Pringle, J. K., A. R. Westerman, A. Schmidt, J. Harrison, D. Shandley, J. Beck, R. E. Donahue & A. Gardiner 2002. Investigating Peak Cavern, Castleton, Derbyshire, UK: integrating cave survey, geophysics, geology and archaeology to create a 3D digital CAD model. *Cave and Karst Science* 29(2): 67-74.

Investigating Peak Cavern, Castleton, Derbyshire, UK: integrating cave survey, geophysics, geology and archaeology to create a 3-D digital CAD model

Pringle, J.K.[1], Westerman, A.R. [1], Schmidt, A. [2], Harrison, J.[3], Shandley, D.[4], Beck, J.[5], Donahue, R.E.[2] & Gardiner, A.R.[1]

[1]Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK. EH14 4AS.

[2]Department of Archaeological Sciences, University of Bradford, UK. BD7 1DP.

[3]Peak Cavern, Castleton, Derbyshire, UK. S33 8WS.

[4]Strata Software, Angel Way, Bradford. BD7 1BX.

[5]The Technical Speleological Group, Chapel Works, Back Street, Castleton, UK. S33 8WE.

Abstract

Non-destructive geophysical imaging techniques have been applied to the sedimentary deposits within the reputedly largest cave entrance chamber in Western Europe. The Vestibule of Peak Cavern is thought to have been the site of human habitation since the Late Palaeolithic. The depth to the cave floor and the sedimentology and archaeology of the cave fill was uncertain.

Ground Penetrating Radar (GPR) is shown to produce good quality images of dry cave deposits and underlying limestone cave floors. The GPR images show the sedimentological and archaeological distribution of the cave-fill, identify buried 'houses' and allow the mostly buried cave floor to be mapped. GPR and ground resistivity images are combined with a Total Station survey of cave topography in a 3D Computer Aided Design (CAD) model. By combining the several lines of evidence within the model, the cave floor is mapped. Further analysis of the CAD model is used to address geological, speleological and archaeological issues.

A follow-up data acquisition program could now be designed to improve the extent and quality of the GPR imagery in order to answer specific questions. Based upon this investigation and recent literature, the oldest deposits, within the Vestibule cave fill, are predicted to be located at the highest level. A 3D-GPR survey is recommended to define the stratigraphy of any lateral accretion surfaces within the cave fill and the effects of human activity in partially remodelling them.

Introduction

The Early Carboniferous Castleton Reef in Derbyshire, UK, (Fig. 01a) hosts an extensive network of linked cave systems, which the Technical Speleological Group has surveyed and continues to explore (Fig. 01b). Peak Cavern is one of several access points near Castleton. The Peak Cavern entrance (or ‘Vestibule’) is unusually large, with considerable cave fill – the depth, sedimentology and archaeology of which were uncertain.

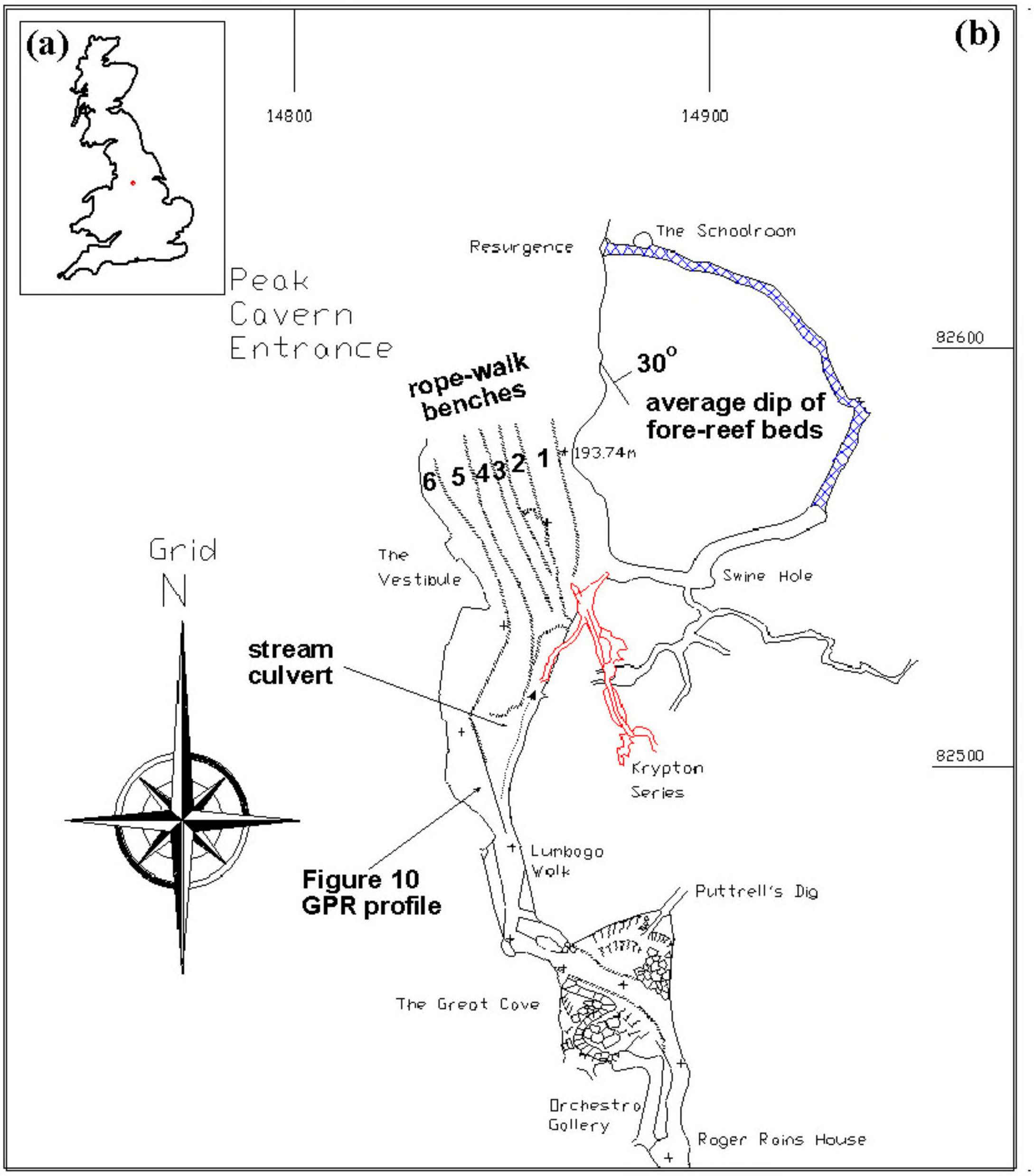

Figure 1. (a) Location map and (b) annotated segment of Peak Cavern cave survey, by the Technical Speleological Group, from an AutoCAD model by J. Beck.

Ford (1999) recommended further investigation of the Vestibule, as it may have been a site of human habitation since the Late Palaeolithic. The Vestibule was first recorded in the Doomsday Book (Hancock, 1999), and there is evidence of rope making at Peak Cavern for the past four or five hundred years, on benches sculpted from the cave earth deposits (Fig. 02). The present day Vestibule area has six terrace benches (Fig. 03) upon which rope-making equipment is preserved for tour parties. There is also an ephemeral riverbed, which exposes the bedrock (Fig. 03). Several ‘houses’ were built or tunnelled into the terraces (Fig. 04), which were occupied by the early rope makers.

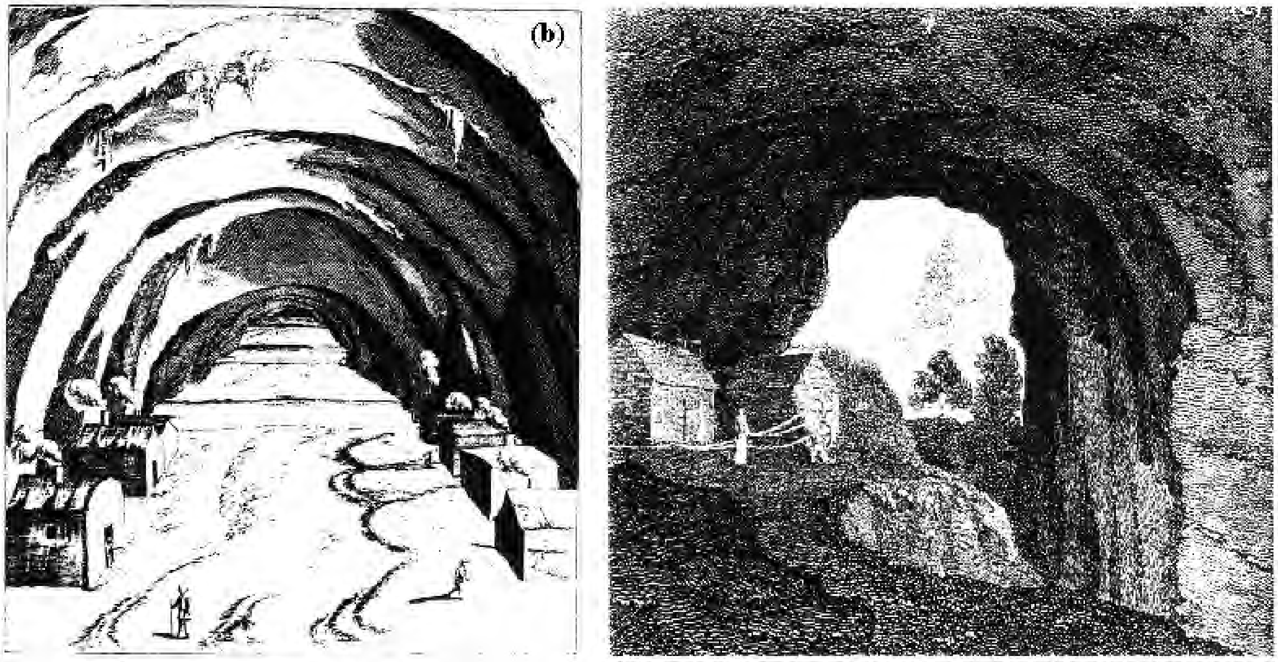

Figure 2. Engravings of the entrance (or Vestibule) of Peak Cavern, (a) by Leigh circa 1700 and (b) by J.Rose, from a drawing by E. Dayes in 'The Beauties of England', 1803. From Woodall (1979).

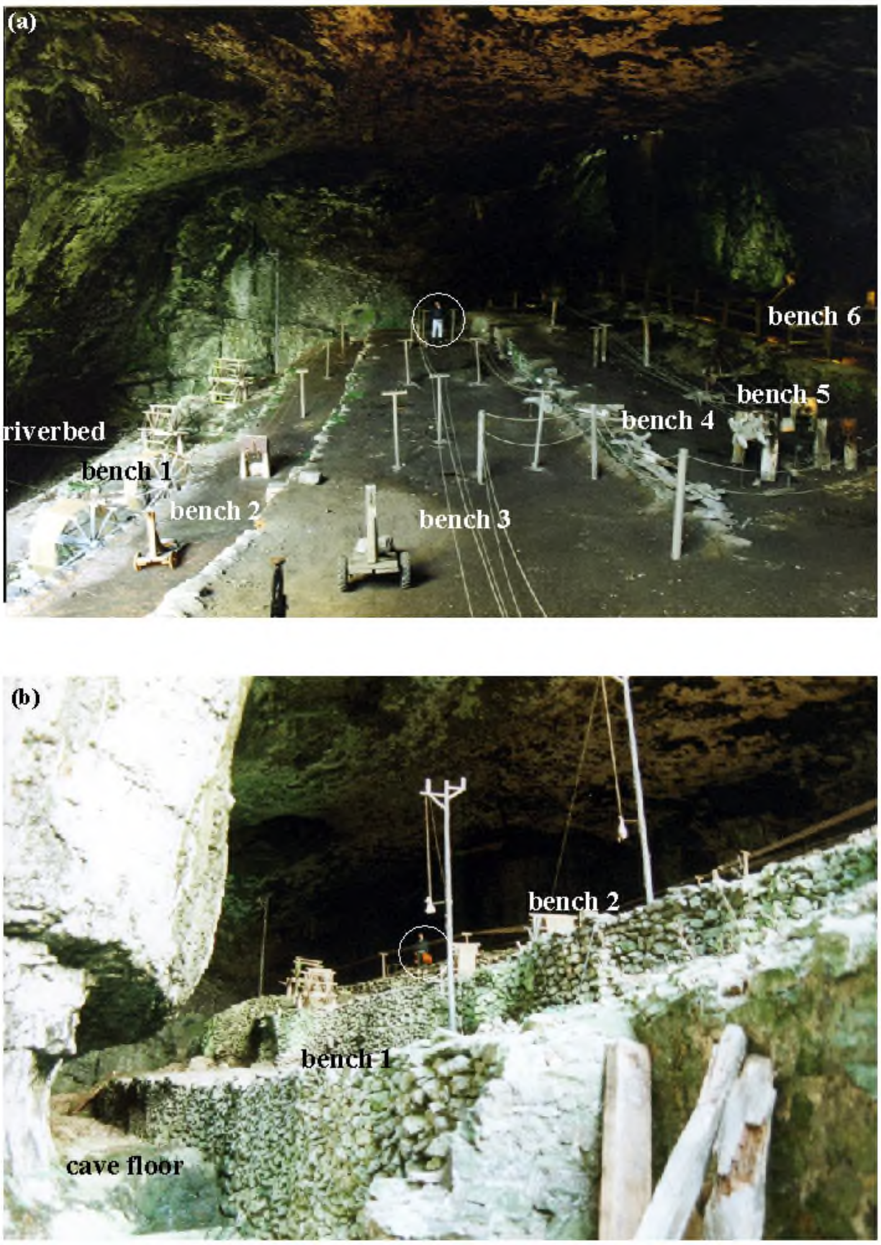

***Figure 3**. Photograph of the Vestibule (figure for scale). The six benches are marked, with the cave floor exposed in the dry streambed. Rope making equipment is still set up on the benches. There are only small amounts of metal above ground level, which did not noticeably affect GPR records.*

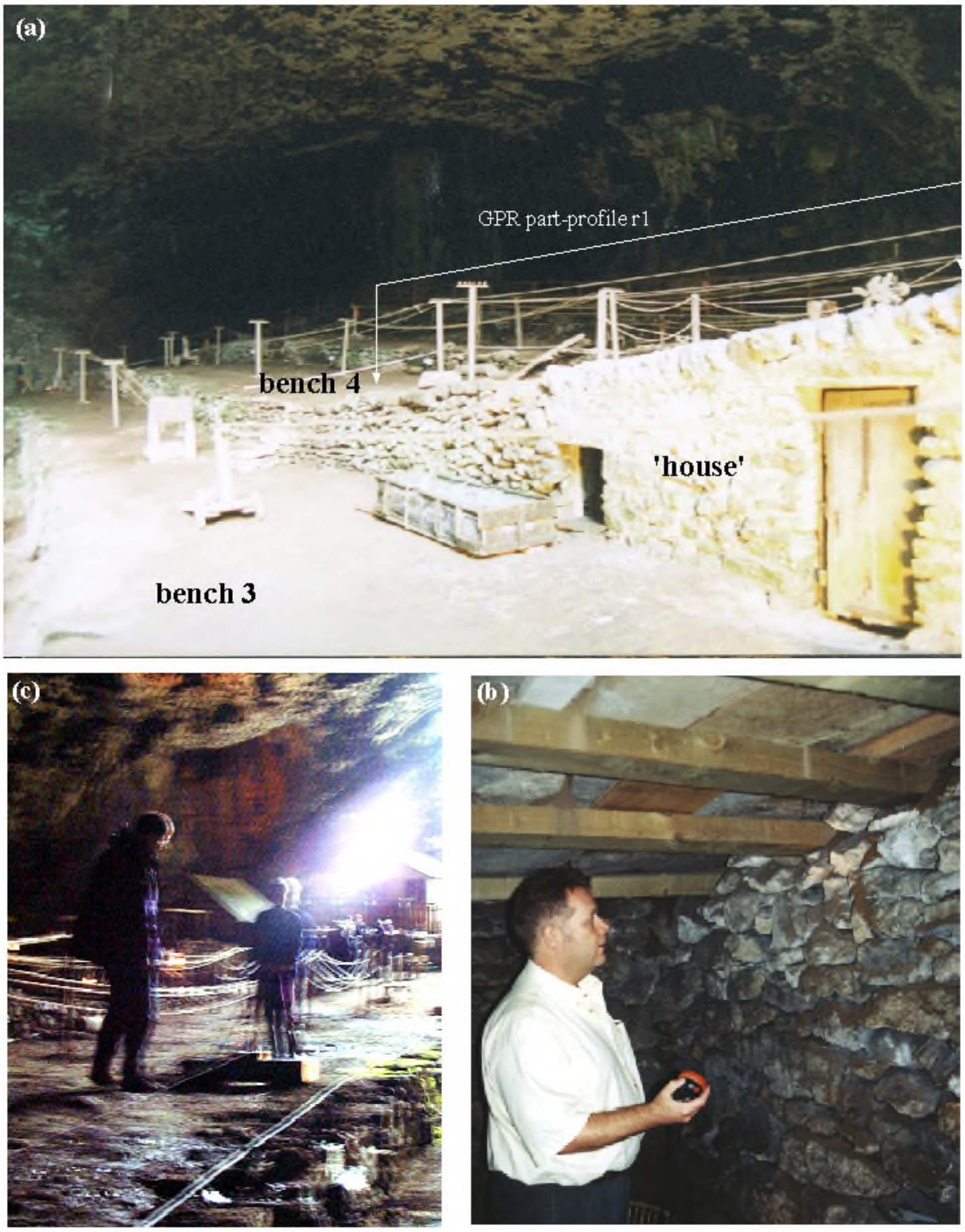

***Figure 4**. Photographs of (a) outside and (b) inside a small ‘house’ under bench 4, used by rope-makers during the 17-19th Centuries. Note that iron supports in the house roof are not exposed.*

In a larger context, Peak Cavern and several nearby show caves are formed within fore-reef facies, dipping at about 30° towards the north or northeast (Ford, 1999). To the south of the fore-reef facies are the gently dipping Carboniferous limestones of the Derbyshire White Peak area, which host lead-zinc-fluorspar mineralisation and residual bituminous hydrocarbons. The reef is an exhumed fossil oilfield, suitable for petroleum reservoir outcrop analogue studies. To the north of the fore-reef facies, the anoxic, distal turbidite Edale Shale Formation floors the Hope and Edale valleys. Additional northerly-sourced turbidites subsequently covered the reef to provide a reservoir seal. The cap rock turbidites are exposed near Castleton at Mam Tor and farther north in the Derbyshire Dark Peak area.

Hancock (1999) undertook a preliminary non-invasive, geophysical study. This provided useful background. His ground resistivity profiles are discussed in the following section. Davis and Annan (1989) showed that GPR could be used to distinguish between soil and rock stratigraphy.

Whilst there have been other GPR studies within cave systems (McMechan *et al.*, 2002:1998, Beres *et al.*, 2001 & Chamberlain *et al.* 2000), these studies have focused on detecting cavities within the limestone, rather than to characterise sedimentary deposits. GPR data was acquired within the cave during a half-day, opportunist visit.

Cave entrance survey

The accurate relative position of data is important for small-scale geophysical surveys. Typically, surveyors' tapes and compass bearings are used to position lines of profile and sample stations. Lehmann and Green (1999) integrated a geo-radar acquisition unit with a self-tracking laser theodolite with target recognition capabilities. In Peak Cavern, additional survey data was needed to position the geophysical images acquired within the cave entrance.

A Total Station theodolite and Penmap acquisition system was used for surveying. The theodolite base station was placed in a prominent position – overlooking the cave entrance by the kiosk, near the viewpoint for Figure 3. Around 450 surveyed points were acquired in reflectorless mode across the cave roof. Surveyors' tapes were laid out to mark the previously acquired geophysical survey lines and surveyed at the same time as the cave topography, particularly the six bench edges and the exposed bedrock in the dry riverbed (Fig. 05). The cave benches and geologically significant locations were also surveyed (using around 100 location points) using a reflector on a pole of known height. Survey data were recorded by the Penmap acquisition system (Fig. 05a), which provides immediate validation of the data points being acquired through a dynamic 3D display – a significant advantage over conventional surveying equipment. Single survey points and groups of points, or 'poly-lines', may be annotated and quality controlled as they are acquired.

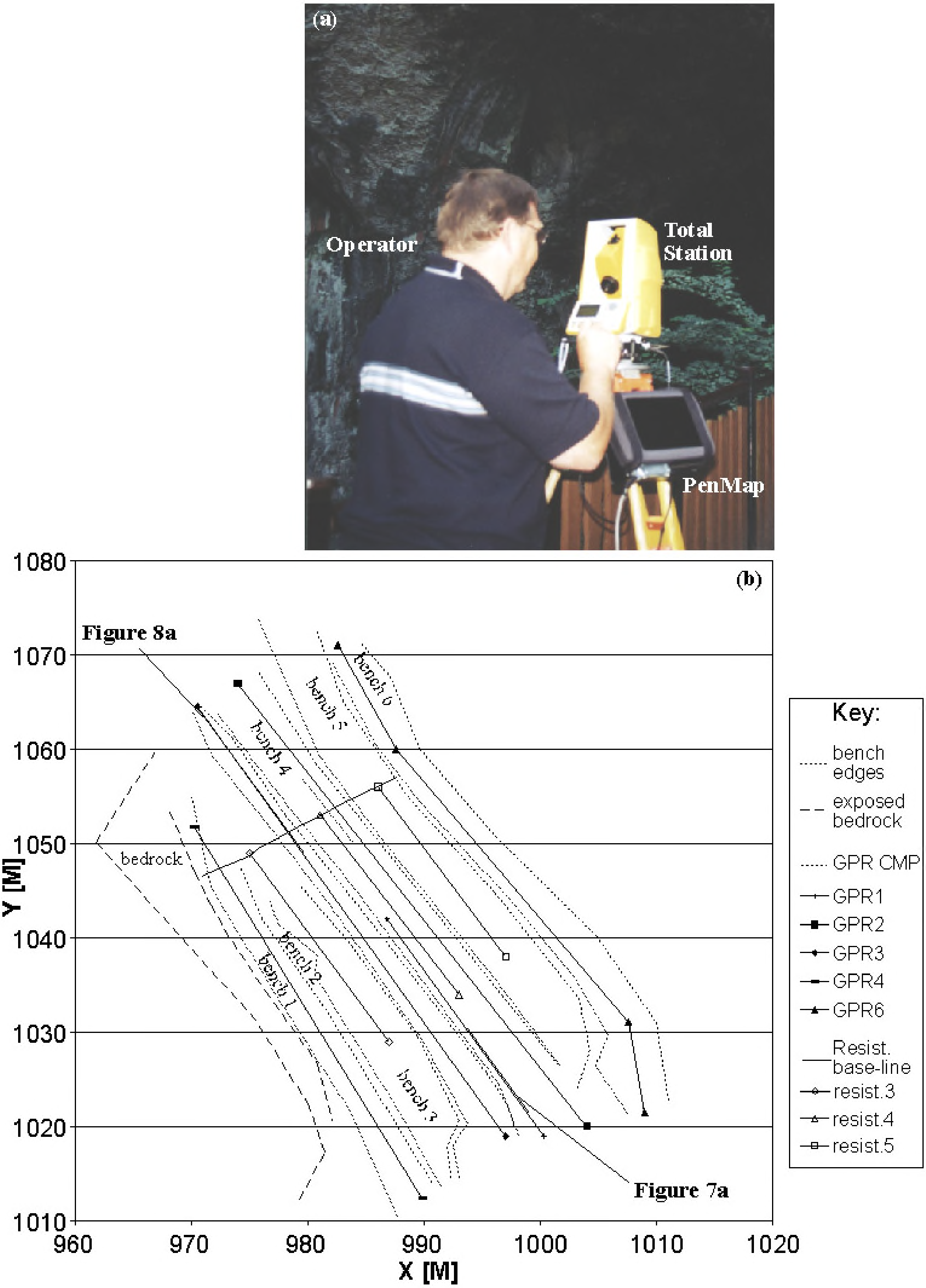

Figure 5. *(a) Surveying the study site, using a Total Station theodolite, Sunscreen PC and PenMap acquisition software (right of tripod). (b) Plan view of the study site, see key for sub-divisions of surveyed bench edges, GPR and resistivity data.*

Resistivity Pseudo-sections

Hancock (1999) used an expanding Wenner array to collect earth resistance data along transects on three benches. The electrode spacing was increased from 0.5m to 5m in steps of 0.5m. Results were plotted as apparent resistivity pseudo-sections. Pseudo-depth was defined as half the electrode spacing and position measured from a baseline inside the vestibule. In Figure 6, ground resistivity values are colour contoured, from high (black) to low (white).

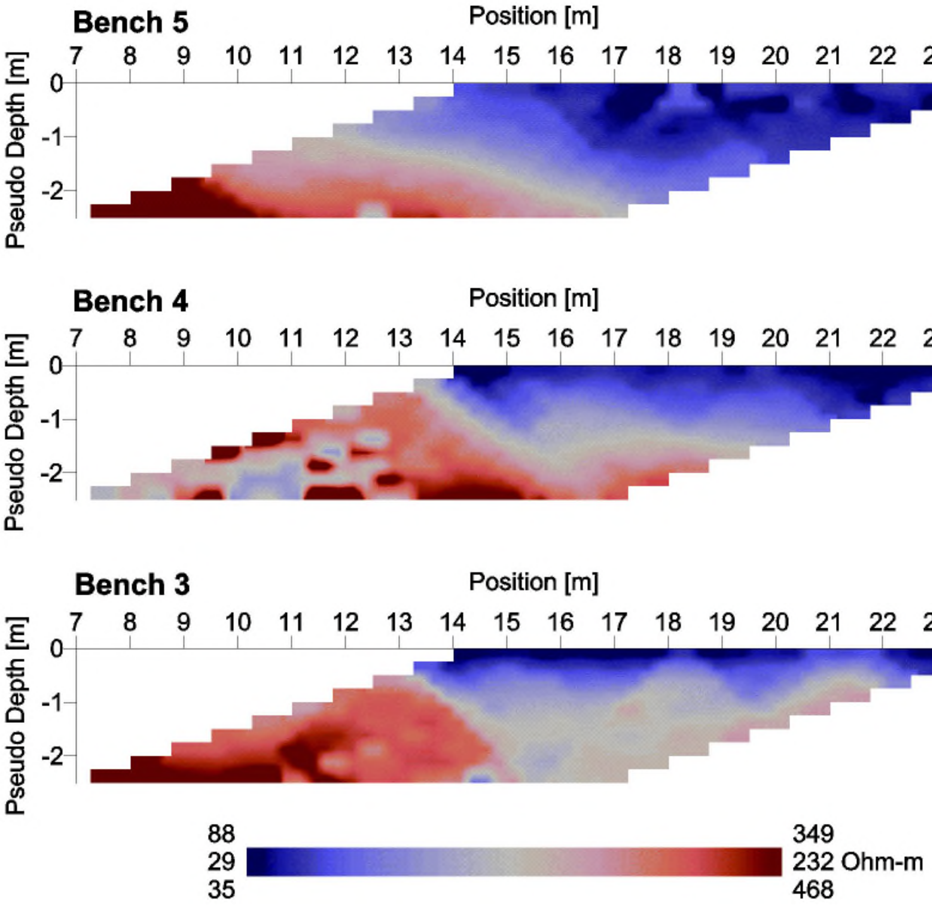

Figure 6. *2-D, resistivity pseudo-sections from Hancock (1999), see Figure 5 for location.*

Increased resistivities can be seen between 17m and 19m, at the bottom of the section on bench 4. The most striking feature in all three sections is the sloping apparent resistivity contrast seen from 12-18m. This was interpreted as an early surface of the alluvial deposits, with a later extension towards the cave's entrance. The more gradual increase found below bench 5 is attributed to its elevated level. Benches 3 and 4 are on a similar, lower level (compare Fig. 03).

The near-surface part of the sections shows several weak chevron, or inverted v-shaped, anomalies of intermediate resistivity. Man-made features may be the cause of these anomalies (Hancock, 1999).

Ground Penetrating Radar (GPR) investigations

GPR acquisition and processing

'Noise' test profiles were first acquired, testing several GPR antenna frequencies using the pulseEKKO™ PE100 system. The 110MHz dominant frequency antennae were chosen to ensure adequate penetration and imaging of the base of the cave beneath the cave fill. Next, a Common

Mid-Point (CMP) gather was acquired, using 0.2 m trace separation (Fig. 05b for location). The CMP was used both to determine an optimum antenna separation for the subsequent constant offset profiles and for velocity analysis (Fig. 07).

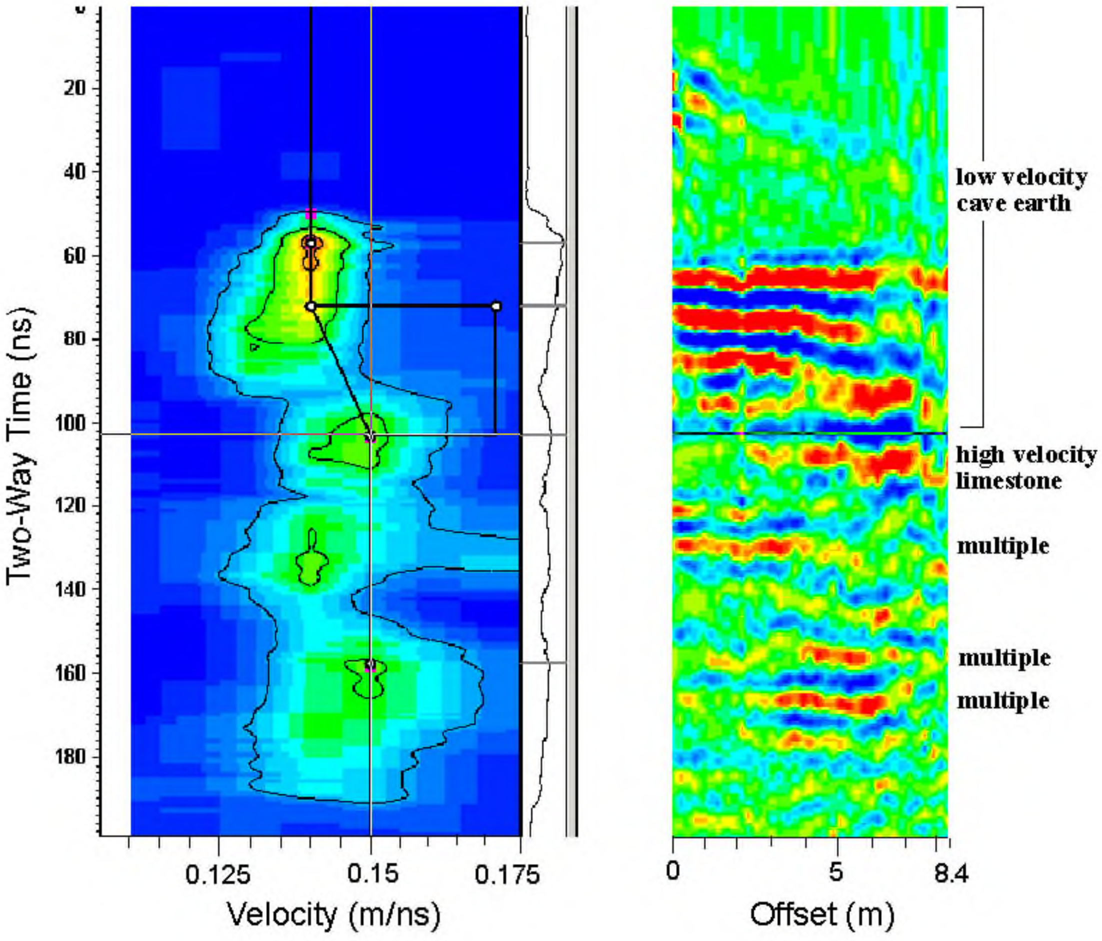

Figure 7. GPR Common Mid-Point (CMP) profile, acquired using 110MHz frequency antennae on bench 4 (see Figure 5 for location). Left side shows ratio of average energy:total energy of CMP traces. Bright areas indicate likely velocities (see text). Right side has Normal Move-Out (NMO) corrected gather, using velocity gather from left side. The marked velocity change is observed between 54 & 102 ns TWT. The average cave velocity was calculated to be 0.28 m/ns. attributed to the base of the cave – between the cave sediments and host limestone.

Figure 7 (left) shows two clear velocity values, relatively low velocity, multiple events between 50 and 80 ns Two-Way Travel-Time (TWT) and a single, higher velocity reflection event around 112 ns TWT. Both main primary events appear to be followed by multiple events at twice the TWT and at the same velocity as their parent primary events – i.e. directly beneath each primary event in the semblance plot. The two distinct velocity layers are attributed to a cave fill layer down to about 95 ns TWT, overlying Carboniferous Limestone, which forms the bedrock of the cave-floor. The Limestone, being more compact and cemented than the overlying cave fill, results in relative faster velocities than that measured from the cave fill sediments.

The initial test survey strongly suggested that the cave fill and cave floor could be distinguished using GPR equipment. The standard Normal Move-Out (NMO) method to obtain a velocity value from the CMP is detailed by Milsom (1996). An average velocity value of 0.28 m/ns was obtained from the CMP. This value was used to convert the subsequent fixed-offset profiles from time to depth. At the time of the survey, the manufacturer’s recommended 1-metre antenna-separation for

110 MHz antennae was chosen. However, the CMP analysis showed a smaller separation would produce better results for the shallowest, archaeological targets in any future GPR surveys. For deeper targets such as within the rock head, a larger antenna separation would give better results.

The six benches that form the dominant topography within the cave entrance were profiled using the GPR fixed offset profile method (see Milsom, 1996). Figure 3 shows the labelled benches, with Figure 5 showing a plan-view of the profile locations. The antennae pair was moved at a constant 0.2m spacing between adjacent traces along each profile. The pulseEKKO™ acquisition software allows repeated pulses to be transmitted and recorded, which significantly improves image quality at greater penetration depths. Of course, it then takes longer to acquire each trace since the repeat traces are summed, incurring a computational time-penalty. It was found that a sum of 16 pulses-echoes produced good results at an acceptable time cost.

One problem encountered when acquiring GPR data in the cave, was the dampness inherent in the study site. Whereas careful covering of delicate equipment was possible, the fixed-offset profile data acquired on the fifth bench were corrupted. This therefore prevented direct comparisons with the pseudo-resistivity section on this level.

After acquisition, the raw GPR data were processed to maximise the amount of information recoverable from the profiles. Variable time delays were subtracted to correct all traces to a common zero-time origin. A gain profile was applied to balance high-amplitude shallow events with relatively low amplitude deeper events. A Time-Variant Spectral Balance (TVSB) was used to reduce noise. The average velocity from the CMP profile, discussed above, was used to convert the fixed-offset profiles from time to depth.

GPR results

The 2-D fixed-offset profiles along the benches show several anomalies, which correspond to exposed features, the most obvious of these being the small ‘house’ under bench 4 and seen in Figure 4. A segment of the GPR profile shows an anomalous absence of reflection events, corresponding to the space under the ‘house’ roof (Fig. 08). Other interpreted features are listed in the Key to Radar Stratigraphy accompanying Figure 8. A previously unidentified void is clearly seen, which may be the site of another collapsed house. Between the ‘house’ and the void, a possible midden or spoil heap is expressed as dipping lateral accretion surfaces overlain by several domed layers. At either edge of the GPR profile segment in Figure 8, possibly undisturbed layers of planar horizontal cave fill are seen, similar to those overlying the cave floor. In the centre of the section, there appears to be a sharp-edged truncation of the deeper tabular cave fill layers, possibly by an excavation that preceded the construction of the ‘house’ and ‘midden’.

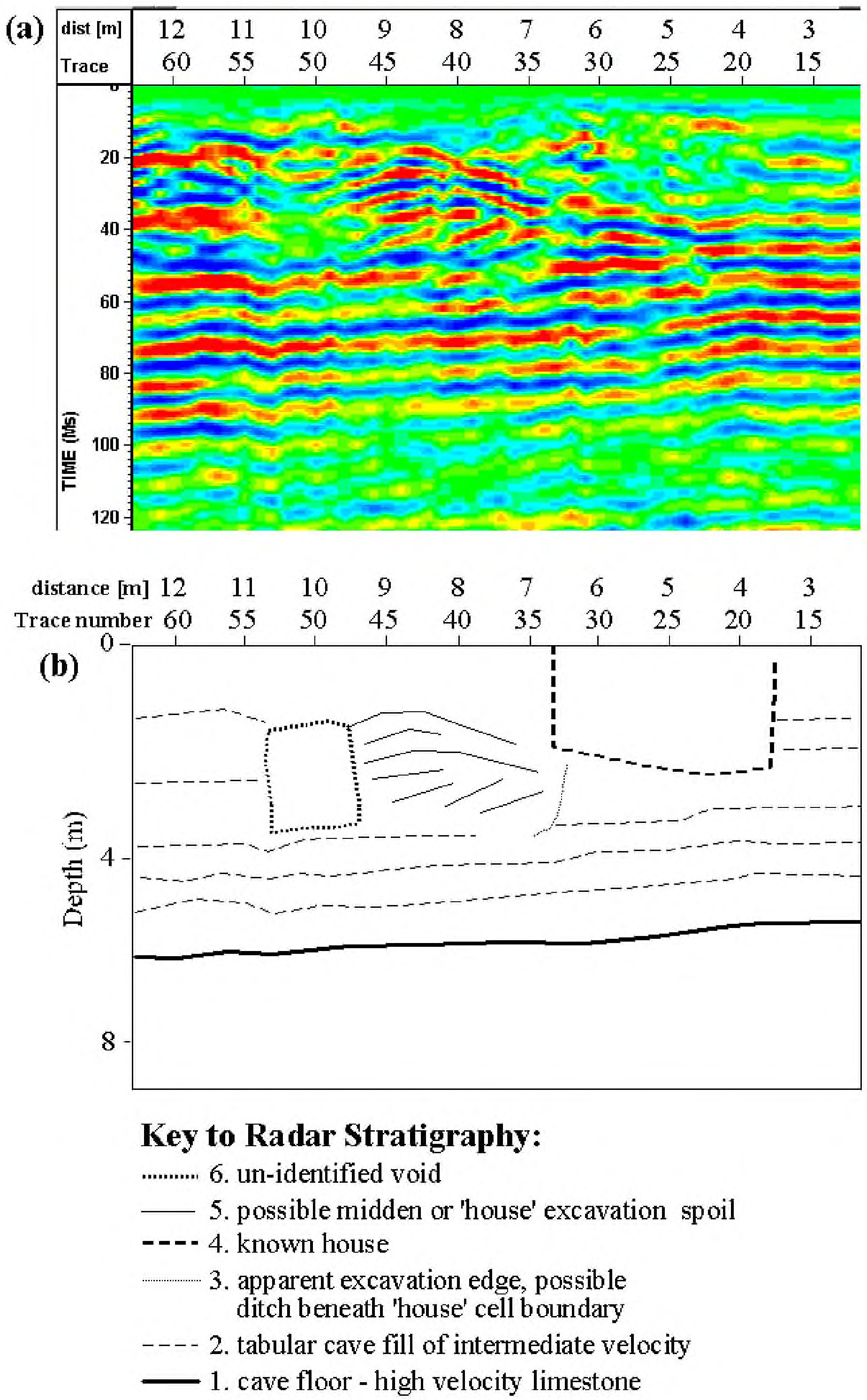

Figure 8. *(a) GPR R1, fixed-offset, part-profile, with (b) interpreted line diagram. A radar stratigraphy is shown.*

The increasing depth of cave fill, from the back of the cave towards the entrance, was seen on several lines. The increasing depth of fill from the back of the cave was consistent across the study site and recalls the high-resistivity wedge seen in all three resistivity pseudo-sections acquired by Hancock (1999). Several diffraction trains are seen in disturbed ground, which correspond to the known locations of electrical cables and pipes, were observed on some GPR profiles, some pipes being observed emerging from a dry-stone retaining wall at the foot of the bench.

The top bench (6) was profiled with fixed-offset GPR for 100m along the main tunnel of the Peak Cavern system, i.e. through ‘Lumbago Walk’ (Fig. 01). The profile traverses over accumulated river deposits that locally formed at bends in the passageway. The GPR profile (Figure 9a) shows complicated stacking of bedforms above the interpreted cave floor reflection event (shown in Figure 05b). Interpreted inclined bedforms are seen to stack laterally on either side of a domal feature, interpreted as being deposited on the channel bend during times of flood.

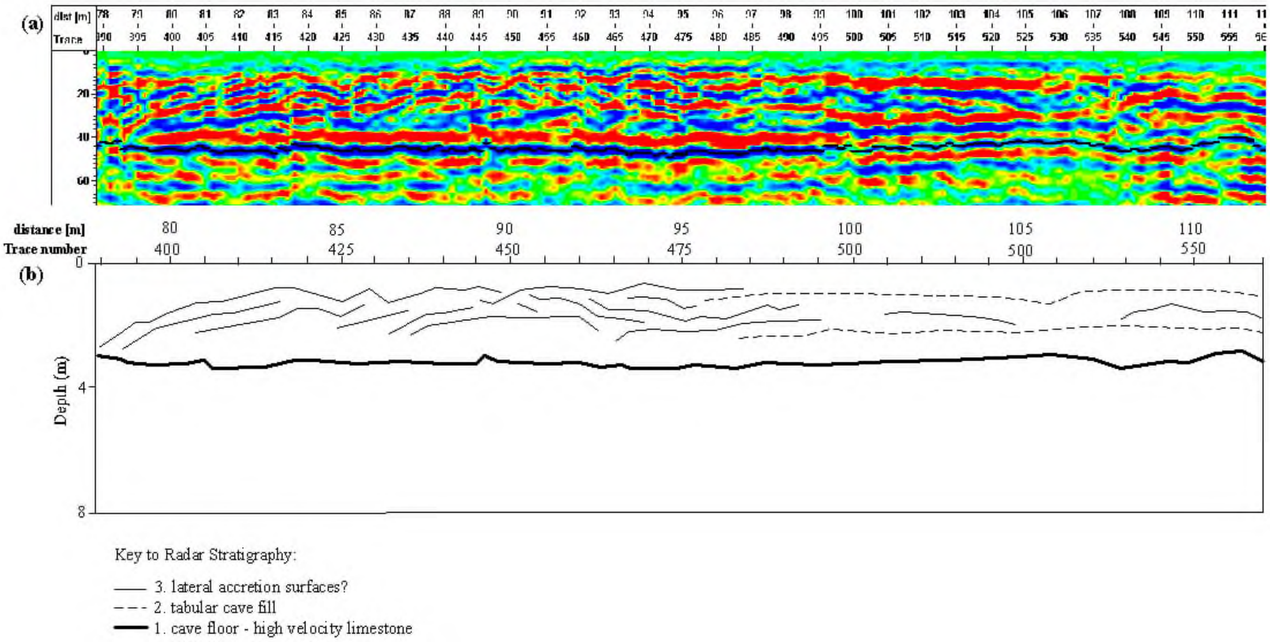

***Figure 9**.* *(a) GPR, 2-D fixed-offset part- profile R6, acquired using 110MHz frequency antennae (see Figure 1 for location), with (b) subsequent line interpretation. The section lies through the stream-bed fill at the back of the cave, the conical lateral accretion surfaces are attributed to sediment stacking during successive spring floods.*

Data integration

There is currently no single software specifically designed to combine archaeological, geological, geophysical and survey data into one ‘shared earth’ model. 3D-CAD software was therefore used to integrate geophysical image data in a framework defined by Total Station survey points (see Pringle *et al.*, 2003). The survey data were partitioned into cave-fill topography, cave roof, stream-bed and cave entrance areas, then gridded and rendered, to produce an accurate, if partial, 3D view (Fig. 10). The GPR images and the pseudo-resistivity sections were attached to vertical frames hung from their surveyed ground level positions.

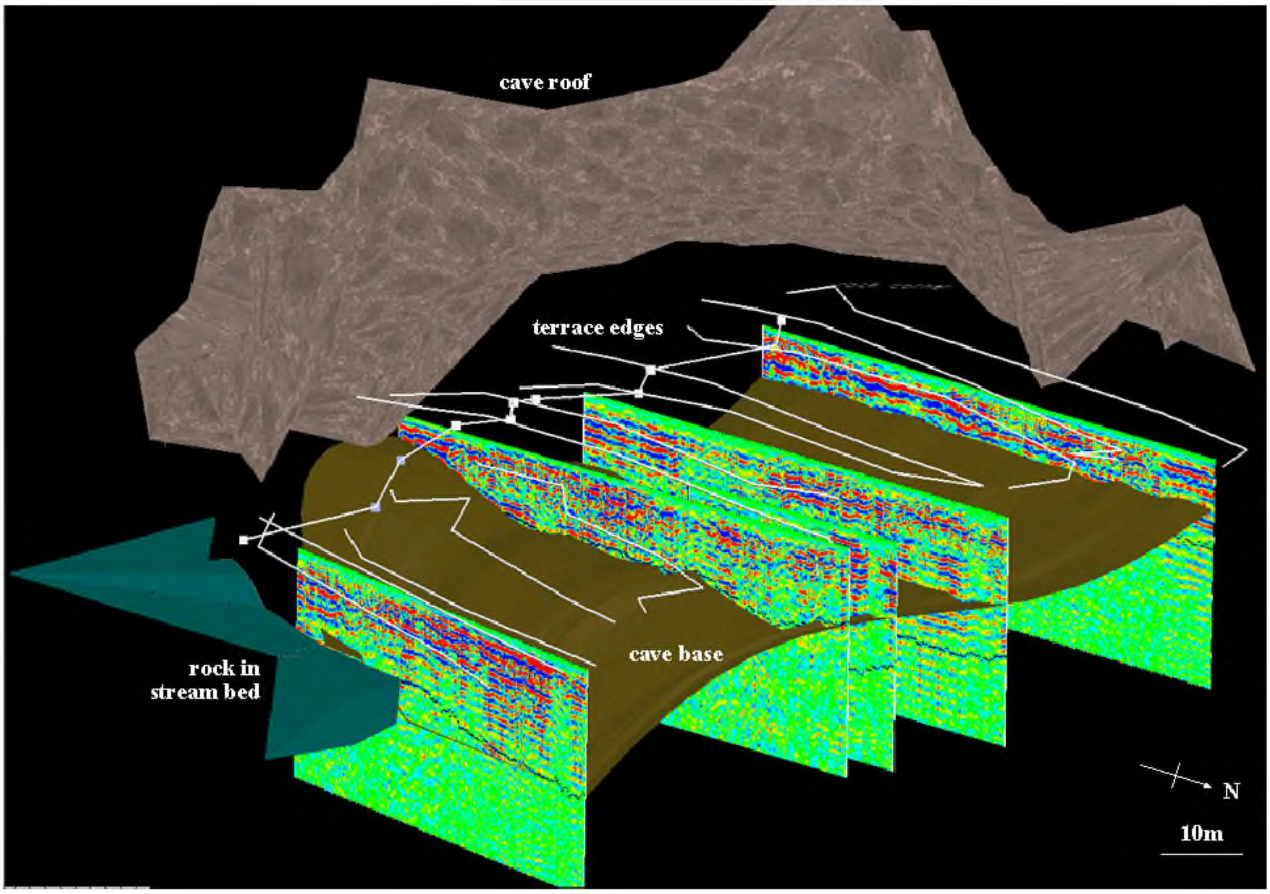

***Figure 10**. Data integration in CAD (Bentley Microstation) software. Survey data, separated into cave floor, walls and roof, were separately gridded into a wire frame mesh. GPR and resistivity geophysical data were then integrated into the dataset, and the cave floor horizon was interpreted.*

The cave floor, or cave base, target was then interpreted as a single surface through all the relevant observations: the surveyed exposed bedrock in the stream, the small outcrops surveyed and 'PenMap' annotated at the foot of some benches, and the cave-floor picks in the GPR CMP and fixed-offset profiles (Fig. 10).

Discussion

The results of the integrated survey and interpretation, shown in Figure 10, strongly suggest that:

The cave floor is broadly parallel to the cave roof. This is consistent with a cave developed in dipping strata and guided by the preferential dissolution of one bed, or a group of adjacent beds.

The cave fill rarely exceeds 6m in thickness (compare the depth scales in Figures 8 and 9), consistent with Dr. Ford's expectation (*pers. comm.*).

This has interesting implications for both cave formation and later, cave sedimentology.

Cave formation

Osborne (2001) recognises "structurally guided network caves" in dipping beds as differing in plan and section from maze caves in sub-horizontal beds. In limestone beds dipping at 30° or more, cave architectures show "large elongate cavities called halls, oriented along strike, and smaller, short cavities called narrows, oriented perpendicular to strike." Hall formation may be guided by the intersection of susceptible beds and fractures, where the process of mixing-corrosion can occur, as discussed in the next paragraph. The Peak Cavern Vestibule would qualify as a ‘hall’, with visible fractures and several small avens and seepage from the roof with stalactites. Once the Vestibule was open to the elements, additional erosional processes, such as freeze-thaw etc. would have further enlarged the ‘hall’.

Westerman (1982) documented the nascent stages of karstification at joint/bedding plane intersections and developed a numerical model for groundwater flow through a fracture network, represented as pipes along the intersections. Sufficient computing power is now available to track solubility parameters (presented by Bogli, 1980) through a ‘pipe-network’ groundwater flow model. A realistic model of bedding planes and fractures on the scale of the Peak Cavern cave system could then be made. The 3D-CAD model presented in this paper illustrates the structural and stratigraphic detail that would be needed across the system before such a flow model could be built. Since the Technical Speleological Group have made an extensive survey of the Peak Cavern system, there is a framework in place to which the necessary geological detail could be added.

Cave sedimentology

The Vestibule deposits are the largest single cave fill accumulation within Peak Cavern, although sedimentary cave fill has been documented throughout the system by Thistlewood *et al.* (1989). Cave sediments formed within the cave entrances developed in the Asbian fore-reef limestone beds with 30º bedding plane dips. Here, the cave architecture fits the ‘hall and narrows’ class of “structurally guided network caves”, typical of host beds dipping at 30º or more, as recognised by Osborne (2001). The cave stream is always constrained to migrate down dip as it erodes a susceptible bed. The upper levels of the developing cave will be left behind, increasingly beyond the reach of even the highest floods. A simple cave sediment stratigraphic sequence may therefore be expected. Such deposits would have some features in common with fluvial point bars, formed as a meander loop migrates across a valley floor (see e.g. Leclerc and Hickin, 1997).

However, lateral accretion surfaces imaged on GPR profiles (Fig. 10), appear to have accumulated on the outside of a bend in the main stream-way (Fig. 01). If this were a fluvial deposit on an unrestricted, non-rock-bound stream in the open air, outside bends would usually be sites of erosion, not deposition. However, as the stream approaches the Peak Cavern Vestibule, it ceased to flow over the cave floor as it would along a broad river valley. The 30º northeasterly bedding plane dips within the Asbian fore-reef limestone beds constrain the active stream to the northeasterly, down-dip wall of the passageway. The stream then leaves the Peak Cavern Vestibule, through the Swinehole (Fig. 01). Therefore the lateral accretion surfaces, imaged in Figure 10, could have accumulated as the stream migrated down dip, leaving the up-dip section of the cave for flood-born sedimentation.

The view presented in Figure 3, may be used to suggest that the large cave fill deposits in the main Peak Cavern Vestibule formed in a similar manner. The bare rock of the cave floor is exposed at the lower left-hand corner of the photograph, where the stream flows during modern floods. The stream is undercutting a massive limestone bed about one metre above the cave floor. The cave is therefore still being extended down the geological dip – although the pictured dip is gentle. During normal rainfall, the Swinehole ‘narrow’ is able to accommodate the flow and conduct it to a still lower level (Fig. 01).

The cave sedimentary sequence in Peak Cavern is therefore unusual in one respect – earlier beds are found in the earlier, upper levels of the ‘hall’ and later beds found at later, lower levels. However, in this case, the down-dip erosion of the streambed, rather than the lateral migration of a meander loop, is inferred to have controlled deposition.

Archaeological Implications

Peak Cavern is believed to have a rich archaeological history (Ford, 1999) but, due to its size, importance and conservation provisions, excavation is inappropriate and in fact prohibited. However, the combined results of geophysical and topographical investigations have produced an interpreted cave floor base. The surface of sedimentary cave fill, prior to earthworks by a long line of human occupants, may be identified on ground resistivity and GPR images, although further work is needed to confirm and elaborate additional details. Geophysics can partially define the cave fill topography before human habitation, plus the extent to which human activity has altered the cave interior. Further analysis of results should permit targeted investigations to reveal the stratigraphy, chronology, archaeological and palaeontology of the cave fill, all of which have been uncertain.

Overview

The previous discussion on cave formation and sedimentology suggests that the oldest deposits in the cave should underlie the higher benches, 5 and 6. The youngest deposits should underlie the lower benches 1 and 2 (compare Fig. 03). A case can be made that the Vestibule and Swinehole sections of Peak Cavern are part of a ‘hall and narrow’, structurally-guided network cave in Asbian fore-reef limestone beds with an average 30º northeasterly dip. The stream appears to be following the strike and cutting down-dip along a susceptible limestone bed. It follows that the earliest part of the Vestibule and the earliest deposits therein are at the highest levels, near the southwestern wall and beneath the higher benches 5 and 6. Internal structure of the cave-fill deposits may be imaged by ground resistivity and, particularly well, by GPR. By analogy with the point bar deposits that form along the inside banks of river channels, successive floods could have left lateral accretion surfaces between deposits of different ages. Geophysical contrasts across such lateral accretion surfaces might be imaged by ground resistivity and GPR so that a stratigraphy could be defined by non-invasive means. All the geophysical profiles acquired to date have been aligned parallel to the benches for ease of operation. In order to image putative lateral accretion surfaces parallel to the benches, geophysical cross-lines would be required perpendicular to the benches. This could be difficult with ground resistivity, but GPR is quite adaptable to that challenge (compare Pringle *et al.*, 2003, and Senechal *et al.*, 2001). It is proposed that a 3D-GPR survey be undertaken, to cover all the benches and tuned to image the internal structure of the cave fill. Several additional CMP surveys would be needed for antenna selection and velocity calibration.

Conclusions

Cave topographic survey, geophysical, geological and archaeological data have been acquired, processed and integrated to form a single, 3-D digital model of the Peak Cavern cave entrance. Subsequent analysis of the data has shown that the cave floor slopes down from west to east, sub-parallel to the roof, consistent with cave erosion along bedding planes.

Geophysical investigations, especially GPR, are an appropriate non-invasive technique for shallow cave archaeological, sedimentological and stratigraphic investigations, but the acquisition parameters need to be refined for specific targets. Detailed surveying is considered critical to provide an accurate framework for the integration of geological, geophysical and archaeological data. 3-D CAD software provides a suitable working environment for combining geometrical information from disparate datasets.

Based on the observations and recent literature, the earliest sedimentary deposits within the Peak Cavern Vestibule are predicted to be at the highest levels, beneath benches 5 and 6. The most recent deposits should be found under the lowest levels, i.e. beneath benches 1 and 2 and close to the modern stream when in flood, where active erosion is still taking place. A 3-D GPR survey is recommended to image sedimentary lateral accretion surfaces within the cave fill that should align parallel to the benches. A radar-stratigraphic framework of the sedimentology and early archaeology of the Peak Cavern Vestibule deposits could then be established.

Further studies should be undertaken throughout the rest of the cave system – building upon the cave survey by the Technical Speleological Group. A comprehensive 3D-CAD model could combine geological and topographical information. A 3D-CAD based, hydraulic flow model could then be used to investigate a range of hypotheses for mineralisation, hydrocarbon charge, cave inception and development formation and evolution within the Castleton Reef.

Acknowledgements

The authors gratefully acknowledge the support of their respective funded research projects at Heriot-Watt and Bradford Universities. Julian Clark is acknowledged for field support and Steve Gourlay for CAD model assistance. Alistair Hancock is acknowledged for field acquisition of the resistivity geophysical data. Rob Ferguson is acknowledged for discussions on fluvial systems. Mike Galbraith and Randy Kolesar of SIS Ltd. (now in GEDCO) and the Bentley Education Network (formed within Bentley Microstation plc) are all thanked for their software support. GPR equipment was supplied on-loan from the National Environmental Research Council (NERC) Geophysical Equipment Pool, based in Edinburgh, UK, with support by Alan Hobbs (also of GEP).

References

Beres M, Luetshcer, M, Olivier R, 2001. Integration of ground-penetrating radar and microgravimetric methods to map shallow caves. *Journal of Applied Geophysics*, 46, 249-262.

Bogli A ,1980. *Karst hydrology and physical speleology*. Springer-Verlag, New York, 284 pages.

Chamberlain AT, Sellers W, Proctor C, *et al.* 2000. Cave detection in limestone using ground penetrating radar. *Journal of Archaeological Sciences*, 27, 957-964.

Davis JL, Annan AP, 1989. Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting*, Vol. 37, 531-551.

Ford TD, 1999. The growth of geological knowledge in the Peak District. *Mercian Geologist*, Vol. 14, 161-190.

Hancock AJ, 1999. *An investigation of the soils and sediment contained within the entrance chamber (or The Vestibule), Peak Cavern, and the assessment of their archaeological significance through the integration of geophysical techniques*. BSc Project, Department of Archaeological Sciences, University of Bradford, 71pp.

Leclerc RF, Hickin EJ, 1997. The internal structure of scrolled floodplain deposits based on ground-penetrating radar, North Thompson River, British Columbia. *Geomorphology*, 21, 17-38.

Lehmann F, Green AG, 1999. Semi-automated georadar data acquisition in three dimensions. *Geophysics*, Vol. 64, 719-731.

McMechan GA, Loucks RG, Mescher P, *et al.* 2002. Characerization of a coalesced, collapsed paleocave reservoir analog using GPR and well-core data. *Geophysics*, 67, 1148-1158.

McMechan GA, Loucks RG, Zeng XX, *et al.* 1998. Ground penetrating radar imaging of a collapsed paleocave system in the Ellenberger dolomite, central Texas. *Journal of Applied Geophysics*, 39, 1-10.

Milsom J, 1996. *Field Geophysics*, 2nd Edition. John Wiley & Sons, 131-141.

Osborne RA, 2001. Halls and narrows: Network caves in dipping limestone, examples from eastern Australia. *Cave and Karst Science, Transactions of the British Cave Research Association*, Vol. 28, 3-14.

Pringle JK, Clark JD, Westerman AR, Gardiner AR, 2003. Using GPR to image 3-D turbidite channel architecture in the Carboniferous Ross Formation, County Clare, Western Ireland. In; Bristow, C.S. & Jol, H. (eds.), *GPR in Sediments*, Geological Society Special Publication Vol. 211, 309-320.

Senechal P, Peroud H, Senechal G, 2001. Interpretation of reflection attributes in a 3-D GPR survey at Valee d'Ossau, Western Pyrenees, France. *Geophysics*, Vol. 65, 5, 1435-1445.

Thistlewood L, Noel MJ, Ford TD, 1989. Palaeomagnetic studies from Peak Cavern, Derbyshire. *Cave & Karst Science symposium abstract*, 14, 3, pp. 106.

Westerman AR, 1982. *The development of secondary porosity & permeability in fractured rock*. Unpublished Ph.D. Thesis, Durham University.

Woodall B, 1979. *Peak Cavern*. Brian Woodall Publishers, Buxton, Derbyshire, UK.