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Cave Detection in Limestone using Ground Penetrating Radar

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Ground penetrating radar (GPR) is becoming a more common component of the standard array of geophysical techniques that are used by archaeologists. In this paper, we report on the use of GPR to survey an area of archaeologically important karst topography at Kitley Caves in Devon, U.K. We describe the use of GPR to detect voids within a limestone outcrop, as an aid to locating cave systems which might contain sediments suitable for excavation. The performance of the GPR equipment is analysed and the results compared to those obtained with an electrical resistance survey carried out at the same location. In particular, the depth of penetration of the GPR is estimated, and we report discernible echo signals from a much greater depth than is usually reported in archaeological applications of GPR.

Keywords: CAVE ARCHAEOLOGY, GEOPHYSICAL PROSPECTION, GPR SURVEY.

Introduction

Caves in hard limestones form natural sediment traps, and they often contain deposits in which archaeological remains and Pleistocene fauna may be preserved (Sutcliffe, 1985). Most known caves either have visible entrances, where natural erosion or roof collapse has exposed the cave, or they are revealed by chance during quarrying, tunnelling or other groundworks. Speleologists suspect that many caves remain undiscovered because they do not reach the ground surface or because their entrances are obscured by unconsolidated surface deposits. Detection of undiscovered caves is important in the evaluation of the environmental and archaeological potential of karst landscapes and in the planning of field research projects in limestone areas.

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There are a number of geophysical techniques that can be used to detect the presence of caves and other voids below the surface. Microgravity is popular and effective since there is clearly a large difference in density between the surrounding substrate and the void (Butler, 1984; Smith & Smith, 1987; Linford, 1998). However, gravity methods have the limitation that they do not detect the actual shape of the void but rather require the surveyor to postulate a possible shape, run a simulation, and see whether the simulated outcome matches the observed data. With a priori knowledge of likely shape (when verifying documentary evidence of a mine or tunnel, for example) this can be very effective, but when prospecting for an unknown cavern it is a major disadvantage. Resistivity tomography can also be used since the resistance of the void will be higher than the surrounding substrate (Noel & Xu, 1992;

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Manzanilla *et al.*, 1994). Unfortunately, limestone itself has a very high resistance which means that this technique is less likely to be successful. A third technique is geophysical diffraction tomography using low-frequency sound waves, an approach which has been used with some success (Levy *et al.*, 1996). The main disadvantage with this technique is that the placing of the geo- and hydrophones required can be difficult and time consuming which makes it less appropriate for prospecting. Previously published fieldwork trials suggest that ground penetrating radar (GPR) is also an effective means of detecting small (i.e. less than 10 m diameter) caves and fissures in karstic terrain (Collins *et al.*, 1994; Benito *et al.*, 1995; Harris *et al.*, 1995).

GPR systems detect reflections from short bursts of electromagnetic radiation emitted by a portable radar transmitter (Millsom, 1996; Conyers & Goodman, 1997). The principles of the method are similar to those of seismic sounding: in the case of GPR the reflections come from objects and layers within the ground which alter the speed of transmission of the radar signal. Thus air-filled voids and layers of water-saturated sediment are strong radar reflectors. The depth of penetration of GPR depends on the frequency of the radar signal as well as the electrical properties of the substrate. The power of the radar transmitter, the sensitivity of the receiver and numerical signal processing of the acquired data are also important considerations.

Previously published archaeological applications of GPR have tended to use antenna centre frequencies of 300 MHz or greater (Goodman *et al.*, 1994; Beck & Weinstein-Evron, 1997; Conyers & Cameron, 1998; Toghe *et al.*, 1998; Dobbs *et al.*, 1999). These radar frequencies provide excellent resolution, but they limit the subsurface depth penetration of the GPR to less than 5 m. On open archaeological sites this depth of penetration is often sufficient to reach the base of any archaeological deposits, and Beck & Weinstein-Evron (1997) have used a 500 MHz GPR inside a cave to detect interfaces between unconsolidated sediments and limestone bedrock at a depth of 2 to 3 m below the surface of the sediment. However, when working from the surface of a limestone outcrop lower radar frequencies are often necessary because archaeological and palaeontological caves may be several tens of metres below the ground surface. The selection of an appropriate antenna frequency is probably the most important choice when undertaking a GPR survey, since lower frequency antennas allow much greater depth penetration, but they will fail to detect small diameter anomalies (Jol, 1995). Lower frequencies also require the use of much larger antennae, which can be unwieldy especially on uneven and densely vegetated terrain.

Post-acquisition processing of the radar data is another area for consideration when using GPR. A digital recording system is required because the GPR system records a continuous datastream, consisting of several thousand datapoints, at each survey station. The data are generally recorded directly onto a laptop computer in raw form, and digital signal processing techniques are used to extract the features of interest. Data from a single transect can be presented as a vertical section showing the depth and location of anomalies along the line of the transect. Data from a grid can be processed to produce three-dimensional models or depth slices—both of which are powerful visualisation tools. One of the major difficulties is that the radar beam is not collimated and reflections are obtained from a broad cone below each recording station. There are a number of mathematical techniques, such as synthetic aperture time-domain focussing (Johansson & Mast, 1994) that attempt to compensate for this problem, but they are often only successful where the substrate is largely homogeneous and when the signal transport properties are well characterised (Nelson, 1994).

Survey Site

The Kitley caves are located in an outcrop of middle Devonian limestone at Yealmpton, South Devon, U.K. (National Grid Reference SX 57505125). Several of the caves are intersected by the former working faces of a disused lime kiln quarry located at Western Torrs, on the northwest side of the narrow gorge formed by the river Yealm (Figure 1). The cave systems penetrate the limestone on both sides of the river Yealm, and they show internal structural features such as tubular passage forms, roof pockets and water table notches that indicate that the caves formed in phreatic (flooded) conditions just below the water table. The caves appear to have developed preferentially along northwest–southeast and northeast–southwest orientations, corresponding to the principal joint sets in the limestone. Around Western Torrs Quarry horizontal networks of caves occur at two main levels, 6 to 21 m above Ordnance Datum (e.g. Show Cave and Hen Hole) and 23·5 to 30 m O.D. (Shelter Cave and Bob's Cave), preserving evidence of former water tables at altitudes of 14 m, 16·5 m and 26 m O.D. On the south side of the river in Yealmpton Cave there is evidence of a yet higher water table at an altitude of 33 m O.D. The altitude of the present day water table is determined by the height of springs draining onto the valley floor at 6 m O.D., suggesting that the water table notches preserved in the caves result from successive changes in the altitude of the valley floor during cave formation.

The Kitley Caves contain breccias, flowstones and unconsolidated cave sediments of Pleistocene and Holocene date, with well-preserved assemblages of faunal remains (Chamberlain & Ray, 1994). Shelter Cave contains a stalagmite floor that is provisionally dated to Oxygen Isotope Stage 5 or 7, as well as

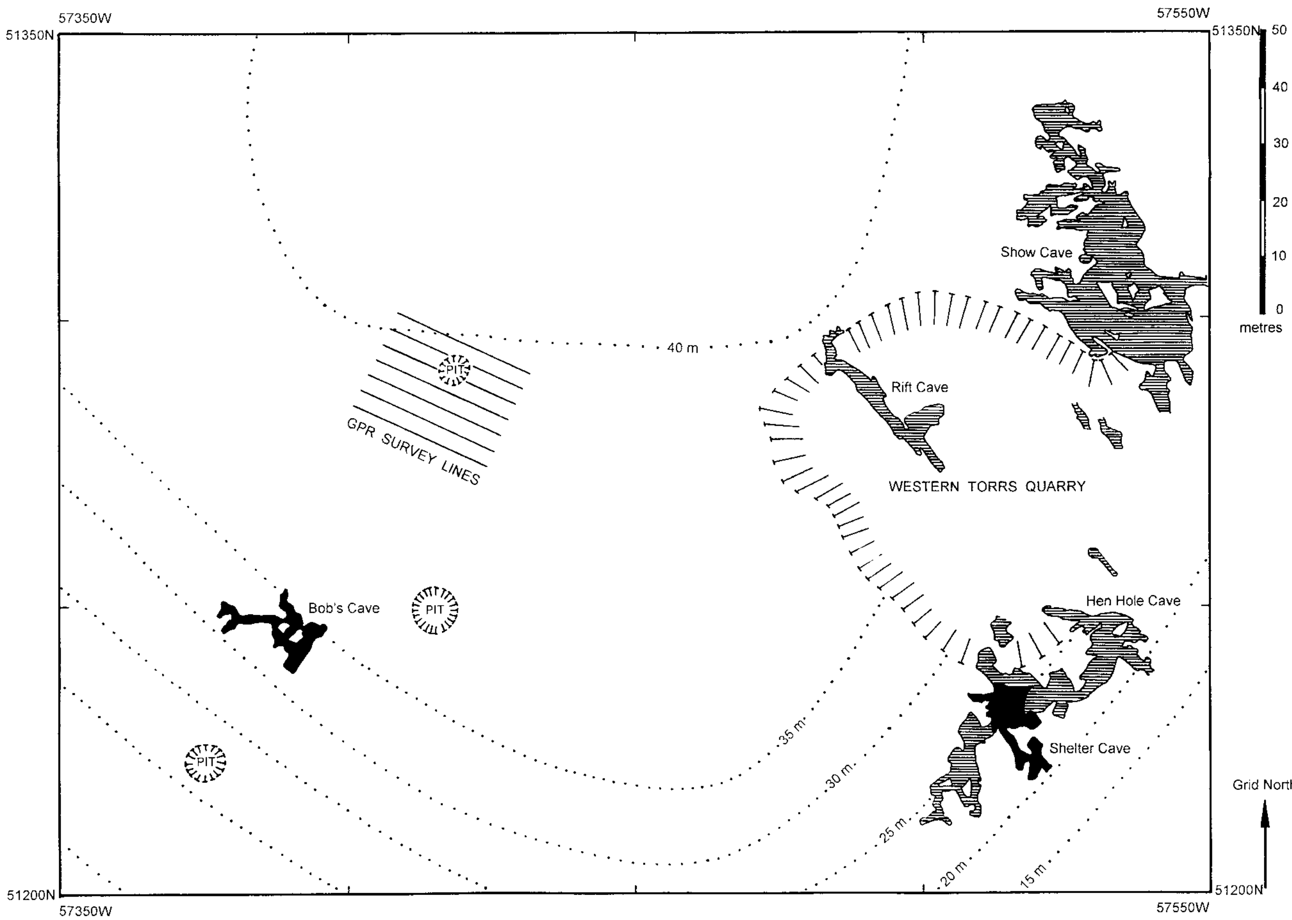

Figure 1. Location of GPR survey site at Western Torrs, Yealmpton, Devon. Contours are drawn at 5 m intervals, and vertical plans of the main low-level (shaded) and high-level cave systems (solid) are superimposed on the map.

later deposits that record the Pleistocene/Holocene transition (Coard & Chamberlain, 1999).

Survey Methods

The operative date of April was chosen with a view to ensuring that the water content of the rocks and sediments was minimised. The ground surface on top of the limestone outcrop forms a plateau at about 40 m O.D., and this surface is at least 30 m above the level of the water table (as judged by sump conditions inside accessible caves). The water table at about 6 m O.D. rises a few metres after heavy winter rainfall but the caves drain rapidly from springs issuing at the base of the limestone outcrop. The surface of the limestone is covered by leaf litter and a thin soil of between 10 and 20 cm depth. The presence of wet surface sediments was especially to be avoided, as these can severely attenuate radar signals.

A Pulse Ekko 100 GPR system was used with an antenna centre frequency of 100 Mhz. The choice of antenna frequency represents an optimal compromise between the depth of penetration and resolution of the subsurface structures: penetration depth decreases but resolution increases at higher antenna frequencies (Jol, 1995). The structures of interest in our survey were located up to 30 m below ground surface, and in the initial stages of this research we were concerned to use antenna frequencies which would penetrate a sufficient distance into the limestone, albeit with a lower resolution than can be achieved using higher radar frequencies.

The operating parameters for the Pulse Ekko 100 GPR system were selected as follows: nominal frequency 100 MHz; antenna separation 1 m; sampling interval 0·8 ns; time window 1 ms; number of stacks 32. "Stacks" are repeated readings taken at a given station location, with the echo signal averaged to improve the signal to noise ratio: the choice of the stacks setting is a compromise between survey time and data quality.

We recorded static radar reflections using a station interval of 0·25 m across several areas of level ground on top of the limestone outcrop at an altitude of around 40 m O.D. At one locality we detected distinct anomalies at different depths, and this area was investigated more thoroughly by recording seven parallel transects of 25 m length (Figure 1). A transect

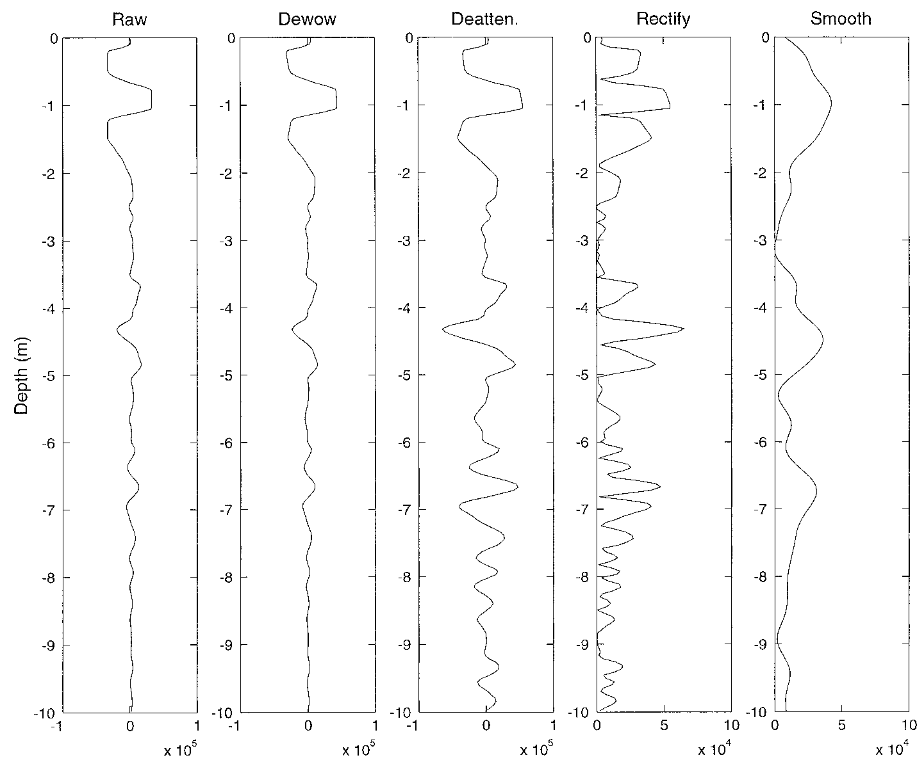

Figure 2. Filtering, deattenuation, rectification and smoothing of the raw GPR signal. Data transformation was performed in Matlab (Mathworks Inc., Massachusetts).

separation of 3 m was utilised: a smaller transect separation is recommended, but this would have over-extended the data collection exercise. The data were collected directly onto a laptop computer, and were processed in Matlab (Mathworks Inc., Massachusetts) using the following protocol.

When a single radar pulse is emitted by the GPR transmitter the raw signal recorded at the GPR receiver (the "trace") consists of an alternating waveform, displayed here (Figure 2, raw data) as a function of depth (d) by assuming a radar velocity (v) in limestone of 0·12 m . ns^{-1} (Milsom, 1996), and using the equation $d=(t-t_0)/2 \, . \, v$, where t=reflection time and t_0=125 ns (time-zero correction).

A signal saturation correction (Figure 2, dewow data) is the recommended preprocessing filter for this model of GPR, and is achieved by applying a running average filter on each trace (Sensors and Software, 1996). A window with the same width as that of one pulsewidth at the nominal frequency was set on the trace. The average value of all points within the window was calculated and subtracted from the central point. The window was then moved along the trace by one pulsewidth and the process repeated.

Each trace was then corrected for attenuation to ensure that radar returns from different depths were given equal weight (Figure 2, deattenuated data). Radar is attenuated in limestone by 0·5 db . m^{-1} (Milsom, 1996). Each trace was therefore amplified by a progressively increasing amount to correct for the signal loss. Note how the radar returns from depths below a few metres are greatly amplified after deattenuation.

Amplitude extraction was the final stage in processing the raw GPR data. The alternating GPR signal was rectified (Figure 2, rectify data) and then passed through a low pass filter (24 dB/octave 8th order IIR Butterworth filter with the cutoff set at 0·8 times the nominal frequency) to remove the ripple (Figure 2, smooth). Due to the quality of the GPR data obtained, and bearing in mind the caveats against excessive postacquisition data manipulation (Conyers & Goodman, 1997), further post-acquisition processing was not performed.

Results and Interpretation

Figure 3 displays the output for the seven parallel transects, with the top 3 m of each trace blanked to remove the ground scatter. The plots represent parallel "slices" through the ground to a depth of 20 m below the ground surface. The intensity of the plot indicates the processed radar reflection strength on a ten-point grey-scale. A large anomaly can be clearly seen starting at approximately 13 m below ground surface (approximately 27 m O.D.) in all transects. A separate, much smaller anomaly can be seen at about 5 m depth at the right hand end of the first four transects. The general scatter of reflections at 4 m depth is probably a surface artefact.

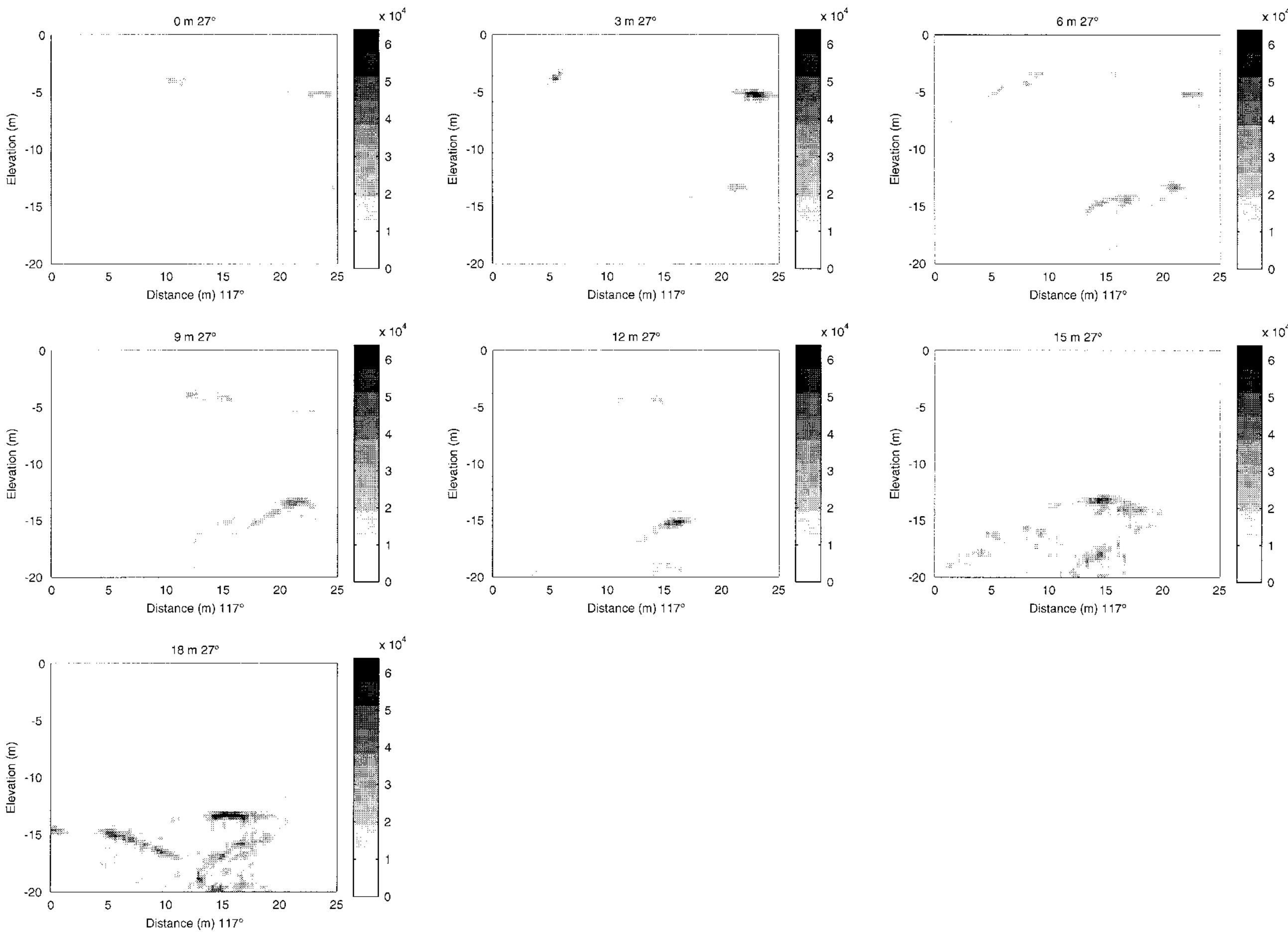

Figure 3. GPR data from parallel 25 m transects. Strength of reflection is measured on a ten-point grey-scale. Transects are oriented along the direction 117° from west (left) to east (right) and are separated by 3 m between adjacent transects. Note the prominent returns at 6 m and 14 m depths.

Figure 4 shows a set of depth (time) slices computed from the transect data by averaging the data in depth intervals of 3 m. These clearly demarcate the small 5 m deep anomaly at the southeastern corner of the survey area, and the more extensive 13 m to 19 m deep anomaly. Neither of these anomalies coincides with the position of the pit feature visible on the ground surface (see Figure 1). Figure 5 illustrates how these depth slices can be arranged as a volume viewed from the north.

Figure 6 shows how the signal strength varies with depth below the ground surface. This signal, which has been corrected for attenuation in the limestone, shows how the noise component increases with depth. There is still clearly a signal present at -20 m, but at -25 m the signal has become lost in the noise. This gives a good estimate of the depth penetration possible with this equipment operated at this frequency on limestone bedrock.

For comparison with an alternative geophysical prospection method we performed a resistivity survey over the same ground area using a Geoscan RM4 resistance meter operated in twin-electrode probe configuration. Resistivity was measured at 1 m intervals across the survey area and the results displayed as a grey-scale contour plot, with the darker shading indicating areas of higher resistivity (Figure 7). Unlike the GPR survey, the resistivity survey was greatly influenced by the presence of the pit which caused the high resistance anomaly in the top centre of the plot. There appears to be no correlation between the location of the presumed shallow surface features identified by resistivity and the deeper anomalies identified by GPR. It is likely that the presence of high resistance solid limestone close to the ground surface masked the effects of any structures located at greater depth.

Discussion

This detailed survey of an area on the top of a limestone outcrop produced results indicating a substantial radar reflection anomaly located at a depth of between 13 and 19 m beneath the present ground

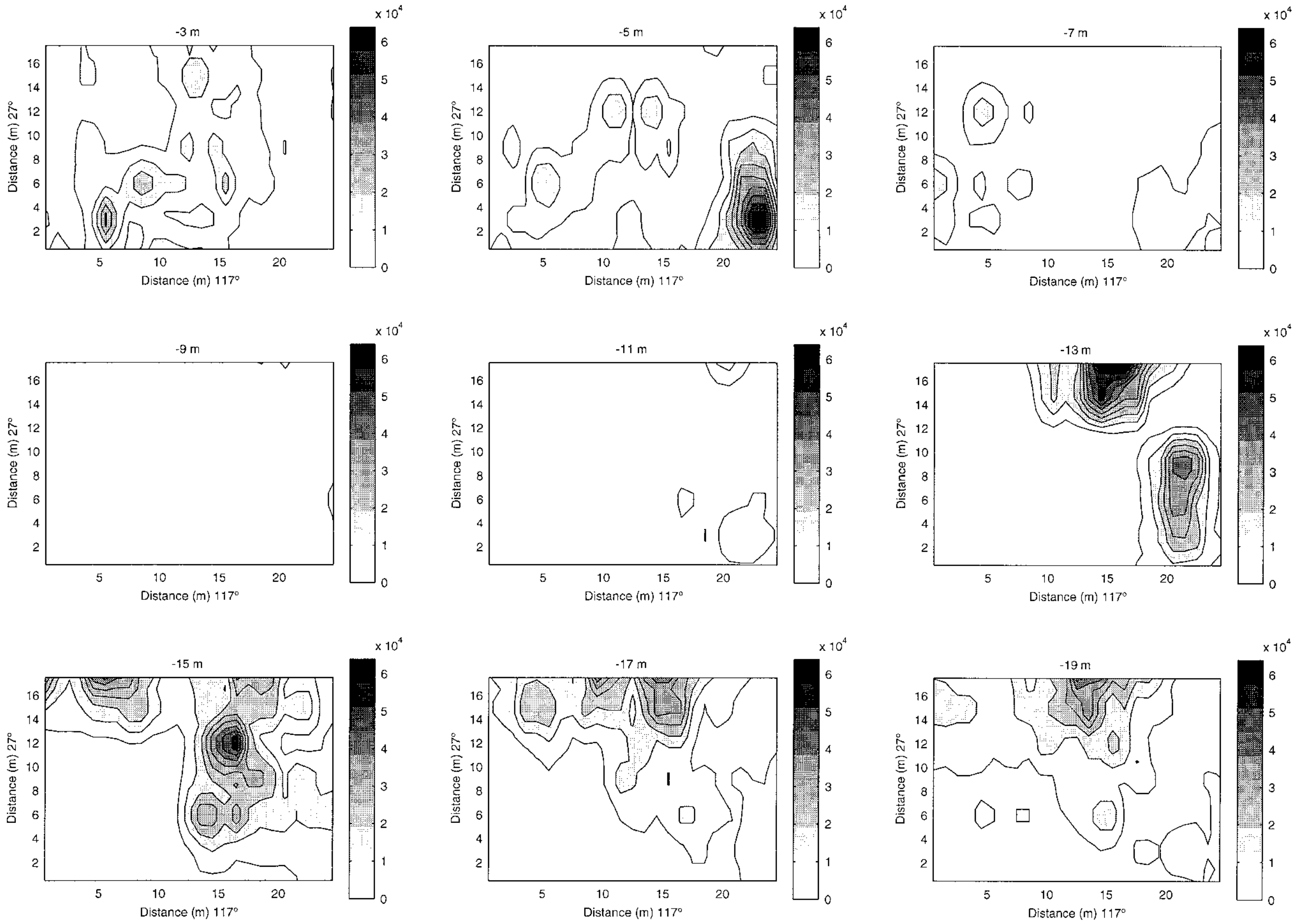

Figure 4. GPR data displayed as horizontal depth slices at 2 m intervals from − 3 m to − 19 m from the ground surface.

surface. We were unfortunately unable to verify its actual nature by surface excavation because of its great depth, but we believe, from the nature of the surrounding geology, that it represents a large subterranean void. This inference is supported by the altitude of the anomaly, the top of which is estimated to be at about 27 m O.D. This altitude corresponds closely to the highest level of horizontal cave development seen nearby at Bob's Cave and Shelter Cave, and suggests that the anomaly detected by GPR is caused by a chamber or passages lying at the same altitude as the known high-level cave systems in the limestone outcrop. The only currently known cave systems at this altitude are those intersected by the steep slope at the margins of the limestone outcrop, but the GPR results indicate that there is a potential for additional cave systems to be discovered away from the margins of the outcrop.

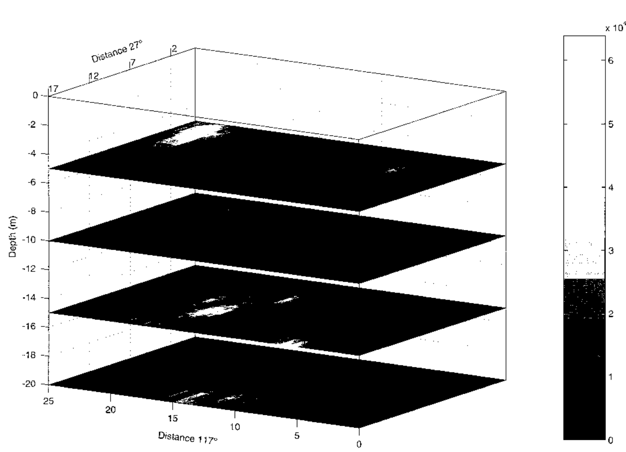

Figure 5. Diagram showing how depth slices can be stacked to give a volume representation. This plot is viewed from the north.

The GPR survey has also proved useful in excluding the possibility that the surface pit feature within the survey area might be a former entrance to a vertical shaft connecting with a hidden cave system. There is no indication on the GPR plots of anything other than solid limestone directly beneath the pit, and no trace of any communicating passage between the ground surface and the deeper anomalies. The maximum depth penetrated by the radar signal was at least 20 m, which is impressive for an easily portable set of equipment and we confirmed that the equipment did indeed detect

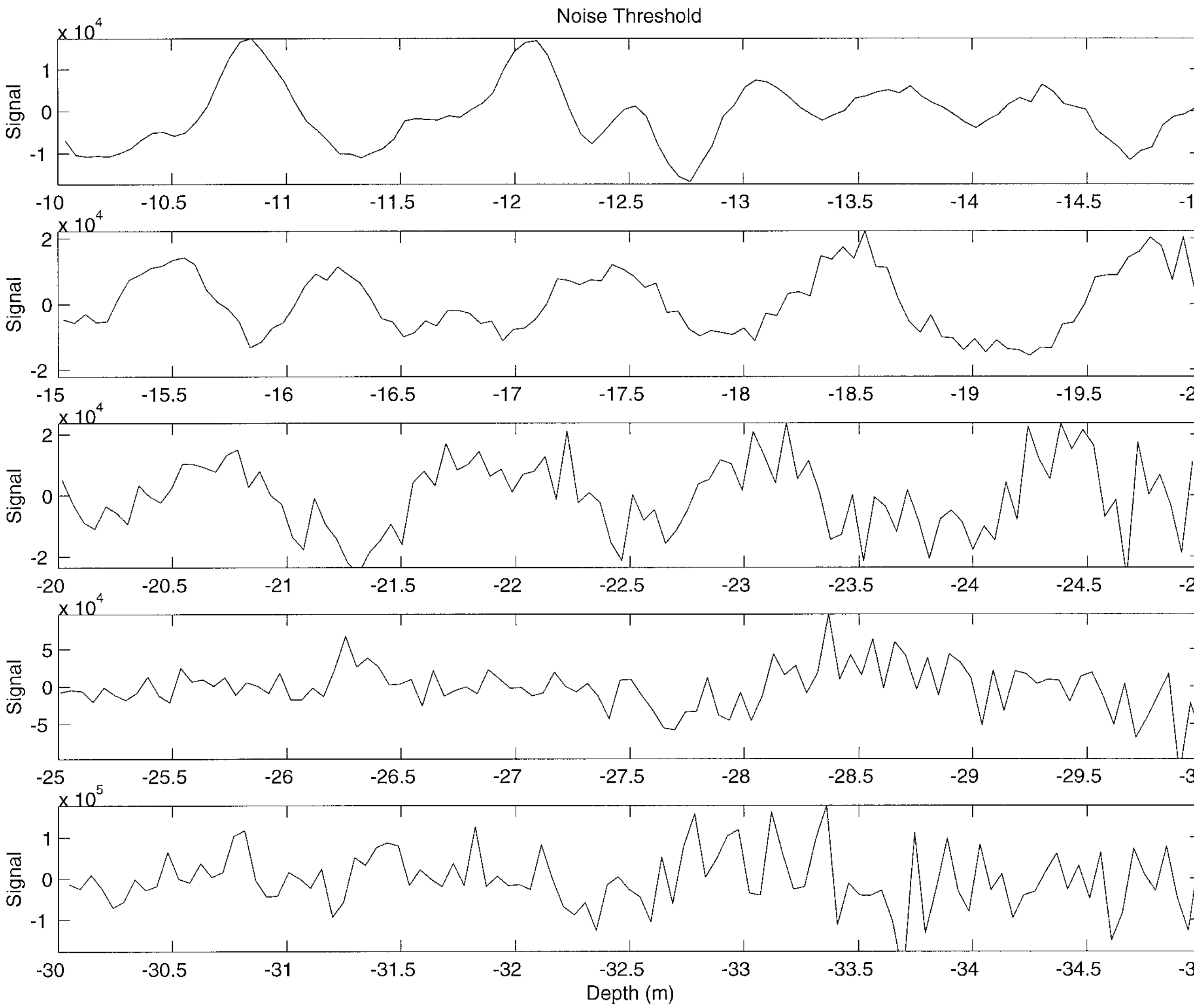

Figure 6. Graph showing how the deattenuated GPR signal varies with depth between − 10 and − 35 m from the ground surface. The signal is completely overwhelmed by noise after about − 25 m.

voids by undertaking recording above known fissures in a quarry face. Our findings agree with preliminary results from a GPR survey conducted above Poole's Cavern at Matlock in Derbyshire, U.K., where penetration depths in Carboniferous limestone of up to 30 m were reported (Eddies & Walker, 1998). The fact that the large GPR anomaly in our survey was not detected by resistivity indicates that GPR was a superior technique in these circumstances. It would be instructive to conduct a microgravity survey in the same area to see whether this technique can replicate the GPR results.

Conclusions

GPR has proved to be an effective method for investigating subsurface structures in limestone to a depth of at least 20 m, with prominent reflections being obtained from voids within cave systems. The exercise was successful in revealing the probable locations of hidden caves, and the results will help to guide future archaeological investigation of the site. From a logistical perspective, data collection in the field using the Pulse Ekko GPR system is only marginally slower than is the case for a resistivity survey, although the GPR equipment is bulkier and less robust under field conditions than resistivity and gradiometry equipment designed specifically for archaeological prospection. Data processing is more time consuming with GPR because a detailed radar trace rather than a single measurement is collected at each station along a transect.

On a more general note, GPR may prove to be a useful method for the field evaluation of limestone outcrops prior to mining and quarrying development.

Figure 7. Plot of ground surface resistivity values measured using a Geoscan RM4 resistance meter.

The further development of reliable methods of subsurface prospection may lead to a renewed interest in the assessment of the hidden archaeological and palaeontological potential of limestone regions.

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