
- The application of 3D GPR aided in the identification of the structure beneath the A690.
- A 100m-survey line suggested that four other smaller fissures might also be present along the A690.
- The signature of the radar reflection from the fissure altered across the road suggesting that it is open at the edges of the road and closed in the middle.
- The nature of the hardcore varies across the northbound carriageway.
- The southbound carriageway did not yield useful data.
- At Houghton Hill, radar penetration was in excess of 7 m and identified complex structure within the Magnesian limestone.
- Two large fissures were imaged on Houghton Hill; these were both longer in extent than seen on the ground.
- Three smaller fissures (35 – 70 m long) were seen on Houghton Hill.

Subsequent to the GPR survey in May 2002 further subsidence to the road occurred in June 2003. Repairs carried out enabled a geological assessment to be made (Young, 2003). Figure 5 shows the fissure exposed beneath the northern carriageway. The fissure is a major feature, an open void up to 0.5 m wide and 1.0 m deep. It is likely that the fissure has experienced further movement or widening since 2002, but would have presented an open void, at least along part of its length, to the GPR survey.

3.2 AGGREGATES; AN ANALOGUE FOR A BEACH

The Geophysics and Marine Geosciences Development of Capability project, 'Investigation of coastal sediment transport' is investigating geophysical techniques that can explore the 'surf zone', the area between the base of the cliff and about one kilometre offshore. This very important zone has been under explored, but an understanding of the processes occurring there are vital if the effect of sea level rise is to be understood. Beaches provide protection for the cliffs and dunes and any changes to beaches could have a dramatic effect on coastal erosion and flooding. However little is known about beaches, their thickness or how they evolve with time. The initial task therefore for the 'Investigation of coastal sediment transport' project is to find geophysical techniques that can generate reliable depths of beaches and the 'Application of ground penetrating radar to geological investigations' project has provided GPR input.

The initial study has investigated an onshore analogue of a beach; that is, a river plain aggregate deposit that is currently being quarried by Tarmac Ltd. The advantages are ease of access and full geological information since the aggregate was quarried after the geophysical surveys. The disadvantage for the study of beaches is that an aggregate deposit has undergone some cementation through the precipitation of minerals and is either drained or saturated with fresh water, whilst a beach is saturated with electrically conductive seawater. The aggregate deposit is located at Holme Pierrepont on the River Trent near Nottingham. The Holme Pierrepont Sand and Gravel forms a terrace (the Holme Pierrepont Terrace) standing up to 2.5 m above the level of the floodplain. The Holme Pierrepont Sand and Gravel is typically 6 to 7 m thick, ranging up to a maximum of 9 m to the west of Newark. Exploration for sand and gravel in the Trent valley has yielded numerous borehole provings but little lithological detail is provided from such sources. The best exposures are provided by active gravel quarries, which are kept dry by pumping and provide fresh faces for study. The Holme Pierrepont deposits consist of poorly-sorted, clast-supported gravel, 6 to 9 m thick, with a medium- to coarse-grained sand matrix, interstratified with lenses of medium- to coarse-grained sand and pebbly sand. Pebbles are generally less than 50 mm across, but there are larger ones that range up to 0.1 m. They are mostly rounded, but sub-rounded to angular shapes also occur. The uppermost 1 to 2 m of the deposit appears unstratified and the remainder shows sub-horizontal stratification or, less commonly, trough cross-stratification. Locally, the long axes of pebbles show horizontal orientation, imparting a pronounced fabric to the deposit; imbrication is rare. Lenses of fine- to medium-grained sand are present at a few levels. These may be planar laminated or, more commonly, planar or trough cross-stratified. Ice wedge casts have been found within the deposit at Hoveringham, commonly at more than one level. The dominant pebble types, usually making up to 70 per cent by number, are quartz and quartzite derived from the Sherwood Sandstone. Also common (comprising between 5 and 10 per cent) are flints derived from the Chalk, sandstone derived from the Triassic Bromsgrove and Sneinton formations, and sandstone, limestone and chert derived from the Carboniferous. Jurassic limestone and ironstone, igneous rocks and coal also occur but are less common. The Holme Pierrepont Sand and Gravel lies on the Mercia Mudstone. A view of the deposits is shown in Figure 6.

Two benches were selected for study at Holme Pierrepont, the thinner '5 m bench' and thicker '10 m bench'. Both had had the topsoil removed and the area for study was 24 m (x direction) by 48 m (y direction). GPR data were collected with the Sensors and Software Pulse Ekko 100 (50 and 100 MHz) and Noggin 250 MHz systems. Over the '5 m bench' 100 and 250 MHz data were collected, whilst over the '10 m bench' it was 50 and 250 MHz. Profiles were every 1 m for the Noggin data and every 6 m for the Pulse Ekko 100 data. A photograph of the Pulse Ekko 100 is shown in Figure 7.

Results with the 100 MHz antennae from the '5 m bench' are shown in Figure 8. The resistive sand and gravel is a very good GPR target and horizontal layering and stratification are evident throughout the deposit. In contrast, the underlying, electrically conductive Mercia Mudstone attenuates the GPR signal and hence the base of the aggregate is clearly visible as a reflection from the top surface of the Mercia Mudstone (indicated by the arrows in Figure 8). The aggregate is between 2.0 and 3.4 m in thickness and is thickest along the left hand edge of the grid and in the centre. A three dimensional block view of these data is shown in Figure 11a. A contour map of the aggregate thickness, based on picks from the basal reflection, is shown in Figure 11b. Similar results from the '10 m bench' with the 50 MHz antennae are shown in

Figure 9. The depth of the deposit is again clearly visible as a basal reflection. The polarity of the data is reversed compared with the '5 m bench' data (blue pick compared to yellow/red) because the antennae were orientated oppositely. The deposit is thicker, between 4.4 and 6.2 m, and shallows towards the bottom of the grid. A contour map of the aggregate thickness, based on picks from the basal reflection, is shown in Figure 11c. Noggin data at 250 MHz were taken over both grids. Representative data from every other line on the '10 m bench' are shown in Figure 10. The depth of penetration is insufficient to define the base of the aggregate deposit and is restricted to about 1.5 m. However, greater resolution is achieved and both dipping and horizontal bedding is apparent.

Both benches were quarried after the geophysical surveys. Excellent agreement was found between the depths of the benches predicted from the GPR data and the quarried depths. In addition the topography of the Mercia Mudstone surface was seen to agree with that predicted from the GPR (see Figures 12 and 13).

The conclusions that can be drawn from the GPR surveys at Holme Pierrepont are as follows:

- With the lower frequency GPR, the aggregate deposits were imaged to their bases, a penetration depth of at least 6.2 m.
- Features, including the topography of the Mercia Mudstone surface, were resolved on the decimeter scale.
- Internal structure, including dipping and horizontal bedding was well defined, especially with the 250 MHz data.
- Excellent agreement was found between predicted and actual depths, suggesting that there were no significant velocity variations within the deposit and that the value of 0.1 m ns^{-1} is an accurate value for sand and gravel.
- GPR is potentially a powerful tool for sand and gravel resource evaluations in freshwater environments.
- Results on a sand and gravel beach are likely to be disappointing due to conductive seawater. However, on a shingle beach at low tide, where air will fill the spaces between the shingles, GPR may have an important role to play in mapping beach thickness.

3.3 THE APPLICABILITY OF GPR IN LANDSLIDE AND SLOPE STABILITY INVESTIGATIONS

Landslides represent a major problem for the built environment, affecting buildings, roads and railways**.** Inland the majority of landslides formed during the last 10,000 years due to glacial and periglacial activity. The most dramatic landslides occur on the coast; a recent example being the spectacular landslide near Scarborough in June 1993 which involved an overnight cliff retreat of 135 m and the destruction of Holbeck Hall Hotel.

The BGS holds a National Landslide Database that contains references to over 8000 slides within England and Wales (DOE, 1994). It is known that many more exist, often concealed under ground that has become degraded and vegetated or superficially remodelled by later events. New landslide activity occurs through natural causes, such as unusually heavy rainfall and the weakening of rock as it weathers. However, more often, movement is a reactivation of a dormant slide that may have moved during the wetter conditions at the end of the last ice age.

Landslides often exhibit a considerable spatial variation in both depth to the slip surface and in the nature of the slip debris. In addition, the situation is often complicated by the presence of complex, frequently perched, water tables. A GPR investigation is most likely to be able to identify a tentatively identified landslide site by a change in character of the GPR response from the material above and below the slip plane. Only in extremely favourable conditions will a reflection from the slip plane be obtained. Traditional methods for investigating landslides have been seismic refraction and vertical electrical soundings (VES) (Cassinis et al., 1984/85; McCann and Forster, 1990). These methods respond well as the body of the landslide is generally characterised by higher moisture and porosity values. Recently, more highly resolved and efficient techniques have been used, such as 2D/3D electrical resistivity tomography (ERT) (Loke and Barker, 1996; Gallipoli et al., 1999-2000); seismic tomography (Jongmans et al., 2000) and time domain methods (TDEM) (Reynolds, 2002). A recent review of 'geophysics for slope stability' by Hack (2000) describes all the modern geophysical approaches, including GPR.

Difficulties exist in the general application of GPR to landslide characterisation and slope stability analysis due, in particular, to the high attenuation of common slide materials (e.g. clays) and the significant depth of most slide structures. This is particularly a problem in the UK, where at least 40% of the 8000 mapped landslides are described as having an upper lithology of clay, marl or mudstone. In England this would generally preclude the use of GPR over most of the slides, to the east and south-east of the Jurassic outcrop. In comparison (assuming thin till), the technique can be recommended in resistive terrains, such as in the South Wales Coalfield where numerous landslides occur in the Pennant sandstones (Conway et al., 1980) and over similar lithologies on the Bradford Sheet (Waters, 1999) where more than 200 slides have been mapped.

There appears to be very little reference to the use of GPR in landslide investigations in the UK. However, Raines et al. (1999) did use GPR with 225 and 50 MHz antennae in the North Cotswolds, to delineate the internal structure of gulls and cambered strata of the inferior Oolite Group of Jurassic age. Signal penetration was about 5 to 6 m on cambered limestone, reducing to about 2 to 3 m over the mainly clay filled gulls. Similarly, in northern Italy, GPR investigations using a 225 MHz antenna were performed to assess the depth and geometry of rock slides and buckles affecting a dip slope of regularly stratified limestones interbedded with marly-clayey horizons in the south-eastern Alps (Pettinelli et al., 1996). This method was chosen because the absence of high cuts in the rock mass and the presence of debris and loosened slabs on the slope did not allow the geometry of the sliding mass to be described solely by means of field mapping.

In the western Swiss Alps, Bruno and Marillier (2001) used a 50 MHz antenna to detect the internal rupture surfaces of a debris flow affecting the lower part of the "Les Peillettes" landslide in the Rhone valley. The results show that they were able to image down to a depth of 40 m within schists and show the groundwater table at 10 m. They concluded that the GPR profiles were able to identify the subsurface boundaries of a rapid debris flow.

Because of extreme precipitation in July 1997, hundreds of landslides developed on flysch slopes of the Carpathian mountain system in the eastern part of the Czech Republic, endangering large inhabitated areas. In this situation, a quick and cost-effective system for slope deformation investigation and monitoring was necessary. A geophysical prospecting system based on extensive use of GPR (Hruska and Hubatka, 2000) has been adjusted for landslide investigation, with scanning performed on longitudinal and transverse lines. This was carried out with a limited number of other geophysical methods, including: dipole electromagnetic profiling, shallow refraction seismics and vertical electrical soundings.

The above examples show that conductive shallow layers often limit the effectiveness of the GPR method, and its successful application on landslides is expected to be strongly site dependant.

3.4 MAPPING OF A TUNNEL SYSTEM

Sub terranean tunnel systems that are within the depth range of GPR are good targets for the technique. Tunnels sometimes need to be mapped when performing site investigations for redevelopment. In addition, many of the survey techniques applied to map tunnels are relevant to mapping cave networks in limestone terrains, especially as limestone is resistive and does not attenuate the GPR signal as strongly as many other lithologies. The survey reported here was undertaken over the Williamson tunnels at Edge Hill, Liverpool.

Joseph Williamson (1769-1840), a Liverpool philanthropist, employed local men to dig tunnels under his land at Long Broom Filed, Mason Street. Vaulting of the tunnels was unnecessary due to the strength of the rock, but spectacular brick arches were produced. Construction occurred randomly, with pits, wells and blind passages creating a tunnel-system many miles long, 1 to 15 m below the surface, 1 to 12 m wide, and up to 15 m high (Hand, 1916; 1927). After Williamson's death, his estate fell into ruin and the location of the tunnels became lost. Over the years, the site has been redeveloped and fallen into disrepair a number of times. An account of the history of the site and some of the other geophysical surveys carried out is given by Cuss and Styles (1999).

In recent years, there has been an increasing interest in finding the tunnels not only for redevelopment, but also in order to open the tunnels as a historic, tourist attraction. GPR surveys with the 250 MHz Noggin were conducted over two sites. The first was conducted as profiles on public paths, roads, grass verges, within a large warehouse, on a cobbled area, and within the tunnels themselves. The second, detailed 3D survey, was conducted over the site of Williamson's original house.

The survey was successful, but some of the data, particularly along roads was affected by cultural features. Cobbles were found to generate ringing of the radar signal. On some streets the survey followed the course of cable TV utilities, which have access boxes every ten metres or so. These void features created a very strong reflection and the conductive cabling does not allow the GPR signal to penetrate much further into the bedrock. All road traverses within the area showed evidence of utilities, be these gas, electricity, water, telephone, or cable TV. The street pylons for lighting created very strong reflections from the GPR signal that is travelling over the ground surface. These created hyperbolae diffractions that could be interpreted as tunnel features. Additionally sideswipe can be generated from curbs, fences, walls, and buildings. Two areas of the survey were conducted with overhead obstructions, within the Magnet Showroom warehouse and within the tunnels. The GPR unit is shielded, but a certain amount of GPR energy will travel vertically upward, as well as downward. Where these overhead obstructions are encountered, reflections are generated that appear to come from depth. However, careful consideration of the time of reflection and the expected GPR velocity can identify these reflections as coming from overhead.

Many of the tunnels and associated underground features were successfully mapped by the survey. Interpretation was helped by data from within Williamson's house where known features enabled calibration of the data. Figure 14 is an annotated radargram from the calibration survey. Tunnel roofs are depicted by broad hyperbolic diffractions whilst the floors generate flat-lying reflections with hyperbolic diffractions at the contact of the floor with the tunnel wall. Some other known features are also shown. This image also shows that the reflectivity of the GPR data varies across the site and this is probably due to near-surface, lateral variability.

The conclusions that can be drawn from the GPR survey over the Williamson's tunnels are as follows:

- The survey was able to successfully map the location of the tunnels, of which the roofs were characterised by broad hyperbolae within the radar images. Some new tunnels were rediscovered.
- It should also be possible to map cave systems within the relatively near surface in karstic terrains with GPR.
- Utilities within the ground and sideswipe from surface features can create spurious reflections within the radargrams.

3.5 SURVEYS FOR INFRASTRUCTURE

Two brief examples are given here of surveys that were conducted with the 250 MHz Noggin over man-made infrastructure. Since infrastructure in the ground will generate a characteristic response within a radargram, it is important to have an appreciation of these responses for separating out the geological response.

The first survey was conducted over the Transport Road Laboratory's (TRL) test track. This is a piece of road where the construction has been carefully logged in order to produce a variety of road types. The radargram is shown in Figure 15. The right of the radar image displays the road construction with a uniform flat reflector from the concrete, underlain by sub-horizontal reflectors from the limestone base. The lower surface of the road is clearly illustrated due to the absorption of the radar signal by the underlying mudstone. Depth conversion has used a velocity of 0.7 m ns^{-1}, obtained from the fitted hyperbolae, but this is probably too low for the section as a whole, as shown by the mismatch with the depths to the layers in the road. The left of the image, from 0 to 12 m, has different characteristics due to steel reinforcing bars (rebars) within the concrete. Each of these rebars generates a strong reflection from which each of the rebars can be mapped. The rebars inhibit the energy that penetrates into the road so that the underlying, sub-horizontal reflectors now appear to be broken up. The road also contained a number of voids and the larger of these, with a thickness greater than 20 cm, generated characteristic hyperbolic diffractions within the image.

The second survey is a good example from a topical problem – the location of former, abandoned mine shafts. Due to the problems of accurate surveying in the past and the loss of many records, the recorded position of old mine shafts is often found to be in error. Hence, there is a constant requirement for a quick, non-invasive method to locate them. Figure 16 is a radargram from over a capped mineshaft at Calverton Colliery, Nottinghamshire. The strong sub-horizontal reflector between 15 and 38 m is from the concrete cap over the mine shaft. The apparent topography along this reflector is most likely due to variations in the overburden. Although GPR will not be successful in every survey to locate shafts, this survey demonstrates the potential of the method.

The conclusions that can be drawn from GPR surveys for infrastructure are as follows:

- Since infrastructure is shallow, it is within the range of high frequency GPR.
- From the characteristic responses within the radargrams it is possible to distinguish steel reinforcing bars, small voids, tunnels and concrete plinths.
- GPR will not always be successful for mapping infrastructure, especially in electrically conductive environments, but it does have many applications in this field.

3.6 INVESTIGATIONS OF CHALK

The chalk outcrop of England is an important lithology that often requires investigation. It is a primary aquifer in these regions and forms the bedrock for many buildings and infrastructure. It is also quarried for cement making and in the past has been mined for lime production. Chalk owes its primary permeability to fractures, so identification of fractures and fracture zones is a key exploration criterion for aquifer management. The remote measurement of fractures from the surface also has applications in cliff stability studies. Given that fractures do not involve an offset in the stratigraphy they represent a difficult discontinuity to map. Another geophysical method, azimuthal apparent resistivity, claims to be able measure fracture orientation and fracture frequency (Taylor and Fleming, 1988). However, this is based on the anisotropic physical properties that the fracture set imposes on the rock mass, rather than mapping of individual fractures. GPR has mapped fractures within granites (Stevens et al., 1995) where there is a large reflection coefficient between the water filled fracture and the host rock. Dussauge-

Peisser et al. (2003) report mapping of fractures in a limestone cliff, although the fractures had been enlarged through dissolution.

Noggin 250 MHz data were collected at two coastal sites on the East Sussex coast at Beachy Head and Birling Gap. The purpose was to try to characterise the chalk in terms of its fracturing, layering, identification of flint bands and the nature of the overburden. The two sites are only 2.5 km apart and are both situated on Seaford Chalk. Seaford Chalk is characterised by sub-vertical fractures that have mapped dominant fracture orientations of 70° and 150°. Beachy Head is on a westerly facing slope that has undergone deep periglacial weathering that might have created randomly orientated fractures near surface and a variety of dissolution features. The site is on the northerly limb of the Beachy Head Anticline and dips at 15° to 20° to the north-west. Birling Gap is west of Beachy Head so, due to the north-westerly dip, the Seaford Chalk that is exposed at the top of Beachy Head is found at about 20 m below the top of the cliff at Birling Gap. A north-westerly-trending fault is clearly visible in the wave-cut platform that intersects the cliff at an oblique angle. The strata at Birling Gap are approximately horizontal. Periglacial weathering is less intense than at Beachy Head and there are less dissolution features.

Representative radargrams from the two sites are shown in Figures 17 and 18. They are similar in form, being generally unreflective, but with some distinct, sub-horizontal reflectors in some of the sections. These sub-horizontal reflectors are tentatively interpreted as flint bands as in places they are also associated with diffractions that may be generated from the uneven upper surface of the band. At Beachy Head their apparent dip is greater than at Birling Gap. This may due to the greater dip of the strata and the slope of the ground surface since no topographic correction has been applied to the data. Individual radargrams where there appears to be little reflectivity may be due to greater thicknesses of near surface clay infill. There is no evidence of individual fractures or a change in radar character suggesting the intensity of fracturing of the rock mass.

The conclusions that can be drawn from the GPR surveys over chalk are as follows:

- There was no evidence in the data of fracturing or bedding of the strata.
- Some distinct sub-horizontal reflectors were detected that are tentatively interpreted as flint bands.

3.7 GREATER MANCHESTER URBAN SURVEY

Many urban investigations are aimed at the shallow sub-surface. The urban environment is not suited for many geophysical methods since it is both electrically and seismically noisy. However, GPR is one of the few methods that is able to operate, although the environment still presents problems as the ground is often disturbed from former land use and there are likely to be reflections and sideswipe from utilities and services.

Noggin 250 MHz data were collected from two sites in Manchester. The purpose of the surveys was to map the depth and extent of two buried channels that were believed to lie at shallow depth. The expected geology was alluvial fill overlying glacial moraine. Two representative radargrams from each of the two sites at Kingsway Park and Bradford are shown in Figure 19. Kingsway Park is a recreation ground that has undergone considerable landscaping. The only significant reflection (and associated multiple) occurs over an area back-filled with rubble. Bradford is the site where the City of Manchester stadium car park was built for the Commonwealth Games in 2002. The survey was carried out before construction took place, but after the terraced housing on the site had been demolished. The only significant reflection occurs at a twtt of 40 ns and appears to dip towards the right of the section. This might be initially interpreted as the upper surface of the buried channel. However, after discussions with the local geologists it appears that the channels are quite deep and almost certainly out of the range of the high frequency radar.

The main conclusion from the GPR survey in Manchester is;

- It is essential that there is clear and concise communication from all members of a project team. This ensures that all aspects of the problem are understood so that GPR is applied in an appropriate manner.

4 Conclusions

4.1 SUMMARY

Radar penetration on limestone was found to be good, with useful data from a depth of 7 m with 250 MHz antennae. Fissures widened by dissolution were mapped and traced on open ground and beneath a road. The signature of the radar reflection from the fissure altered across the road suggesting that it is open at the edges of the road and closed in the middle. Over fractured chalk, good penetration was again achieved, although individual fractures were not resolved. A number of reflectors are tentatively interpreted as flint bands. The non-linearity and lack of continuity of these reflections may result from a variable cover sequence and changes in the thickness of the flint bands. The Holme Pierrepont sand and gravel deposit was imaged to its base by 50 and 100 MHz radar and the topography of the underlying Mercia Mudstone surface was mapped. Internal structure was well defined, especially with 250 MHz antennae. Hence, GPR could have a major role to play in aggregate resource assessment and could be applied to the mapping of shingle beach thickness. Landslides represent a significant geohazard that can damage property and infrastructure. In areas of surface geology comprising mudrock, clay or till, where landslides often occur, GPR will have only a limited role to play due to the attenuation of the radar signal by the conductive ground. In regions of more resistive terrain then sliding and cambering of the ground can be mapped with GPR.

GPR surveys were able to successfully map the location of tunnels, of which the roofs were characterised by broad hyperbolae within the radar images. In some cases, a horizontal reflection was also returned from the floor of the tunnel. It should be possible to map cave systems within the relatively near surface in karstic terrains with GPR. Infrastructure that is often at shallow depth is within the range of high frequency GPR. From the characteristic responses within the radargrams it is possible to distinguish steel reinforcing bars, small voids, and concrete plinths.

4.2 WHERE CAN GPR BE USED?

GPR is a logistically simple system comprising a transmitter and receiver antennae pair (or single antenna) separated by, at most, 2 m. It is a completely non-destructive system that emits pulsed, low power, microwave energy. It can be deployed almost anywhere and so it is ground and site conditions that determine the suitability for a GPR survey. Green field sites would usually be surveyed for geological reasons and so the sub-surface needs to be reasonably clay free. Geological investigations are often required to explore to some depth and so a depth of penetration of several meters, or ideally greater than ten meters is needed. Brown field sites are often investigated for redevelopment and so there is a requirement to map buried foundations and artefacts at shallow depth. With care GPR can be used in the urban environment where many other geophysical techniques cannot be deployed. GPR can map utilities, tunnels, voids as well as the near surface geology and so may be valuable as a technique to identify and perhaps eliminate sources of noise in larger scale surveys exploiting other geophysical techniques. Spurious anomalies can result from sideswipe of surface features such as kerbs and air reflections can be obtained from metallic objects above ground. Increasing problems in many areas are caused by mobile phone masts whose frequencies of transmission overlap those used by GPR. Their effect is to generate high frequency noise within the radar traces. GPR has been used successfully along roads and so surveys can run from grassed areas onto tarmac and concrete. With high frequency radar, the construction of roads can be imaged allowing the depth of the base to be mapped and steel reinforcing bars to be located.

4.3 WHEN IS GPR MOST EFFECTIVE?

- The radar signal is attenuated by electrically conductive ground conditions. Hence, very poor penetration is achieved over mudstone, clay or marl, or over sediments that are saturated in saline water, as in many coastal situations. Over electrically resistive ground, such as sand and gravel, the converse is true and it is possible to obtain reflections from depths of 15 m or more. Ice, which is highly resistive, is virtually transparent to GPR.
- The varying attenuation properties of earth materials can be used to advantage by GPR. The distinctly different radar characteristics enable areas of clay or sand and gravel to be rapidly mapped out.
- The depth of penetration of GPR is also determined by scattering of the radar signal in the ground. As the frequency increases, small-scale features such as fine scale bedding, cracks and joints become radar targets that reflect and scatter the signal. Hence, there is a trade-off between obtaining high-resolution data and deeper penetration.
- Resolution of features is determined by the radar frequency, i.e. the higher the frequency the greater the resolution. However, a thin layer may still give a distinct reflection although it will not be possible to resolve the dimensions of the layer.
- Contrasts between the dielectric constants of earth materials determine the radar reflectivity of the ground. Since water has a high dielectric constant, a distinct water table would be expected to generate a strong reflection. The radar reflectivity of many unconsolidated sediments will be determined by the combination of rock matrix, air and water. Thus, seasonal variations in ground moisture content might be measured, qualitatively, by the change in radar reflectivity.
- GPR has a high rate of data collection enabling detailed data sets to be collected rapidly.

4.4 TWO-DIMENSIONAL VERSUS THREE-DIMENSIONAL SURVEYING

GPR data is collected along profiles in two-dimensions. Sometimes profiles are recorded in isolation and sometimes an area is investigated with widely spaced profiles. In this mode only distinct reflectors and zones of characteristic reflectivity will be mappable. Some features will generate a radar response that is very difficult to identify when compared with other parts of the radargram. Only by taking data along closely spaced profiles and generating a pseudo three-dimensional data set will continuous features become apparent. Other, spurious, reflections will not be continuous throughout the data set. In addition, three-dimensional data makes it possible to estimate the true dip and strike of interpreted features.

5 Recommendations

One of the objectives of the “Application of ground penetrating radar to geological investigations” project is to bring increased awareness of GPR to relevant Programme Managers and project leaders across the BGS. This in turn should lead to a greater integration of GPR into multidisciplinary projects. This section makes a number of recommendations in order to achieve this aim.

- This report will be sent to all relevant Programme Managers so that they can circulate the report to all project staff.
- The new BGS Programme to be launched in April 2005 is likely to have an increased emphasis on investigations at the more detailed site level. These are likely to be shallow investigations on environmental issues, soil mapping, applied geology, coastal studies etc. Applied after consultation, GPR could add significantly to these studies and hence Programme Managers and project leaders should be aware of the potential of GPR. There may be opportunities in NERC Thematic Programmes and Programme Managers should contact those with GPR skills when they become aware of such opportunities.
- Commissioned Research also presents opportunities for GPR, especially when offering skills to multidisciplinary projects where the project team are assembled from a number of organisations. The user community will drive such projects and hence GPR will be only one of a number of tools used to address the problems posed. Again the awareness of Programme Managers to the potential of GPR will be critical.
- There may also be opportunities for GPR within the commercial programme, but this will require the active marketing of the capability. A minimum requirement will be the production and distribution of flyers and inclusion of GPR capability on the BGS stand at relevant Trade Fairs.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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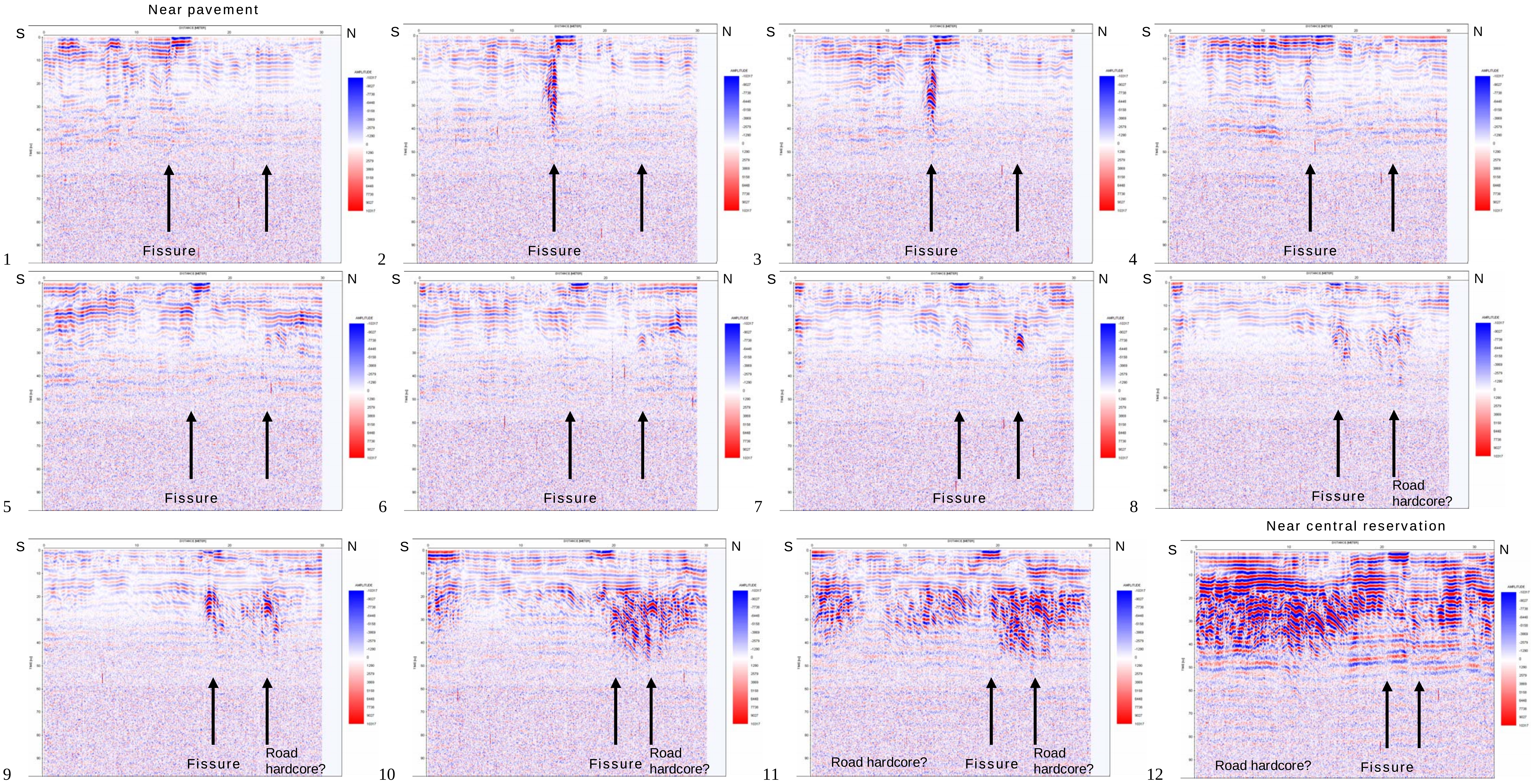


Figure 2. Radargrams of 250 MHz data for 12 of the lines conducted along the northbound carriageway of the A690. As highlighted, the fissure can be seen on almost all of the cross-sections. Assuming a radar velocity of 0.0679 m ns^{-1}, each section has a full depth extent of 6.65 m, with useful penetration not exceeding 3 m.

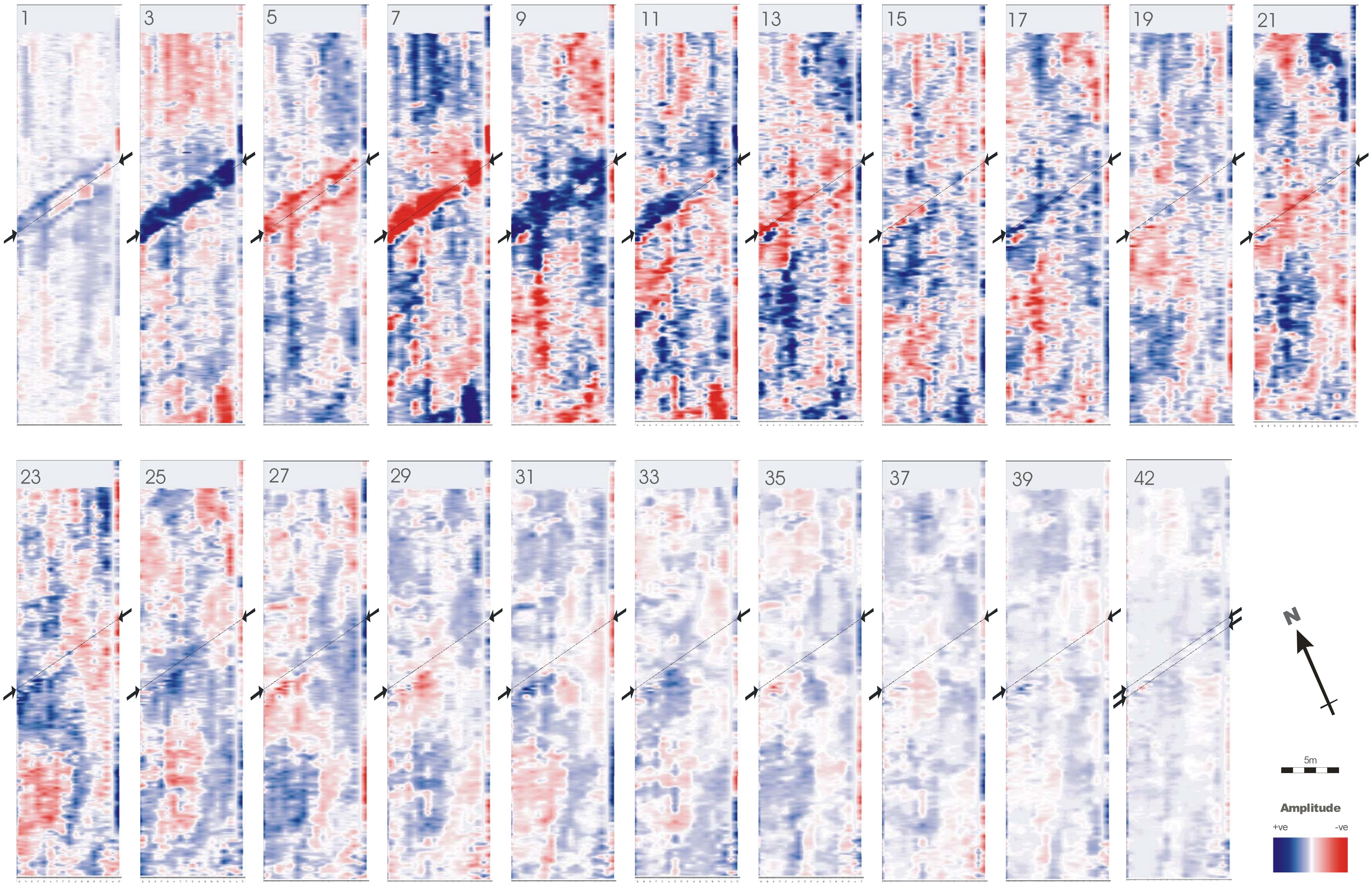


Figure 3. Time slices of GPR generated from a 3D data representation. Each successive map represents increasing depth. The location of the known fissure is highlighted. Depth slices from 1 to 42 represent the surface level down to a depth of approximately 1m, assuming a radar velocity of 0.0679 m ns^{-1}.

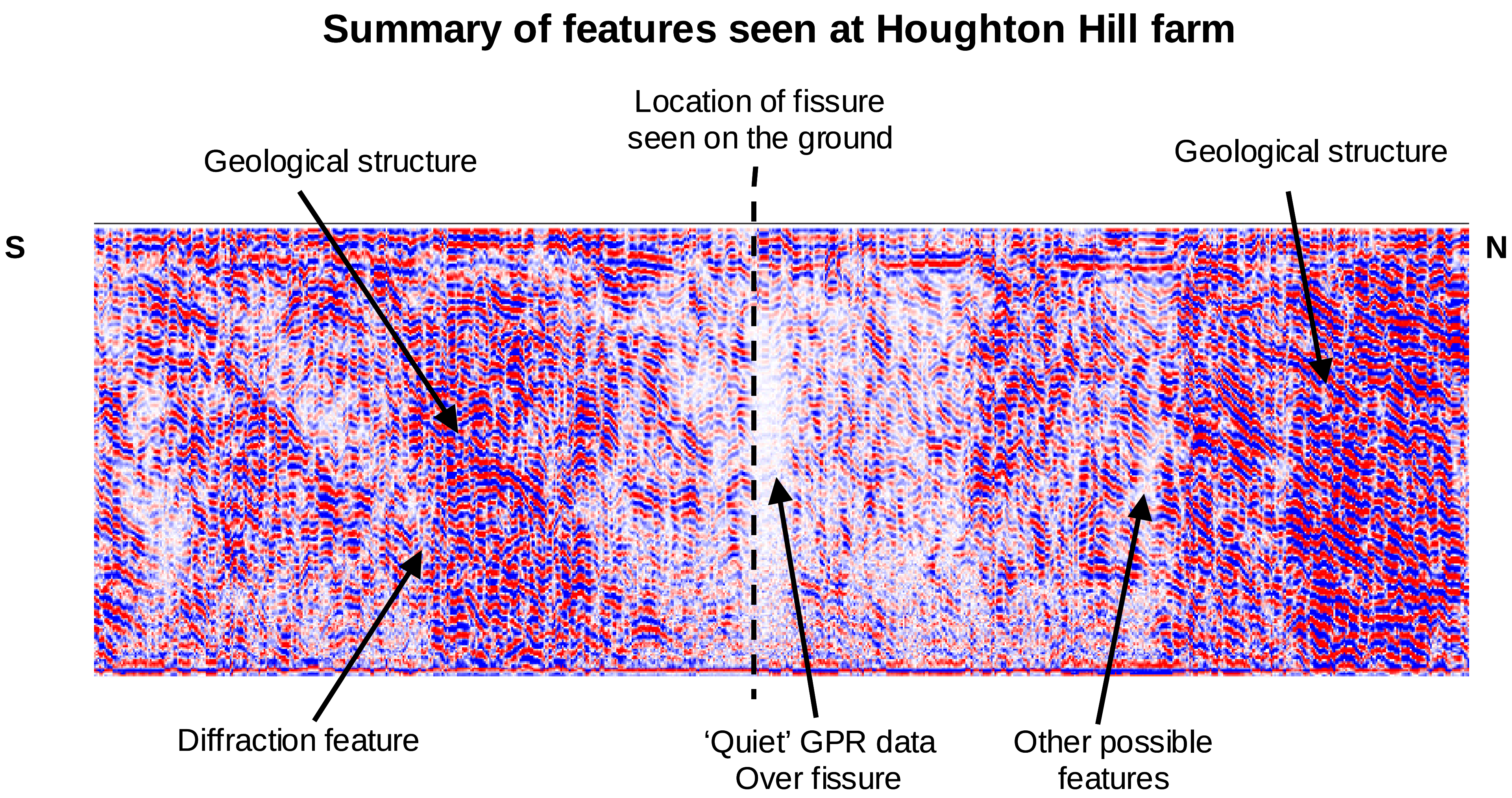


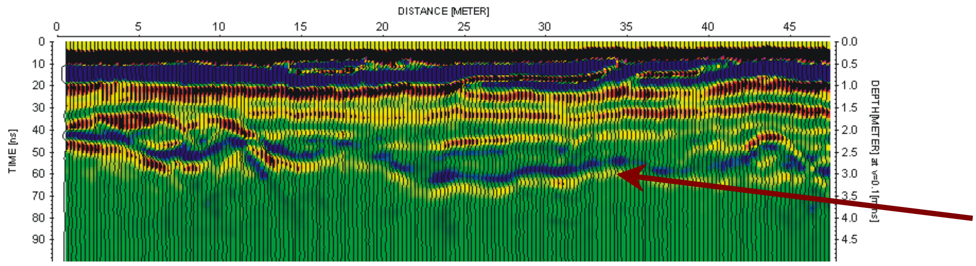
Figure 4. Summary of the general features seen at Houghton Hill farm. The fissure is shown as a shadow feature. Considerable geological structure is observed. Other shadow zones may suggest smaller scale fissures. A diffraction feature is also seen at depth and could also be a fissure. Assuming a radar velocity of 0.0715 m ns^{-1}, the section has a full depth extent of 7m.

Figure 5. Fissure exposed beneath the near-side lane of the north-bound carriageway of the A690, 20 June 2003. Walls of solid dolomitic limestone and an open fissure beneath the tarmac can be clearly seen.

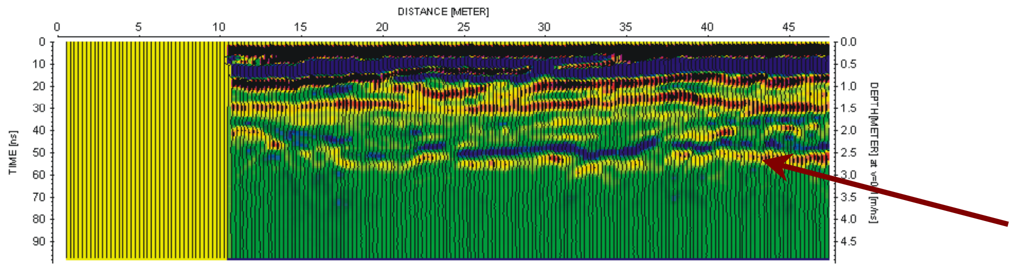
Figure 6. The Holme Pierrepont Sand and Gravel deposit overlying Mercia Mudstone.

Figure 7. The Pulse Ekko 100 with 100 MHz antennae, in use on the '5m bench' at Holme Pierrepont.

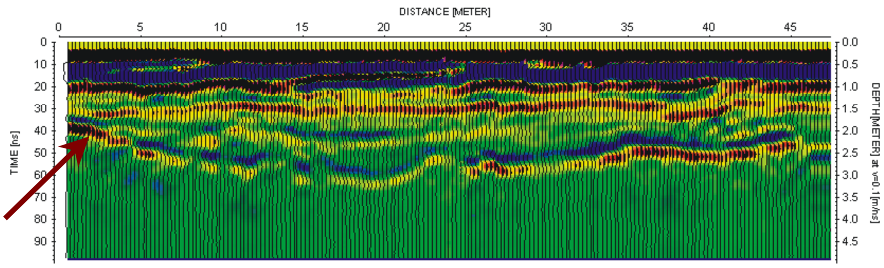
Line x = 0



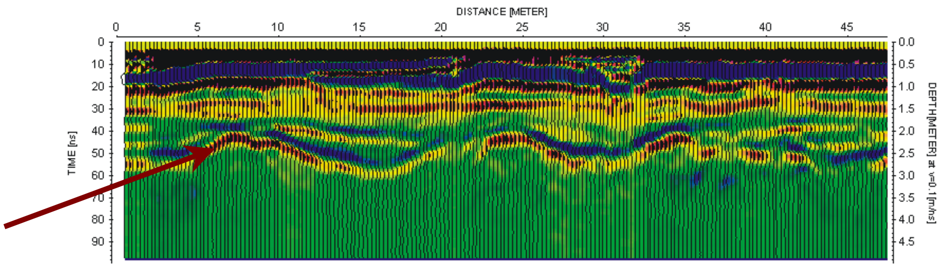
Line x = 6



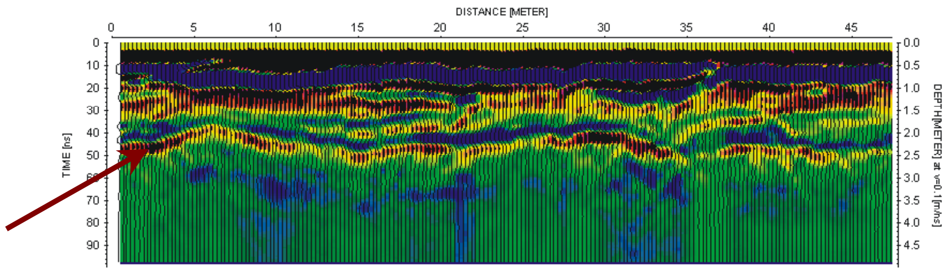
Line x = 12



Line x = 18



Line x = 24



Line y = 24

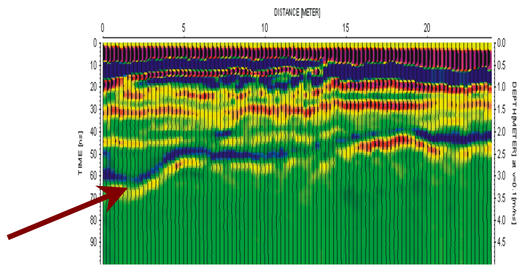
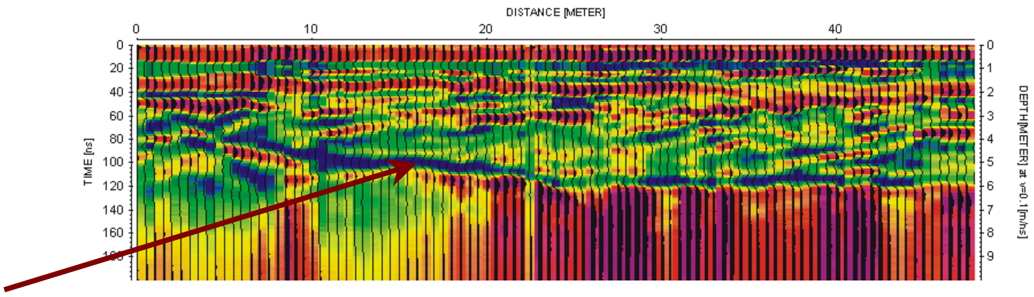
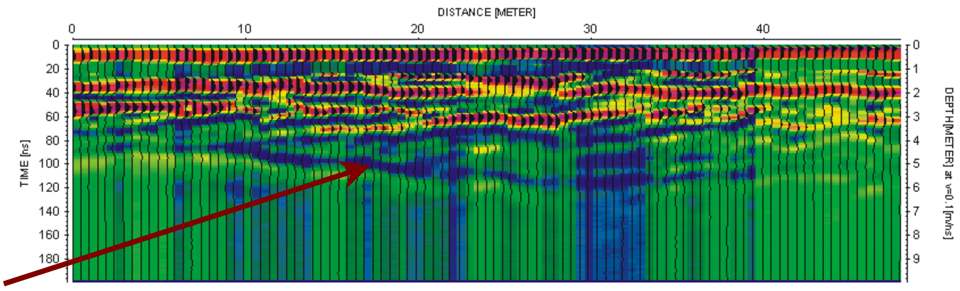


Figure 8. Radargrams of 100 MHz data from the '5 m bench' at Holme Pierrepont. Data were collected along five lines in the x direction and one line in the y direction. Depth conversion based on a velocity of 0.1 m ns^{-1}. Mercia Mudstone reflector indicated by an arrow.

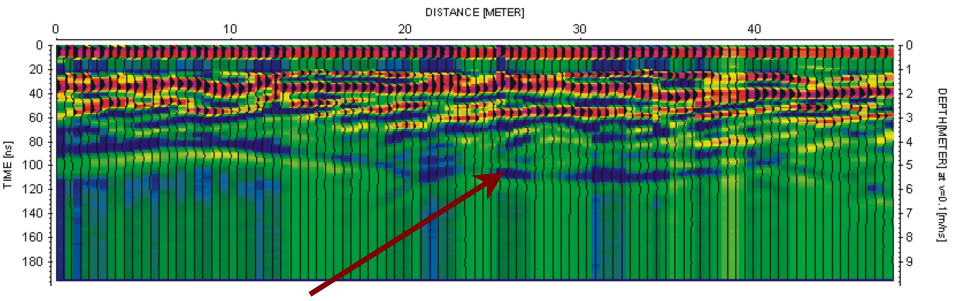
Line x = 0



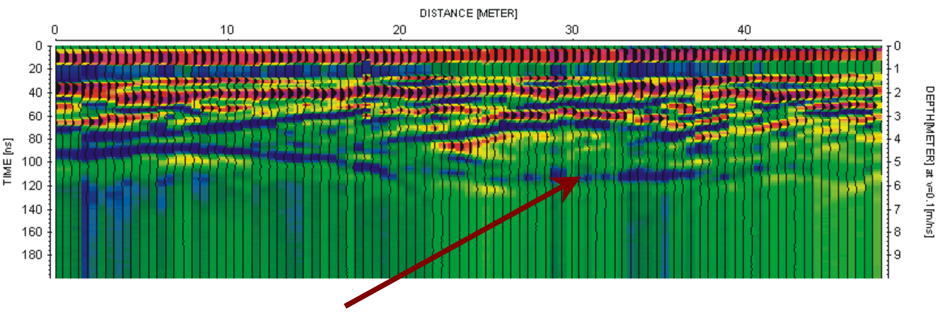
Line x = 6



Line x = 12



Line x = 18



Line x = 24

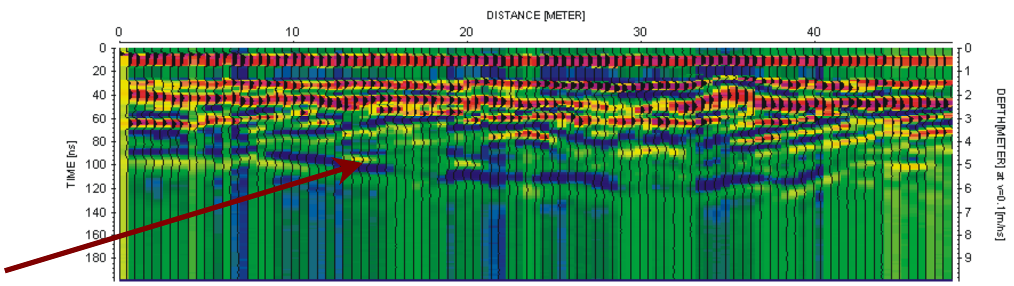
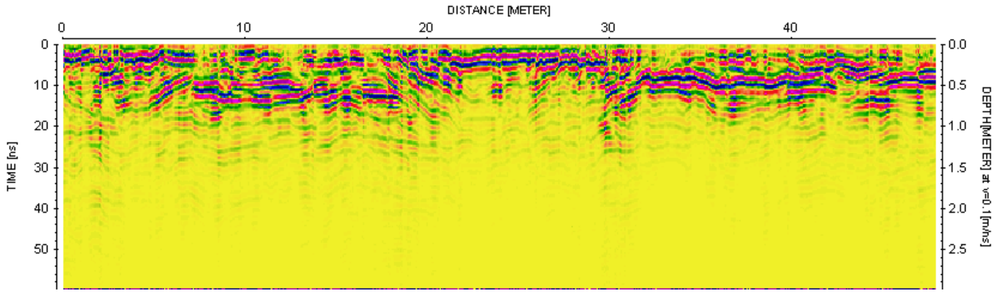


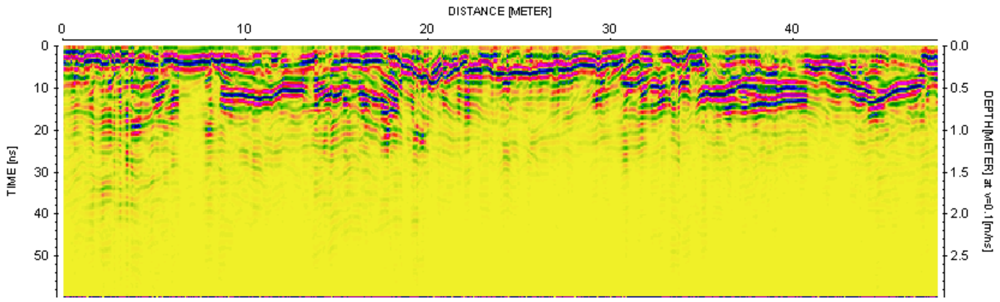
Figure 9. Radargrams of 50 MHz data from the '10 m bench' at Holme Pierrepont. Data were collected along five lines in the x direction. Depth conversion based on a velocity of 0.1 m ns^{-1}. The Mercia Mudstone reflector is indicated by an arrow.

Holme Pierrepont, 10 m bench, 250 MHz data

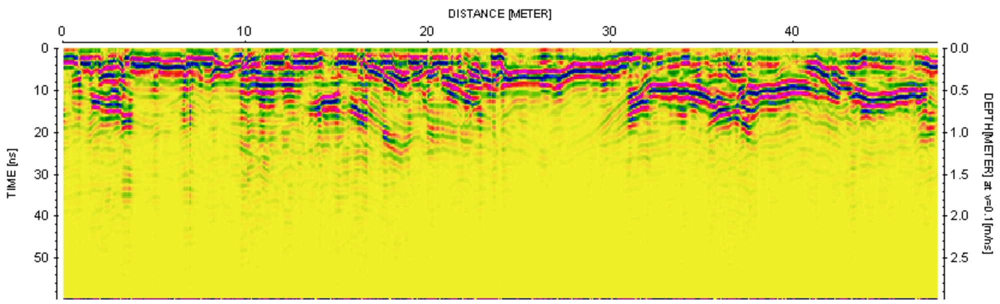
Line x = 2



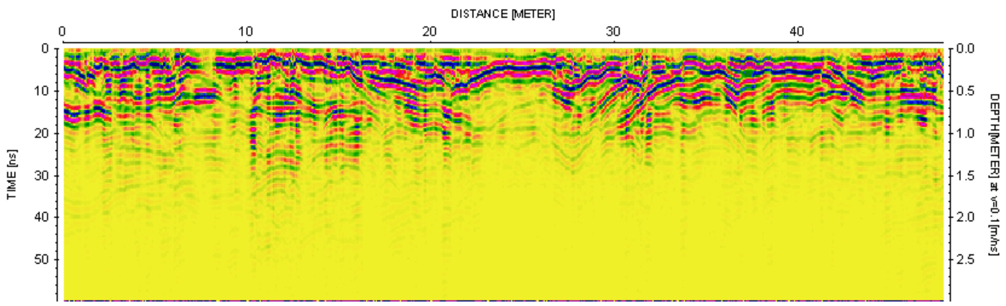
Line x = 4



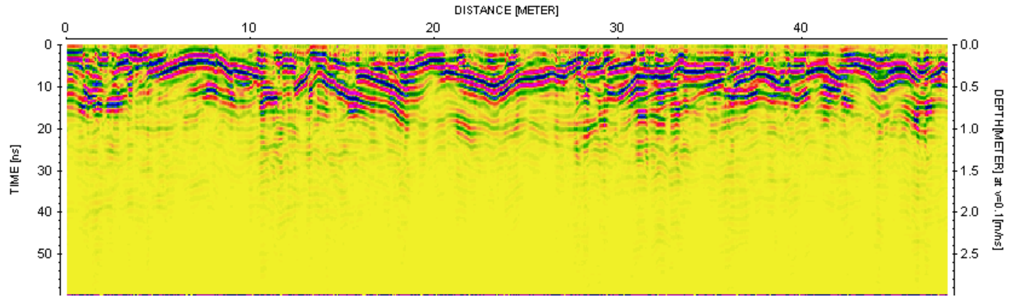
Line x = 6



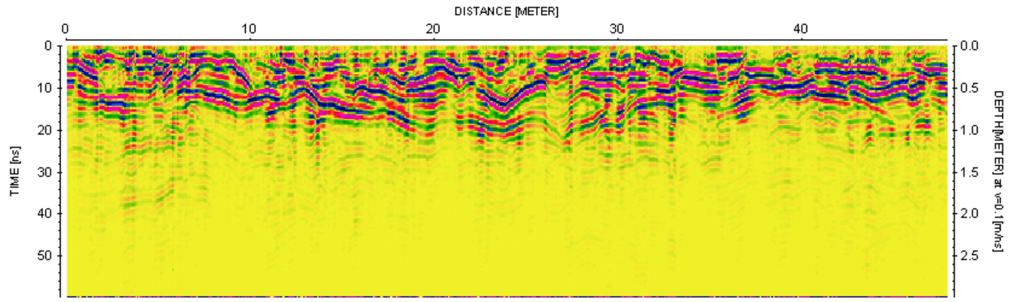
Line x = 8



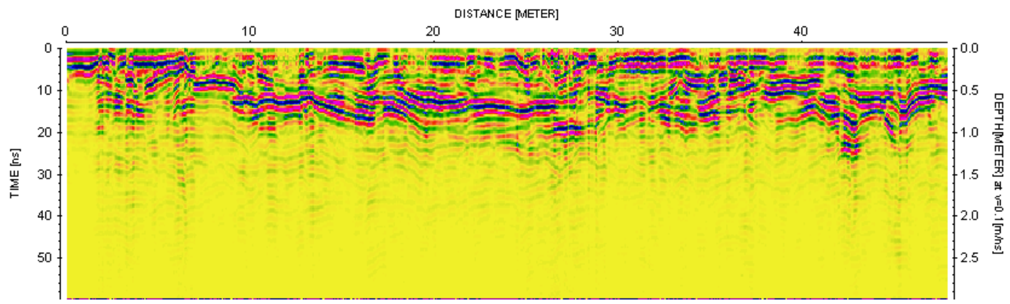
Line x = 10



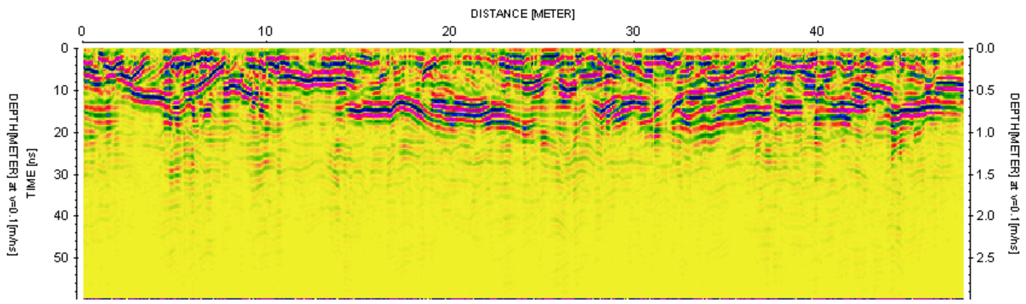
Line x = 12



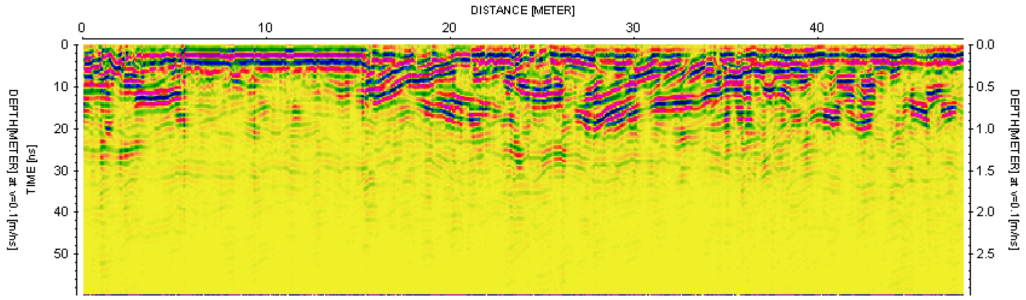
Line x = 14



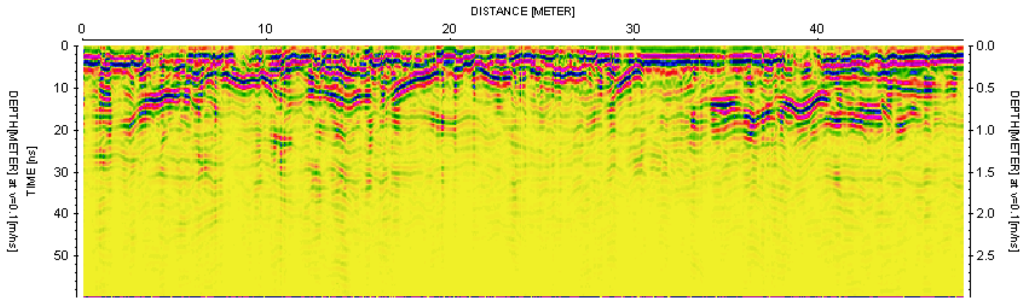
Line x = 16



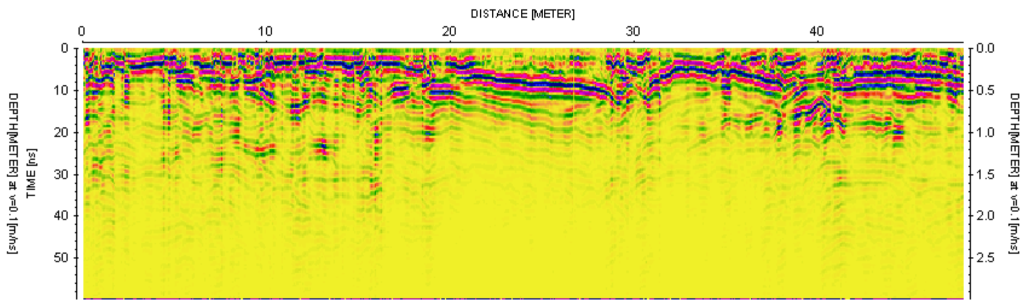
Line x = 18



Line x = 20



Line x = 22



Line x = 24

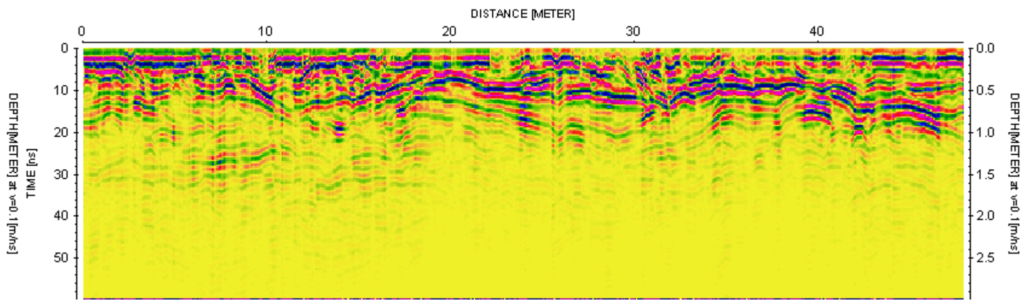
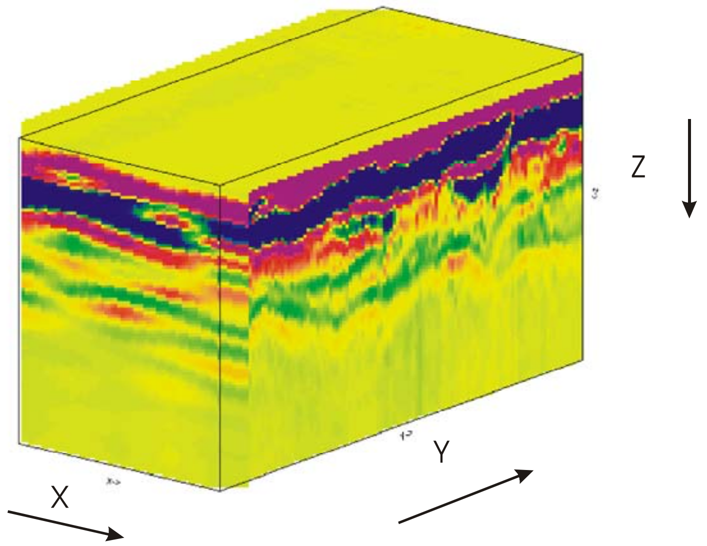
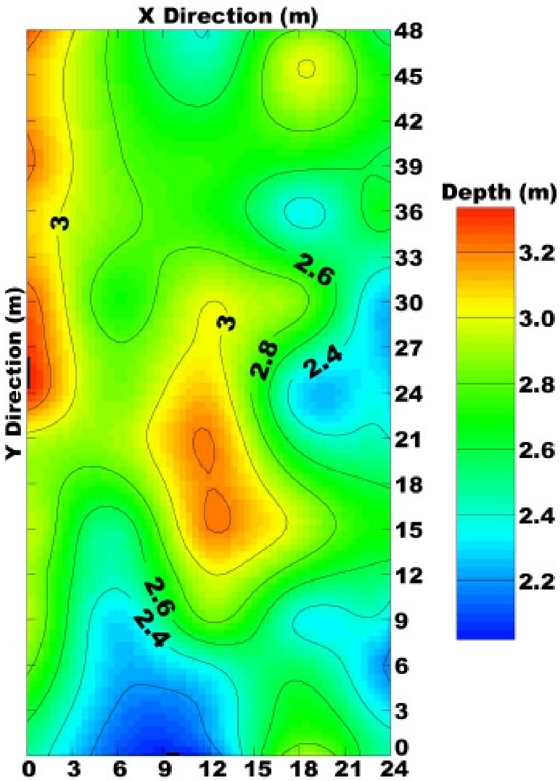


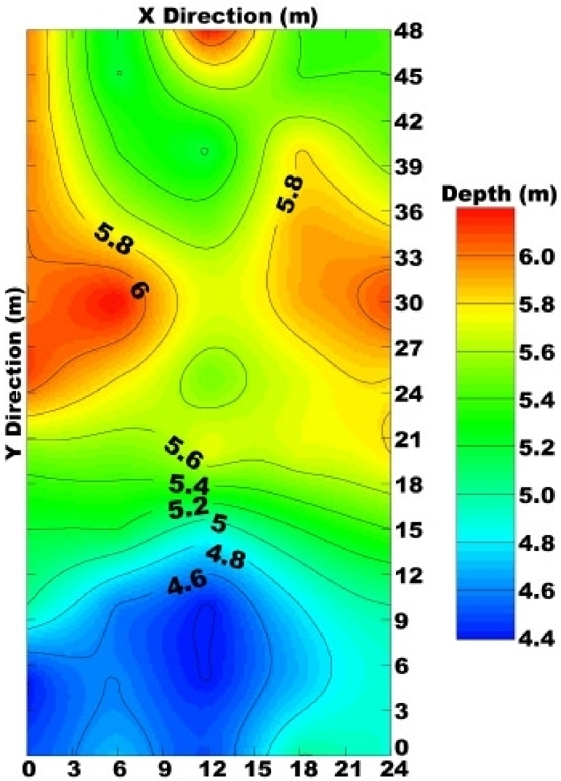
Figure 10. Radargrams of 250 MHz data from the '10 m bench' at Holme Pierrepont. Data are shown for every other line in the x direction. Depth conversion based on a velocity of 0.1 m ns^{-1}.



a) Three dimensional block data view, ‘5 m bench’, 100 MHz data



b) ‘5 m bench’, depth to base of aggregate



c) ‘10 m bench’, depth to base of aggregate

Figure 11. Three-dimensional view of the ‘5 m bench’ and contour plots of the base reflector from the ‘5m’ and ‘10 m bench’.

Figure 12. Excavation of the '5 m bench', approximately along the line x = 6, between y = 14 and 20. The hummocky surface of the Mercia Mudstone shallows towards the bottom of the grid, as seen in the GPR 100 MHz data.

Figure 13. Approximately 4.9 m of gravelly sands (Holme Pierrepont Sand and Gravel) overlying very soft - firm red clays with very hard siltstone bands of the Gunthorpe Formation (Mercia Mudstone). Grey-green reduction zones can also be seen in the Mercia Mudstone. Vertical section at approximately x = 12, y = 0, on the '10m bench'.

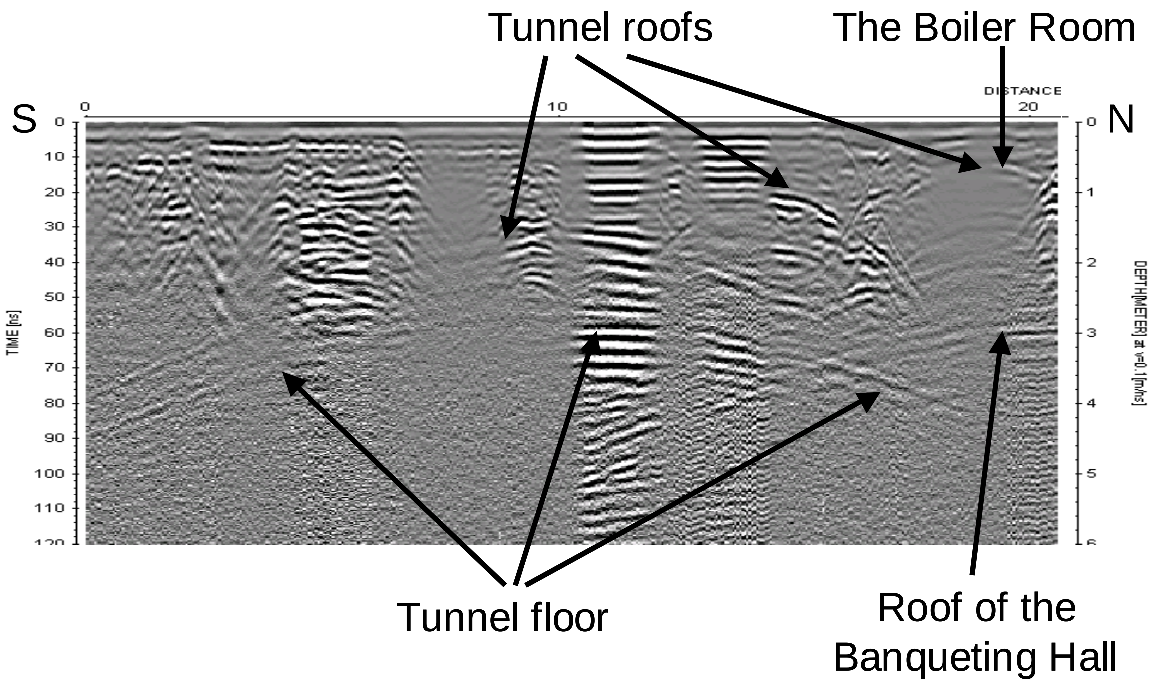


Figure 14. GPR results from over known tunnels. This traverse is taken from within Williamson's house area. This image shows the roof and floor of the "Boiler Room" tunnel, the roof of the "Banqueting Hall" and the roof and floor of one other tunnel.

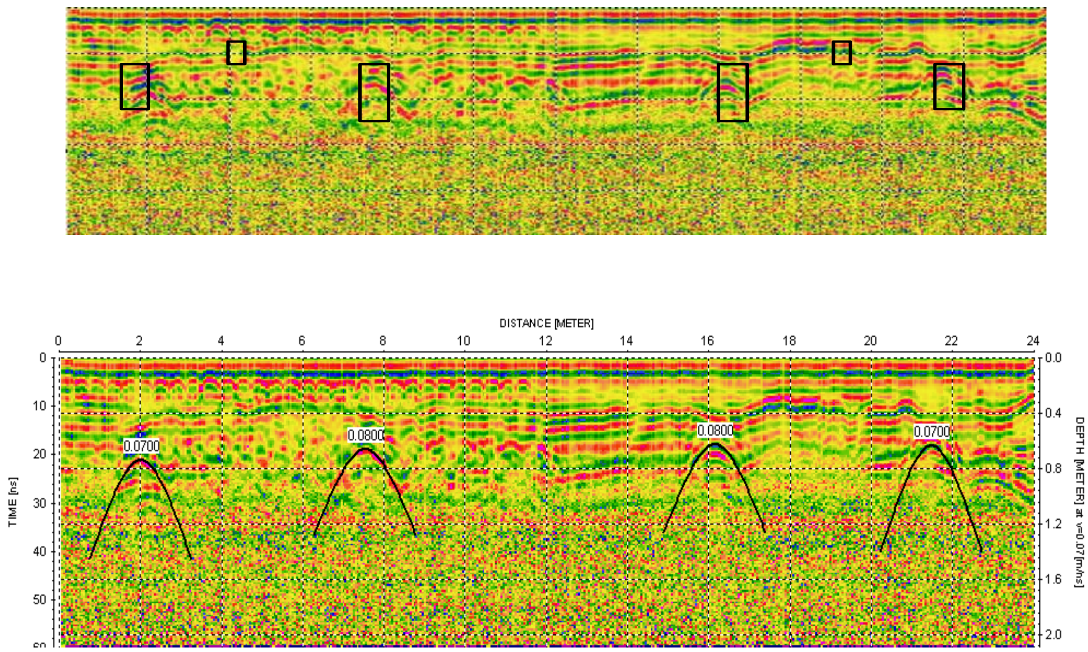


Figure 15. Radargram from the TRL road test track illustrating a number of features. The black squares in the upper image shows the location of voids. GPR hyperbolae from the voids are highlighted in the lower image where they have been used to estimate radar velocities.

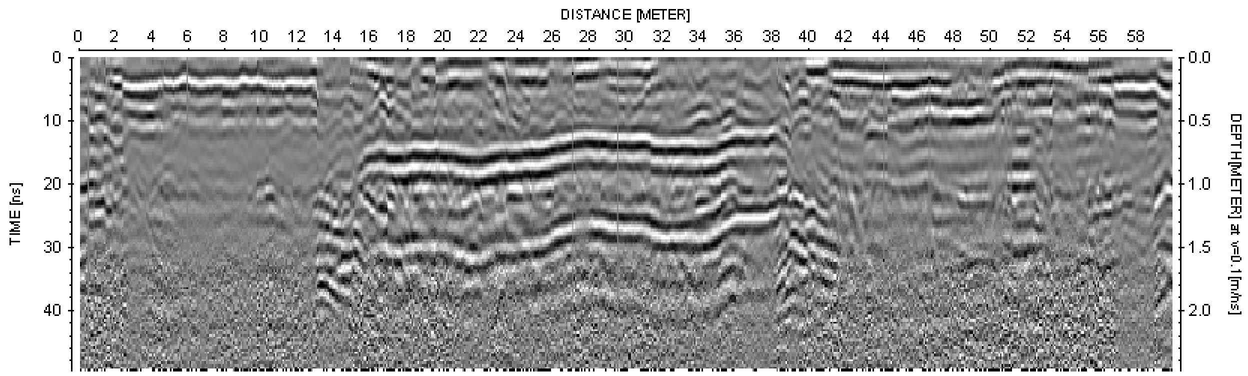


Figure 16. Radargram from Calverton Colliery, Nottinghamshire. The strong sub-horizontal reflector between 15 and 38 m is from the concrete cap over the mine shaft.

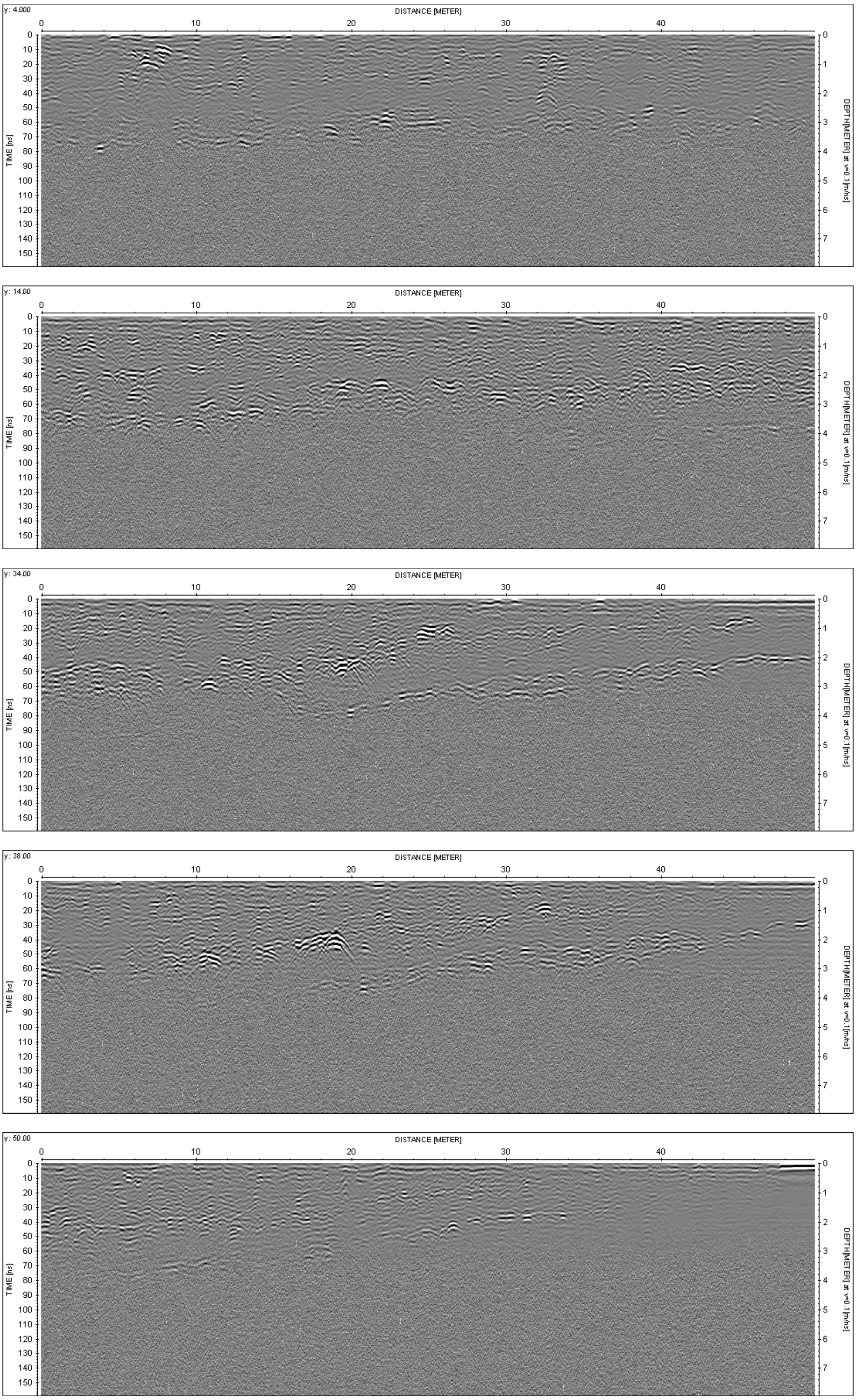


Figure 17. Representative radargrams from the Seaford Chalk at Birling Gap.

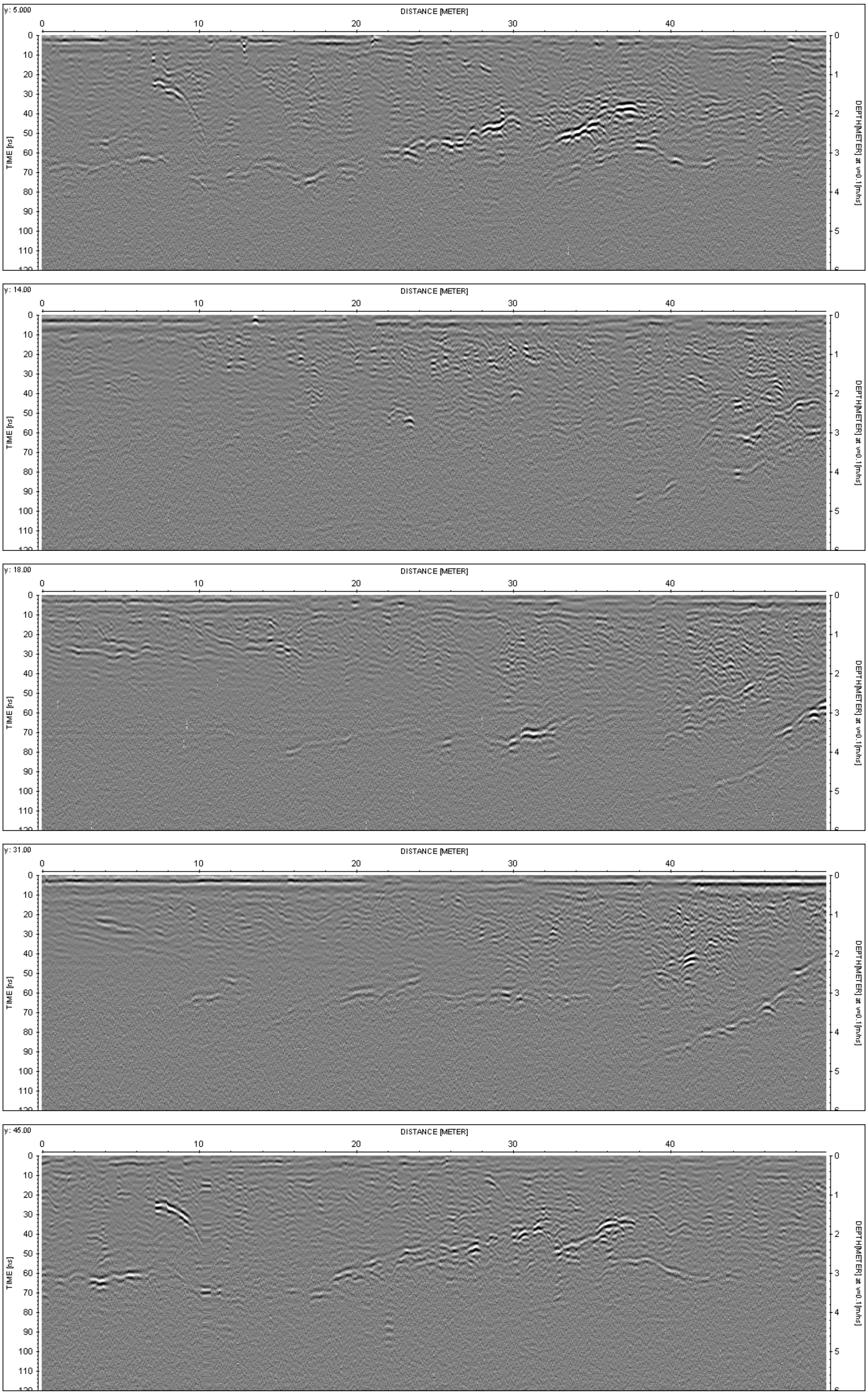
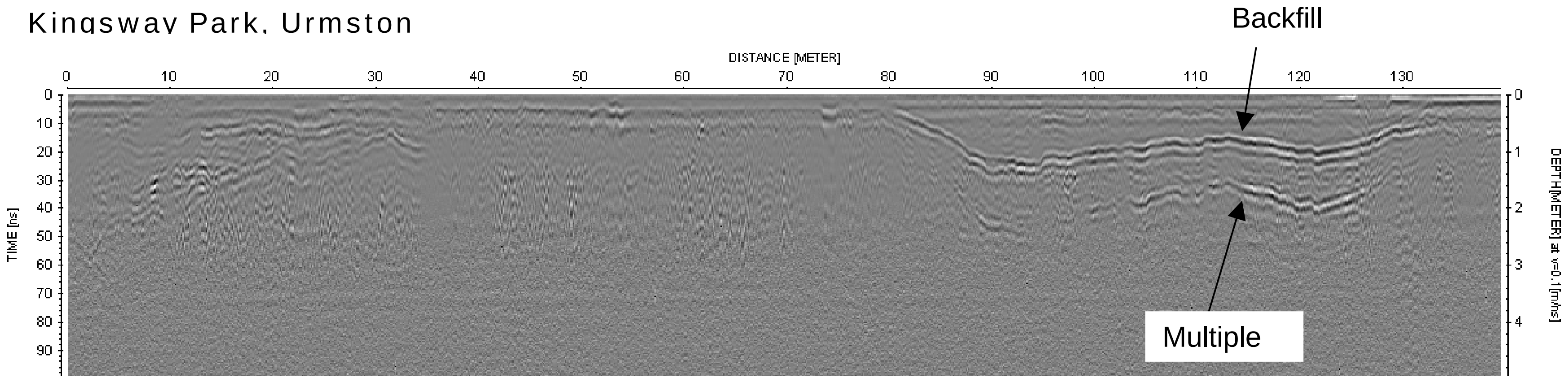


Figure 18. Representative radargrams from the Seaford Chalk at Beachy Head.



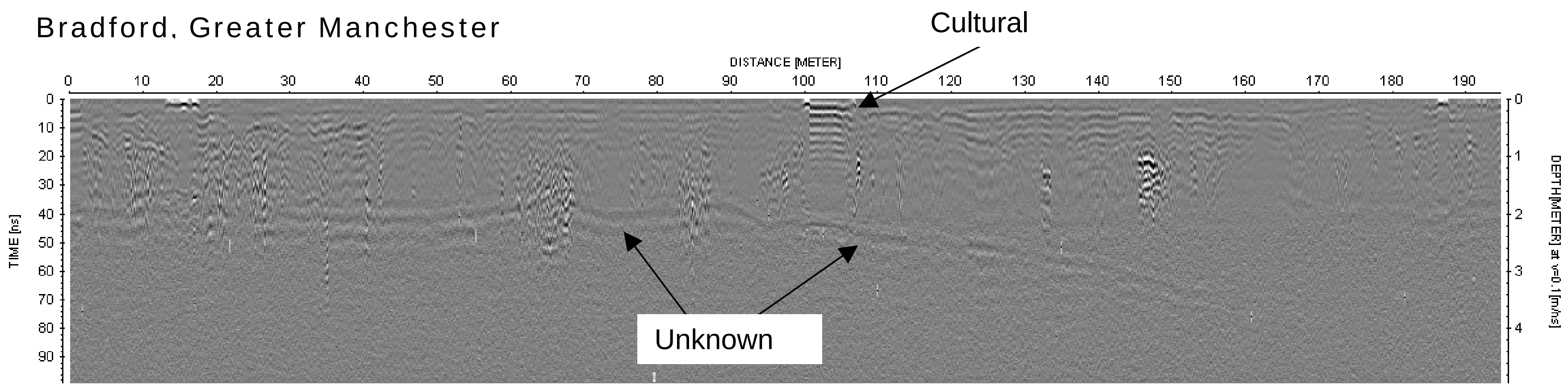


Figure 19. Radargrams from two sites within the urban district of Manchester.