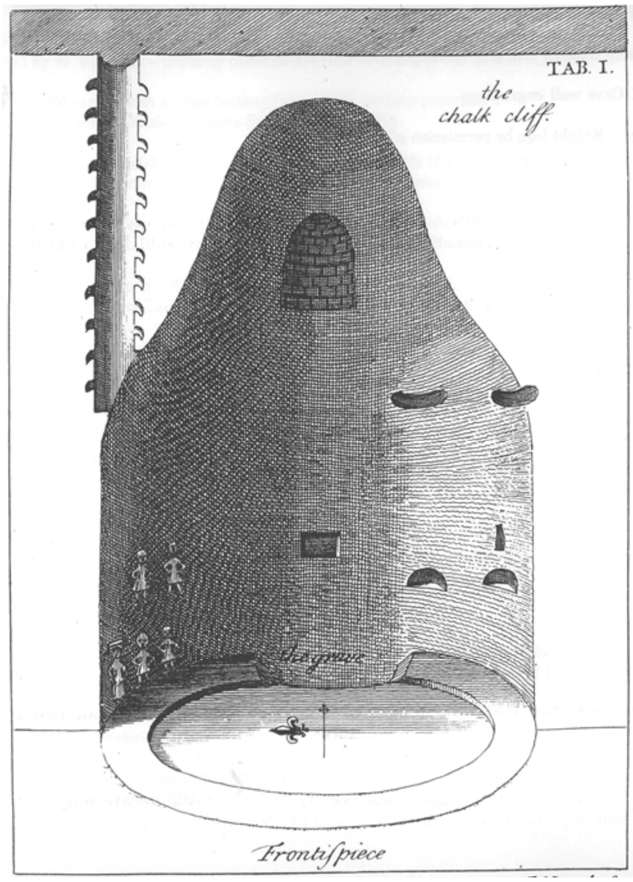
TOBIT CURTEIS ASSOCIATES LLP

RESEARCH AND CONSERVATION TREATMENT OF ROYSTON CAVE, HERTFORDSHIRE: STAGE II



FINAL REPORT FOR THE FRIENDS OF ROYSTON CAVE

MARCH 2014

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1.0 SUMMARY

The Stage II research and treatment programmes at Royston Cave have improved both the condition of the carvings and their environment, as well as the understanding of their original date. The project has been spread over a number of years, allowing problems to be understood and addressed methodically, using an iterative approach. The works have led to significant improvements in the cave by identifying and limiting water ingress, assessing and mitigating, when possible, the risks from vibrations, external air ingress and microbiological, insect and worm activity. Remedial treatment has stabilised the most vulnerable areas of the carving and research has also enabled a more informed date for the carvings to be determined.

Dating the carvings has always been difficult, in part due to the chalk deterioration, as well as a result of later additions and reworking of the figures. Research was commissioned during Stage II to look at the costume and armour for possible dating features. This led to a possible date range from 1350-1650 being suggested, with the researcher indicating that a date towards the first part of this range is probable. This was based primarily on the style of costume, swords, crucifixion and crowns found within the carvings.

Monitoring of vibration levels within the cave was used to assess the effects of traffic, deliveries and visitors. All the levels recorded during the monitored period were low and pose little risk of causing losses to the carved surfaces. It was suggested that where micro-cracks already exist, vibrations may lead to a loss of the chalk surface. More recently the carvings underwent a conservation stabilisation treatment, which consolidated micro-cracks and previously damaged areas. The treatment was limited to areas that were vulnerable and has reduced the risk of further major losses to the carvings. Trials to assess the deterioration rate of the carvings were unsuccessful as additional debris from visitors and via the ceiling vent was collected alongside any chalk. Previous 3D scans, and the photographic record created during Stage II, could be repeated and used alongside regular, future condition surveys to assess any continuing deterioration. This would ensure that any micro-cracks are identified in good time, and further consolidation could be undertaken as required, to prevent any significant future loss to the carvings.

Identification and removal of brandling worms has reduced burrowing and damage to the carvings. After successful identification of the small translucent worms as the larvae of the fungus gnat, a UV lamp was introduced. This has limited the adult population, decreasing larvae numbers by interrupting the breeding cycle. This simple but practical intervention has reduced the damage caused by the larvae to the carvings surface and use of the UV lamp should be continued.

Potential nutrients for the worms were restricted by the survey and repair of drains that run close to the cave. This has significantly reduced water ingress into the main part of the cave, with the hollow in the floor rarely filling with water, following this intervention. However some water ingress continues, with small leaks reported in the cave entrance corridor, especially after prolonged and heavy rain. Due to the subterranean nature of the cave and the bedding planes that run through the chalk material, it will be difficult to prevent all water ingress. This will require ongoing management to ensure that any leaks are limited and continue to be dealt with swiftly, liaising with the water companies as necessary.

Environmental monitoring has shown that the microclimate at the base of the cave, near the carvings, is relatively stable and the current control methods should be continued. Air ingress, via the entrance door and ceiling vent, leads to greater instability in these areas. However, it facilitates the natural ventilation of the cave, removing the carbon dioxide (CO_2) generated by visitors. Trials to seal the vent, led to a slow, but noticeable rise in CO_2, indicating that the cave should not be sealed. The inclusion of the current filter has limited large debris entering the cave. This should be maintained by regular cleaning to ensure that blockages do not lead to rising CO_2 levels in the cave. It may be prudent to continue to monitor CO_2 levels to ensure that they remain low and dissipate overnight, as has currently been observed.

2.0 Introduction

Royston Cave is carved into a bed of soft chalk less than a metre under Melbourn Street, in the centre of the town of Royston in Hertfordshire. Although the cave probably originally predates the medieval period, it appears that it was enlarged and carved with both Christian and mystical symbols at some point between the 14th and 16th centuries. It was then rediscovered in the middle of the 18th century. No record of the cave before the 18th century is known, but since this time there has been continual deterioration of the carved detail. Over the course of the last fifty years, numerous attempts have been made to understand the deterioration and to repair the damaged carving. However, most studies have ended prematurely and only limited remedial measures have been implemented.

In 2007, the cave was examined by English Heritage and it was recommended that a detailed survey should be undertaken in order to better understand the underlying causes of deterioration, so that effective preventive conservation measures could be designed. The condition survey was undertaken by Tobit Curteis Associates in 2009 and formed Stage I of the project[1]. This led to the proposal for Stage II of the project, to undertake detailed research and treatment at Royston Cave, the results of which form this report.

3.0 Royston Cave

The small market town of Royston is located, some twelve miles to the south west of Cambridge, on the historic crossroads of the Icknield Way and Ermine Street. The town sits on a thick bed of late Cretaceous chalk which runs to the north-east and up to the Norfolk coast. Below this is a bed of gault clay which comes to the surface some way to the north.[2] Although the chalk beds are hundreds of metres deep in some places, very few beds are suitable for building material (the harder chalk known as Clunch, sourced in the lower beds, is one such material) the rest being too soft and friable.[3]

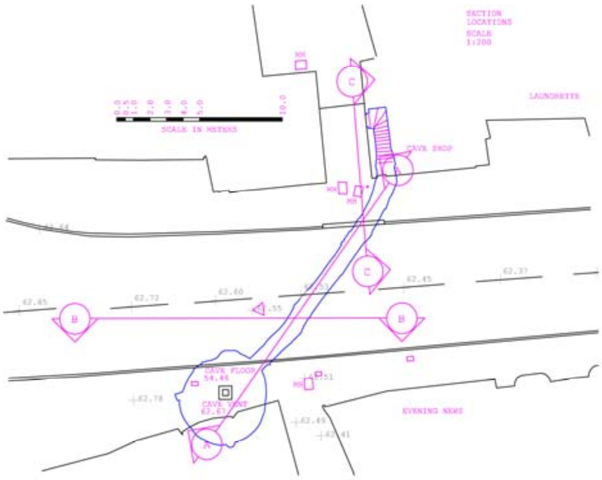
Figure 1. Royston High Street, with the cave entrance in the background and the grill above the vent in the foreground.

[1] Tobit Curteis Associates LLP (2009) Condition Survey and Development of a Conservation Programme for Royston Cave, Hertfordshire (see Appendix I)
[2] British Geological Survey, *British Regional Geology, London and The Thames Valley*, London, 1996
[3] Eyers, J., *The Building Stones of Bedfordshire*, www.bedsrigs.org.uk/leaflets/RIGSBuildStones.pdf, accessed on 29/06/09

The cave is entered via a tunnel which comes up to the side of No. 8 Melbourn Street. The cave itself is situated on the other side of the road partially beneath No. 3 and No. 5 Melbourn Street, which was formally the post office and is now a betting shop.[4] The cave is Grade I listed.[5]

3.1 The Structure

The cave is a tall bell like structure, the top of which is approximately 80cm below the pavement level. The cave, which has uneven dimensions, is approximately 510cm in diameter and 750cm in height. The centre of the cave is approximately 20cm below a step which forms a ledge around almost the entire circumference of the cave. The base is at approximately 54.4m above sea level and the pavement above is at 62.7m above sea level.



Figures 2 & 3. Plan and section of the cave.

Figure 4. View of the tunnel leading down to the cave.

Figure 5. View of and the upper part of the cave showing the bricked up top and opening to the pavement, the partially closed ventilation shaft on the right and the original entrance at the bottom.

At the top of the cave, there are the remains of a tiled closure, which is now largely lost, and an open shaft to the grille on the pavement above. The cave entrance tunnel, which was built in 1790, is on the NNE wall. The original entrance to the cave is the shaft, which enters from above on the WNW side at half height and is cut with foot and hand holds. To the north, above the present entrance, is a second

[4] The cave is at grid reference TL3562940711 and has a postcode of SG8 7BZ.
[5] Historic Buildings Listing 161823

smaller shaft that is now closed, with concrete sections at the top, but is thought to have been a ventilation shaft. The lower part of the shaft is built up with carefully cut masonry blocks, some of which have now fallen away.

While some of the walls appear to have been intentionally carved, other areas have the appearance of natural formations. The bedding planes of the chalk are clearly visible, running the full circumference of the cave, and the chalk within the different beds varies in quality.

It has been suggested that the cave may originally have been a Neolithic flint mine.[6] However, there is very little evidence of flints in the walls, as is the case at Grimes Graves, an extensive Neolithic flint mining works some 40 miles to the north east, near Thetford. If the cave is indeed Neolithic in date, it appears more likely that it may have been a marl pit, for the mining of building chalk.[7]

3.2 Decoration

The main area of carved decoration is in a band on the lower 200 cm of the cave walls. This comprises a number of recognisable Christian scenes, including Crucifixions, the figures of St Christopher and St Catherine, St Lawrence, the Holy Family, a knight thought to be St George, and a number of crowned figures. There are also many figurative and decorative motifs, apparently with mystical symbolism, including a prancing horse and a female fertility figure.[8]

The iconography in the cave has been the subject of a number of extensive studies from the moment it was discovered, some of which have been highly acrimonious.[9] In more recent years a number of detailed studies have suggested links with the Order of Knights Templar, whose presence in Royston is well documented, as well as with the Order of Masons.[10]

Throughout the cave, there are widespread areas of incised graffiti. The graffiti is concentrated on the lower part of the cave, on and amongst the figures. In many cases, the graffiti included dates from the mid to late 19th century. In addition to graffiti showing text and dates there are a number of incised figurative elements, including hearts within hands, a symbol of charity with Masonic links. In the case of the older graffiti and incisions, the deterioration was such that it was extremely difficult in places to distinguish between original and later incised decoration. It also

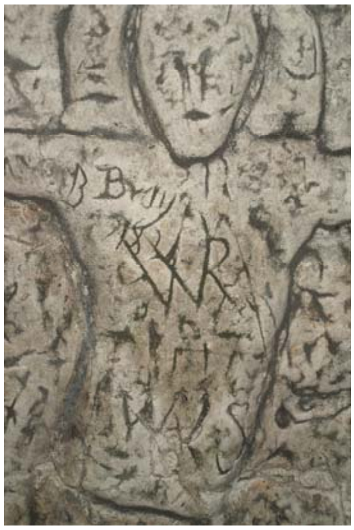
[6] Beamon 1992
[7] I am most grateful to Dr Peter Topping for his comments on this matter.
[8] VCH 1912
[9] Stukeley 1742
[10] Op. Cit. Beamon 1992 and Houldcroft 2004

appears possible that some of the figures have been manipulated or re-carved, in an attempt to tidy them up, or make them conform to a particular set of meanings.[11]

Figure 6. (Previous page) Panoramic view of the carved lower walls of the cave.

Figures 7, 8 & 9 (Above, left & bottom left) Details of the carvings including St Catherine, the Crucifixion, St Lawrence, the horse and the female fertility symbol.

Figures 10 & 11 (Below & bottom right) Incisions and graffiti on the figures and background.



Due to the friable nature of the chalk and the loss of so much detail, little material evidence survives making dating difficult. In addition, the graffiti and the possible manipulation of some of the images, which has occurred since their discovery, further complicate the situation.

Some polychrome decoration was identified on areas of the carvings, analysis of which indicated the presence of red and yellow ochre. However, there was no evidence to indicate the date of the polychromy and whether it was original or a later addition.

3.3 Stage I Condition Survey

The condition survey in 2009 examined the rate of deterioration of the carvings and the underlying mechanism for the decay.[1] The results indicated that deteriogens included environmental factors, biological growth, vibration and vandalism, as well as water ingress from flooding.

Figures 12 & 13. Pigment on the background of the figures and in the incisions.

The primary deterioration mechanism was thought to be minor dimensional change of the chalk, as a result of fluctuations in the moisture content, resulting largely from periodic flooding. This led to internal stresses causing fine cracks to occur, often in the vertical plane between the raised carved detail and the main face of the cave. The fissures were then colonised by microbiological growth and insects, causing the cracks to enlarge and eventually those sections of carving to fall away. In conjunction, damage to the chalk was being caused by worms that feed on nutrients in the chalk, which have entered as a result of flooding with foul water.

The Stage I report also recommended the worms be identified and possible biocide treatments to remove them be investigated. This work produced a photographic record which combined with a 3D laser model provides detailed surface records of the carvings. [12]

[12] Tobit Curteis Associates, *Condition Survey and Development of a Conservation Programme for Royston Cave, Hertfordshire, Report for The Friends of Royston cave*, October 2009

The previous study included a number of suggestions, which were then outlined further in the proposal for the Stage II works.[13] It is these research, monitoring, repair and treatment elements which are discussed in the present report.

4.0 Stage II Investigations

4.1 Timeline for Stage II Works

Date	**Work Undertaken**
Autumn 2010	Drain repairs carried out
October 2010	Environmental Monitoring installed
November 2010	Vibration Monitoring
March 2011	Worms identified (but not larvae)
July 2011	Conservation – Stabilisation and soil removal
February 2012	Date of Carvings report
February 2012	Microbiological Survey report (including fly and larvae identification)
April 2012	Lots of water reported in the cave[14]
June 2012	Pavement grille tested / CO_2 levels rise / Grille removed / Cave again reported to be wet
July 2012	UV insect control lamp installed
April 2013	Filter installed on vent and repairs to East Shaft (CO_2 levels monitored with visitor numbers to ensure this does not cause additional problems)
September 2013	Flooding occurring

4.2 Dating of the Carvings

As discussed above, dating the carvings has proved contentious because of the lack of evidence related to the materials. In order to provide a more informed understanding of the stylistic evidence, a study of the costume, armour and arms displayed in the carvings, was undertaken. This work used the English Heritage photographs from 2008, alongside previously published antiquarian illustrations of the carvings[15].

A further difficulty was that on the surviving carvings many of the costume, and other, details are heavily degraded or may have been adjusted at a later date. However, costumes which could be discerned showed similarities with images on the tomb of Edward III, as well as tomb effigies of William of Hatfield and William of Windsor. Whilst there is some disagreement over when the William of Hatfield effigy was made, the suggested dates range from circa 1340 to the 1380s. The male garments include short skirts, with nipped in waistlines and for women flattened, inverted, U-shaped headdresses, although the deterioration of the carvings means it was difficult to determine if these were headdresses or simply their hairstyle. These headdresses are reported to have been in vogue from circa 1360 to 1380. On this basis, the author suggests a possible date between 1360 and 1390.

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[13] Tobit Curteis Associates (2010) *Proposal for the Stage II Research and Treatment of Royston Cave, Hertfordshire* (see Appendix II)
[14] Flood reports made by James Robinson. General wetting in the tunnel occurs more regularly.
[15] Philip J. Lankester, *Internal Indications of the Date of the Carvings in the Cave at Royston, Hertfordshire*, unpublished report, 2nd February 2012. The full report can be found in Appendix III

No armour could be clearly identified; however, a number of shields and swords are discussed. Two shields are clearly visible with the oval shaped one bearing no resemblance to known medieval shields. The second, which appears to be associated, with the head above is described as a more conventionally 'heater' shaped shield with decorative incised lines. Previous authors have interpreted these lines as bearing a coat of arms or letters, but these are not sufficiently clear in the images to confirm. However this shape of shield is reported to date from any time during or immediately after the 13th century.

Figure 14. Detail of the carvings showing the 'heater' shaped shield with decorative incised lines.

Figure 15. Figure holding a sword with a possible small oval shield on the opposite elbow.

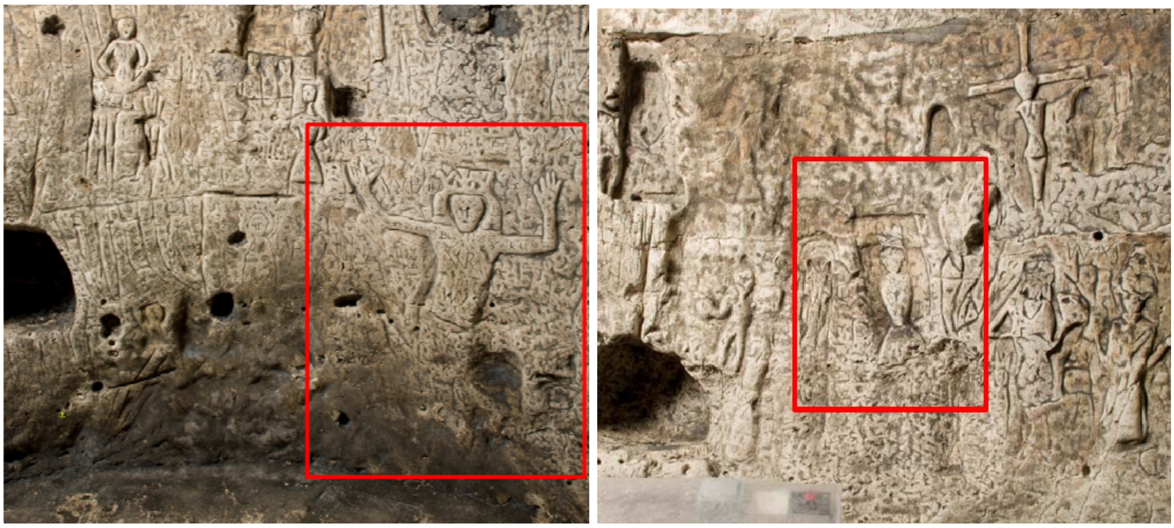
Two further possible shields were identified, formed of incised circles decorated with three concentric rings. It is proposed these may be buckler shields, however these were in use from much earlier and continued to be used till the sixteenth century and so do not help with dating. A further possible oval shield on the elbow of one figure holding a sword is identified; however the shape is described as not recognisably medieval in form.

Two definite swords and one possible sword were identified, including the one in the figure above. However, the author notes that dating medieval swords is often difficult as the general form changed relatively little and variations were often used alongside each other for many years. No distinguishing features were found which would help identify the above photographed example, or the identified possible sword, the vertical sword in the red box in the figure below. The other diagonal sword, closer to the horse, has a tapering blade and is suggested to date from circa 1350.

Figure 16. Detail showing swords inside the red box with one possible round shield containing the concentric rings. To the right of the red box are the pair of figures with crowns and St Catherine, with a crown, is at the top right hand corner of the red box.

In the religious imagery, three crucifixions are identified; however these contain almost no features that were useful to date the carvings. The exception was the larger crucifixion shown above, flanked by two figures, normally the Virgin Mary and St John. In this example Christ's feet are crossed, possibly indicating three nails have been used. This symbolism is reported to begin as early as the 12th century but only becomes commonly used from the mid-13thcentury.

A number of crowns were also identified, including a pair of crowns just to the right of the vertical cross above and that of St Catherine, along with some further possible crowns (shown below). The pair of crowns was thought to represent three tall fleurs-de-lis intersected by two smaller, lower trefoils, found on English coins after 1300. St Catherine's crown does not resemble a medieval crown, but is thought to be an inaccurately drawn version of the pair of crowns design. The additional identified possible crowns do not have dating features or are too deteriorated for any to be distinguished. Based on the arches joining the uprights on the pair of crowns and, assuming St Catherine's crown was derived from similarly designed badges, they are unlikely to date from before circa 1350.



Figures 17 & 18**.** Details of the carvings showing the further possible crown images.

Further research possibilities are outlined, but the lack of additional dating options in the carvings are noted. However the potential of tin-lead alloy religious and secular badges as a source of similar designs to the carvings is suggested as one possible source of information on lay piety depictions. In concluding it is suggested that the carvings are unlikely to have been executed before 1350. Although some of the graffiti is likely to date from after the cave's rediscovery in 1742, it is suggested that the carvings could be as late as 1600-1650. This means the carvings could date from between 1350-1650, however the author suggests it is more likely that they date from nearer the beginning of this range.

4.3 Deterioration Monitoring

An assessment of the long term rate of deterioration was undertaken in the Stage I research. This was hampered by the limited photographic material available. The results indicated that the rate of historic deterioration was not uniform, with varying rates of deterioration depending on changes in the underlying causes. However, the available information suggested that most major losses occurred before the second half of the 20th century, but considerable small scale loss had occurred since this date.[16]

During the stage II work, trials were undertaken to collect chalk debris and worm droppings in selected areas of the cave to give a broad indication of the rate of deterioration. However this proved difficult to determine as the trays filled with other debris from visitors and outside. Photographic documentation of the carvings and cave surfaces, along with the previous scanning data provide an accurate, dated record of the condition. Further scanning or high quality photographic imaging could be used to compare the condition against this record in the future. If repeated regularly, for example every 5-10 years, a good photographic record, alongside a condition survey, will enable a broad deterioration rate to be determined.

4.4 Vibration Investigation

The initial research suggested that vibration was not the principal cause of the carving deterioration; the cave is located beneath the high street and therefore may remain vulnerable to the vibration effects of traffic. Although the volume of traffic has decreased since the Royston Bypass opened in 1986, the proposed pedestrianisation of the central area of Royston may have implications, especially during the construction phase, on vibration levels in the cave. To evaluate current traffic-induced vibration levels, a study of current vibration levels and the possible effect on the structure was undertaken by the Morton

[16] Op. Cit. Curteis , 2009, pp.14-16

Partnership.[17] In order to evaluate current vibration levels, a short programme of monitoring was out by Civil Engineering Dynamic*, i*n conjunction with the filming of road use above the cave.[18]

The vibration monitoring recorded low levels of background traffic, with higher peaks (up to 0.05 mms^{-1}) when heavy goods vehicles, buses or tractors pass overhead, or stop at the nearby traffic lights. Tests inside the cave showed vibration levels from heel stamps on the wooden deck were significantly reduced compared to those on the chalk surface. The vibrations from people walking on the wooden deck were lower and did not show up above the traffic vibrations. Therefore, it was concluded that visitor related vibration has little effect on the inner cave surfaces. Both the traffic and vibration levels are reported to be insignificant and not contributing to damage mechanisms. A much higher level of vibration (0.1 mms^{-1}) was recorded during a test which dropped an empty beer barrel on the pavement above the cave. On this basis it was suggested it would be prudent to prevent unloading of heavy goods on the pavement above the cave.

Figures 19 & 20. Vibration monitoring in progress.

All the vibration levels recorded are significantly below the conservative limit of 3 mms^{-1} generally applied to historic monuments.[19] When these results are converted to acceleration (given in g[20]) even the barrel drop test only yields an acceleration of 0.0137g. These values are all significantly below the recommended vibration limits for museum collections which vary between 0.2g and 0.5g[21]. However as noted by Gibb et al. (2008)[22] vibrations at low frequencies will cause greater displacements than those at higher frequencies. From the data shown in Appendix IV the vibrations recorded were mostly at low frequencies and, therefore, may lead to greater movement in areas with existing micro-cracks.

[17] The Morton Partnership are one of the most experienced firms of structural engineers working on historic buildings in the UK.
[18] Monitoring was specified by The Morton Partnership. Civil Engineering Dynamics Ltd (2010) *Royston Cave Vibration Monitoring report* (see Appendix IV)
[19] See 4.17 from Appendix IV
[20] The report uses %g but to prevent confusion these are reported as in values of g to allow comparison with published literature on vibration for collections.
[21] Thicket, D. (2002) *Vibration damage levels for museum objects*. In Preprints ICOM-CC 13th Triennial Meeting Rio de Janeiro 22-27 September 2002. London: James & James, 90-95
Watts, S., Berry, J., de Joia, A. And Philpottt, F. (2002) *In control or simply monitoring? The protection of museum collections from dust and vibration during building works*. In Preprints ICOM-CC 13th Triennial Meeting Rio de Janeiro 22-27 September 2002. London: James & James, 108-115.
[22] Gibb, I., Phillips, A., Hallett, K. And Frame, K. (2008) *Shake, rattle and roll: vibration effects at the Hampton Court Music Festival*. Conservation Science 2007: Papers from the Conference held in Milan, Italy, 10-11 May 2007. London: Archetype, 36-39.

The Morton Partnership comments on the data that "it is clear that traffic is the principal and most frequent vibration generator, with other secondary activities, such as off-loading, being less frequent, although generating higher levels of vibration"[23]. They reiterate the comments on preventing unloading of vehicles and recommend this does not occur within 25m either side of the cave. A suggested alternative option would be to manage deliveries using additional equipment, such as drop sacks, to prevent high impacts or vibrations. In addition they comment that whilst traffic related vibration is unlikely to be the cause of defects in the carvings, where micro-cracks exist, the traffic vibration may be a sufficient trigger to lead to the collapse of the chalk and loss of surface details.

It seems apparent that increased levels of traffic vibration above the cave, such as the prolonged presence of heavy goods vehicles or the implementation of speed bumps etc. could have a long term deleterious impact on the condition of the cave and should be discouraged. Interventions such as the possible pedestrianisation of this area have the potential to cause damage, either as a result of local vibration –inducing ground work (hammering and drilling etc) or from the repositioning of traffic features, such as traffic lights.

4.5 Conservation Treatment

The Stage I condition survey identified a number of fine hairline cracks which had formed behind areas of raised detail (as shown below). This was thought to be an early stage in the delamination process, leading to losses of carved details. In the areas of cracking where the risk of loss was high, remedial conservation treatment was undertaken to stabilise the carving.[24] Treatment was undertaken in July 2011 and full details are given in the conservation report in Appendix VI.

Figures 21 & 22. Detail showing the crack between the carved face and chalk substrate behind, and soft hydraulic lime mortar repair.

A careful assessment of conservation treatments was made as any significant alteration to the porosity of the material at the interface between the raised detail and the bedrock might in fact exacerbate the failure mechanism. After a period of testing, re-adhesion was carried out using a suspension of calcium hydroxide nano particles in ethanol [CaloSil E-50]. It was anticipated that a lime-based approach of this type would produce a calcium carbonate matrix with characteristics similar to the original structure but

[23] The Morton Partnership (2011) Royston Cave, Royston, Hertfordshire (see Appendix V)

[24] Full details of the conservation treatment can be found in Tobit Curteis Associates LLP (2011) Preliminary Report on the Remedial Conservation Treatment at Royston Cave, Hertfordshire (see Appendix VI)

that the small particles in the nano-dispersion would provide greater penetration, improving the adhesive and cohesive properties.

Carved areas with previous losses, which now had vulnerable edges and surfaces, were treated with small mortar repairs. A number of tests for suitable materials led to the selection of a mortar made from 2:3:3 NHL2 weakly hydraulic lime: marble dust: silver sand. This gave a stable and soft mortar, similar to the chalk material, both visually and in strength. Where coarse damage had occurred to the surface as a result of worm activity, a weak hydraulic lime grout was injected behind flaking areas before a soft hydraulic lime repair was applied. The treatment areas were limited to those areas where the risk of further loss of material was likely to be significant. This has increased the carvings' stability but cannot remove the risk of damage while the underlying causes of deterioration remain.

4.6 Worm Damage and Remedial Measures

The cave contained both large purple and small translucent worms. The effect of the worm activity is to cause a loss of cohesion and collapse of certain sections of the softer chalk and a consequent loss of the carved detail. The large purple worms measuring less than 40mm in length were identified as *Eisenia fetida*, known by a variety of common names, including the redworm or brandling worm.[25] *Dendrodrilus rubidus* was also identified, more commonly referred to as earthworms.[26]

Having identified the pink worms causing some of the deterioration to the carvings, it was determined that there were very few possible treatment methods to eliminate them. This is in part due to the withdrawal of many biocides, or their use being unknown for caves, and so requiring licences or additional research. The drying of the cave as a pest treatment is impractical as moisture will continue to come through the chalk, and the increased moisture exchange at surface level would further damage the carvings. A possible alternative which was considered was the use of anoxic gases; however these pose a significant risk to human health when used in a cave and so were also considered unfeasible.

Figures 21 & 22. Red worms emerging from crack in the chalk. Note the worm casts on the surface.

As a suitable biocide treatment could not be found, it was decided that the most effective method to limit their destructive effect, was to reduce their habitat within the cave and, therefore, reduce the

[25] Idenitified by J. M. Schmid-Araya at Queen Mary University and confirmed by E. Sherlock at the Natural History Museum.
[26] Idenitified by E. Sherlock at the Natural History Museum.

number of worms present. This involved removing the large volumes of soil and other debris that had built up at the base of the cave and, in particular, on the step below the carvings and on the horizontal surfaces in the chalk openings. Large areas of the soil were found to be heavily compacted, although the areas where most worms were found were less so. Tests showed careful mechanical removal was most successful, and was the safest means to remove the soil layer but leave the chalk substrate beneath intact. Material was removed using scalpels, small dental tools and soft brushes, with any residues removed with soft brushes and vacuum cleaners. A number of additional carvings showing lying figures, similar to the 18th century illustrations were revealed by the removal of the soil[27].

Figures 23 & 24. The compacted soil on the step and the exposed carvings when the soil was removed.

Further worms were observed falling from the east shaft in July 2012. The shaft was examined in October 2012 and the mud and soil containing the worm population were removed. The top of the shaft was found to comprise concrete slabs which had mortar on all except one side. Mortar repairs to the east shaft were made in April 2013 to prevent additional worms entering via this route. While a limited number of worms remain present, the population of the purple worms has been greatly reduced.

Figure 25. Repairs were made to the top of the east shaft in 2013.

[27] This work was undertaken during the Conservation Stabilisation Treatment and is documented in the same report (see Appendix VI).

4.7 Microbiological Activity

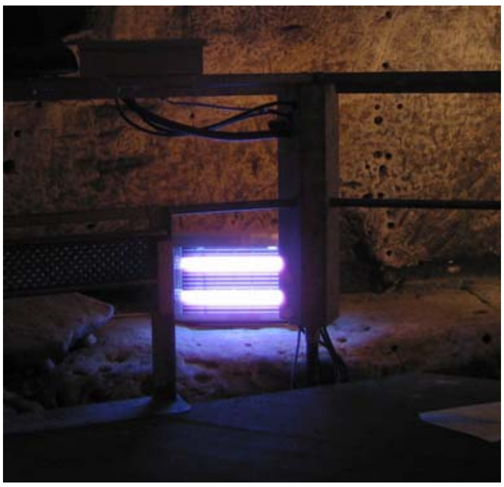
Following the conservation stabilisation treatment, black fungal growth appeared on some treated areas. As a result, a microbiological survey was carried out by Industrial Microbiological Services Ltd (IMSL).[28] During a visit to the cave IMSL sampled selected surface areas using sterile swabs to investigate fungal, bacterial and algal growth. A specimen of a fly and larvae (the small translucent worm) that had been observed on the chalk surface, were also collected.

Fungal and bacterial identification found a very limited number of species were present in the cave. There were two dominant fungi [*Gliomastix murorum* and two strains of *Penicillium brevi-compactum*], two additional strains were isolated at low frequency but could not be grown within the laboratory and were therefore not identifiable. A limited number of bacteria species were found, with most from the *Bacillus* genus. However the authors highlight this may arise from the limited sampling and a wider array of species would be anticipated. The algal population (adjacent to the lamp in the access corridor) were identified as *Protococcus sp*. On the ceiling above the entry into the cave *Cholorococcum humicola* was identified alongside *Protococcus sp*.

None of the species identified are human pathogens and no growth was observed in tests designed to detect bacteria associated with sewage leakages, although the authors note this may still be present in the ground. The report indicates *Gliomastix murorum* may have been the cause of the black growth and further tests were carried out. It was later suggested that some aspect of the conservation treatment may have stressed a pre-existing organism which was previously present in an invisible form. Its defence mechanism created a black form, with high spore content, which was then visible on the surface in treated areas. This material was later removed with IMS / water swabs and has not reoccurred.

4.8 Gnats Larvae Identification and Removal

IMSL additionally identified the fly and larvae found in the cave as a type of Fungus Gnat [*Speolepta leptogaster*]. This species is reported to be almost always associated with caves and cave-like habitats. The larvae of this species are thought to have been misidentified as moth larvae previously. Methods were sought to remove these numerous insect pests from the cave, as the larvae stage leave deposits on the surface of the carvings, which are particularly disfiguring.

Figures 25 & 26. Biocide lamp in position.

As with the larger worms (above) biocide and alternative methods, such as pheromone traps, were investigated but ruled out. It was suggested by IMSL that a UV light might be attractive to the adults,

[28] Industrial Microbiological Services Ltd (2012) Microbiological Survey of Selected Wall Surfaces at Royston Cave (see Appendix VII)

which would trap them and interfere with the breeding cycle, thus reducing the numbers of new larvae which form. A UV insect lamp was installed in July 2012 and tests later that year showed it to be functioning correctly.[29] The rate of attrition of the gnat population is difficult to assess, but reports from site staff indicate that the numbers of larvae have decreased. The light is now set on a timer for 8 hours overnight, rather than 24 hour operation, after an increase in green microbiological growth was reported in front of the lamp.

As previously suggested lights in the cave should only be turned on when it is in use, to limit any potential microbial growth. In addition use of the UV lamp should continue as this will further reduce the gnat population. As this species is reported to live in caves, it is likely that recolonisation may slowly occur if use of the UV light was to be discontinued. Limiting the possible breeding cycle by removing the adult fly, continues to be the best control option for preventing damage to the carvings by the small translucent larvae.

4.9 Water Infiltration

Leaks and floods in the cave, specifically from sewage pipes, were thought to be providing food sources for the worms. Water infiltration has been observed over many years in the cave, apparently from public drains and possibly the drains of the fast food outlet on the north side of the road.[30]

A survey of the drains close to the cave, undertaken in 2009, identified a number of small leaks in both the foul water drainage and surface water drainage that may be leading to water ingress in the cave.[31] The pipes were cleaned and relined in October 2010, to prevent further sewage or water ingress from these sources.[32]

Figures 27 & 28. Repairs being undertaken to the drains in October 2010.

This has significantly reduced the number and severity of water infiltration into the cave. In particular in the area referred to as "the grave", the slightly deeper area to the right of the entrance tunnel within the cave, has almost completely ceased to fill with water.

[29] The system installed was a PestWest Chameleon 1x2IP http://www.pestwest.com/products/professional-sticky-traps/chameleon-1x2/
[30] A report on the drain leaks was prepared in September 2000 by Peter Houldcroft.
[31] Manestream Ltd (2009) CCTV Report (030897-DP) (See Appendix VIII) See also Tobit Curteis Associates report 2009 (Appendix I)
[32] Survey and repair works were carried out by Manestream Ltd. The areas of damage to the main drain (center of the road) and the surface water drain (north side of the road) identified in the survey were repaired with resin bonded liners.


Figures 29 & 30 Water in the tunnel shaft in January 2013.

However, there continue to be a number of smaller leaks mainly located in the entrance corridor to the cave, especially during periods of heavy and prolonged rain. This suggests that additional sources of water, such as old, unrecorded, drain pipes and water courses exist. Although probably disused they will transport any accumulated water that gathers inside them. However water ingress could also occur from ground water through the bedding planes of the chalk after heavy rain, which would be almost impossible to prevent. Therefore it is likely the cave will continue to have occasional water infiltration, which will require careful management. As long as this is limited to small infrequent leaks in the corridor, these leaks pose minimal risk to the carvings.

5.0 ENVIRONMENTAL MONITORING PROGRAMME

5.1 Aims

The previous study noted that possible fluctuations in the microclimate may be responsible for damage to the carvings. Therefore, an environmental monitoring programme was established to understand the current microclimate within the cave and assess any impact this would have on the carvings and their condition in the future. The environmental monitoring programme involved gathering microclimatic data over a long period to examine the levels and patterns of microclimatic change, the factors influencing them, and the likely effect on the fabric. Areas of particular interest were 1) the precise hygral and thermal buffering capacity of the cave, 2) the influence of visitor use, 3) the effect of air leakage and 4) the effects of condensation events on the carvings.

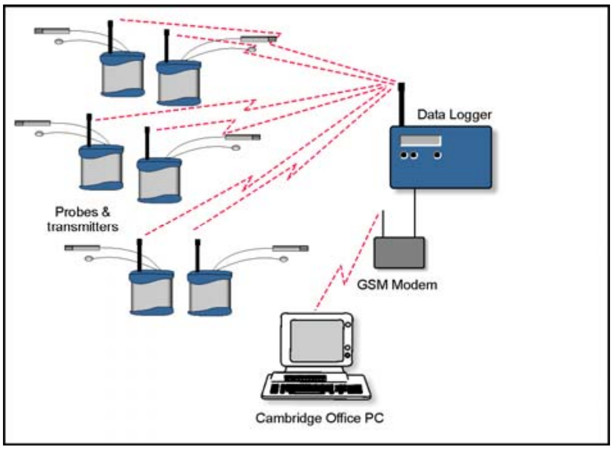


Figure 31. Illustration of the equipment set up.

5.2 Parameters

The measured parameters are relative humidity (RH), ambient temperature (AT), surface temperature (ST) and carbon dioxide levels (CO_2). The parameters to be calculated are dew point temperature (DPT), condensation and absolute humidity (AH).

5.3 Sensor Locations

Sensors were positioned in order to gather data and compare areas within the cave. On the upper parts of the cave, access was limited, so precise sensor locations were determined, to some extent, by access.

Serial	Location	RH	AT	ST	CO_2
14129	External	*	*		
14128	North side low	*	*	*	
14131	North side high	*	*	*	
14130	Top of stairs	*	*	*	
9263	CO_2	*	*		*

5.4 Equipment

The environmental monitoring was undertaken using an Eltek Squirrel radio telemetry datalogger (see Figure 19). In order to avoid the problems which caused the loss of data in previous programmes, equipment designed for extremely high humidity operation was employed. RH and AT were measured using Rotronic Hygroclip S sensors and ST with EU-U thermistors.[33] The datalogger was accessed via a GSM modem on the Vodafone network and data was downloaded and analysed using Eltek Darca Heritage software. Data was logged at 15 minute intervals throughout the project and downloaded at regular intervals. The monitoring system was installed in mid-October 2010 and has continued for just over 3 years.

[33] The published accuracy levels for the sensors are: Hygroclip S RH +/- 1.5%, AT+/- 0.3°C. EU-U-V2, ST +/- 0.2°C.GD47 CO_2 +/- 50 ppm +3% of measured value (at 25°C, 1013 mBar)

All the sensors on the north side low transmitter are at 1.35m above the cave floor, whereas the north side high sensor (RH/AT) is at 6.2m with the ST sensor placed at 3.8m above the floor. Surface temperature sensors were held in place on the surface using Plastazote.

5.5 Monitoring Results

5.5.1 External Conditions

External conditions are similar for all three years of data with an RH range between approximately 15% and 100%, with an average of 77%. Ambient temperature (AT) had maximum and minimum values of 32.1°C and -8.9°C, with an average of 11.4°C. During the spring and summer months, diurnal RH fluctuations were regularly >40%, while AT fluctuations were regularly >5°C. Conditions during the winter months were typically more stable, particularly for RH. Maximum and minimum AH values were 17.6 and 1.8 gm^{-3}.

5.5.2 Top of the Stairs Microclimate

When looking at the data from all the internal monitoring positions the fluctuations are greatest at the top of the stairs, with <3°C daily temperature changes and regular RH fluctuations of <30%. The conditions are generally very similar to external conditions, as might be expected from the position of the transmitter, just inside the external door. This means that during the summer months the RH is much lower at the top of the stairs compared with inside the cave, where it is often close to 75% RH and can be as low as 40% RH. At the same time the low level north side is between 90-100% RH. Winter RH levels are higher, varying between 95-100% RH.

This is a reversal of the trend seen inside the cave, where the summer is higher than the winter. The minimum RH was 38.6%, the maximum 100%,with an average of 93.1%. The temperature range was also greater between 5.1°C and 26.8°C, giving an average of 14.8°C, around 2°C warmer than the average temperatures at other monitored points inside the cave.

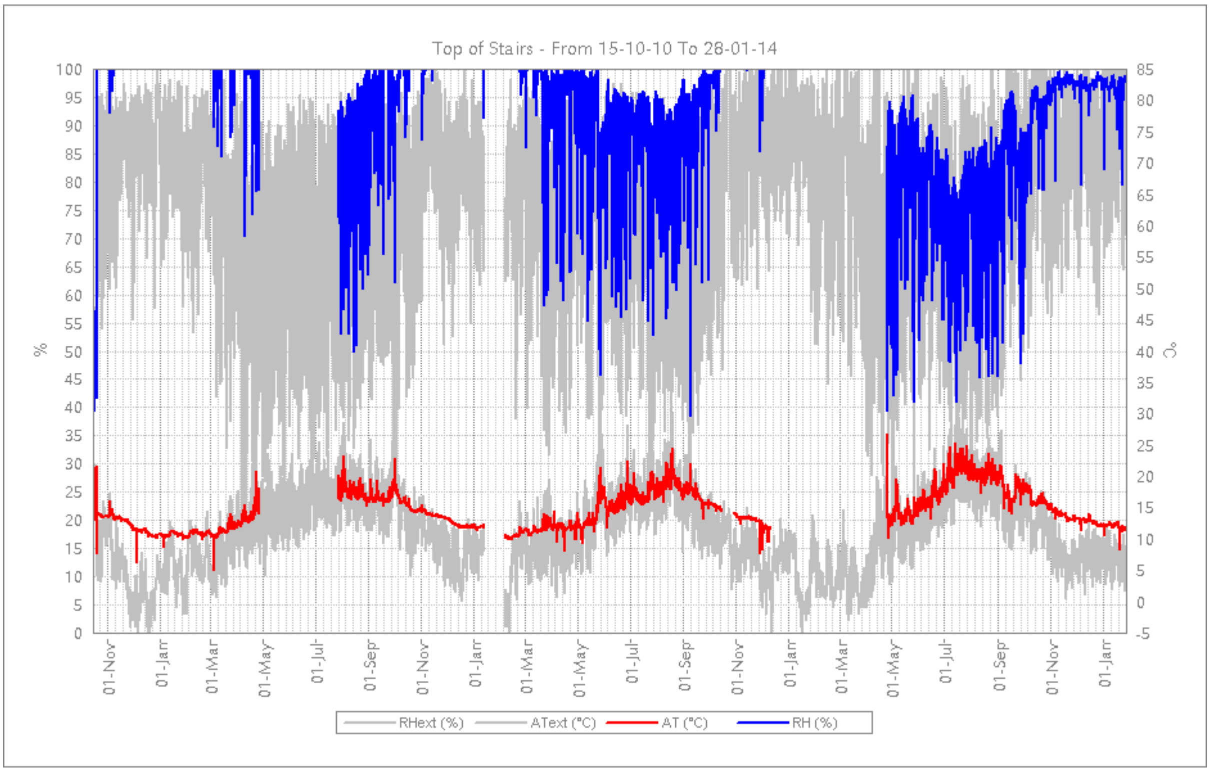


Figure 32. AT/RH data for the top of stairs monitoring position inside the cave and external conditions (2011-2013).

At the top of the stairs the AH follows the pattern of the external environment more closely than at the other monitoring points. The external AH decreases in the summer but remains higher than the external levels during the winter. This gives an average of 11.8 gm^{-3}, very similar to the external average of 11.4 gm^{-3}. While the maximum (16.6 gm^{-3}) is similar to external values, the minimum is higher (5.3 gm^{-3}).

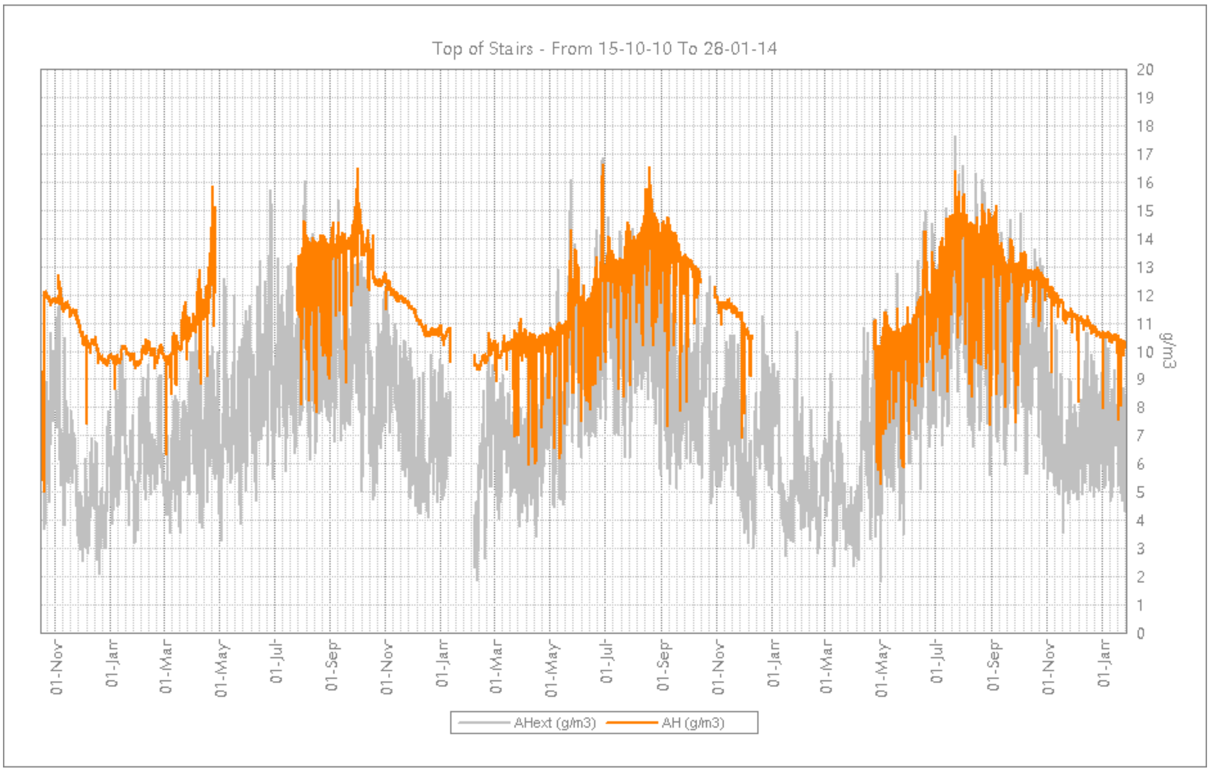


Figure 33. AH data for the top of stairs monitoring position inside the cave and external conditions (2011-2013).

5.5.3 Cave Microclimate

In general, temperatures are relatively stable throughout the year within the cave, with average temperatures inside approximately 12.5°C. This is because the chalk provides significant thermal mass, buffering internal temperatures.

In summer, whilst the temperature outside might be above 25°C, inside the temperature could be as low as 15°C cooler. In the winter this trend is reversed. When the external temperature can be 5°C, the internal temperature is often at least 10°C. There is also a noticeable thermal lag, as the chalk takes longer to absorb the heat and re-emit it. This means that while the warmest external temperatures are usually seen in July, internally the warmest period is normally August. The temperature varies relatively little with minimums in the winter close to 9°C and in the summer usually peaking around 19°C. Generally RH levels are high throughout the year, with average values in excess of 90%. The size and number of fluctuations in RH depends on the monitoring location and are discussed in greater detail below.

Low level conditions

The low level north side sensor shows similar trends to the CO_2 sensor location (discussed below). As shown in the figure below, the temperature is relatively stable with a minimum of 8.9°C and maximum of 18.8°C. The average AT was 12.4°C.

In this lower part of the cave temperature fluctuations change with the presence of visitors, rather than as a result of external conditions. These visitor-induced temperature fluctuations also lead to decreases in RH. The maximum and minimum RH was 100% and 84.3% respectively, with an average of 99.7% and the RH remains between 90% and 100% almost constantly.

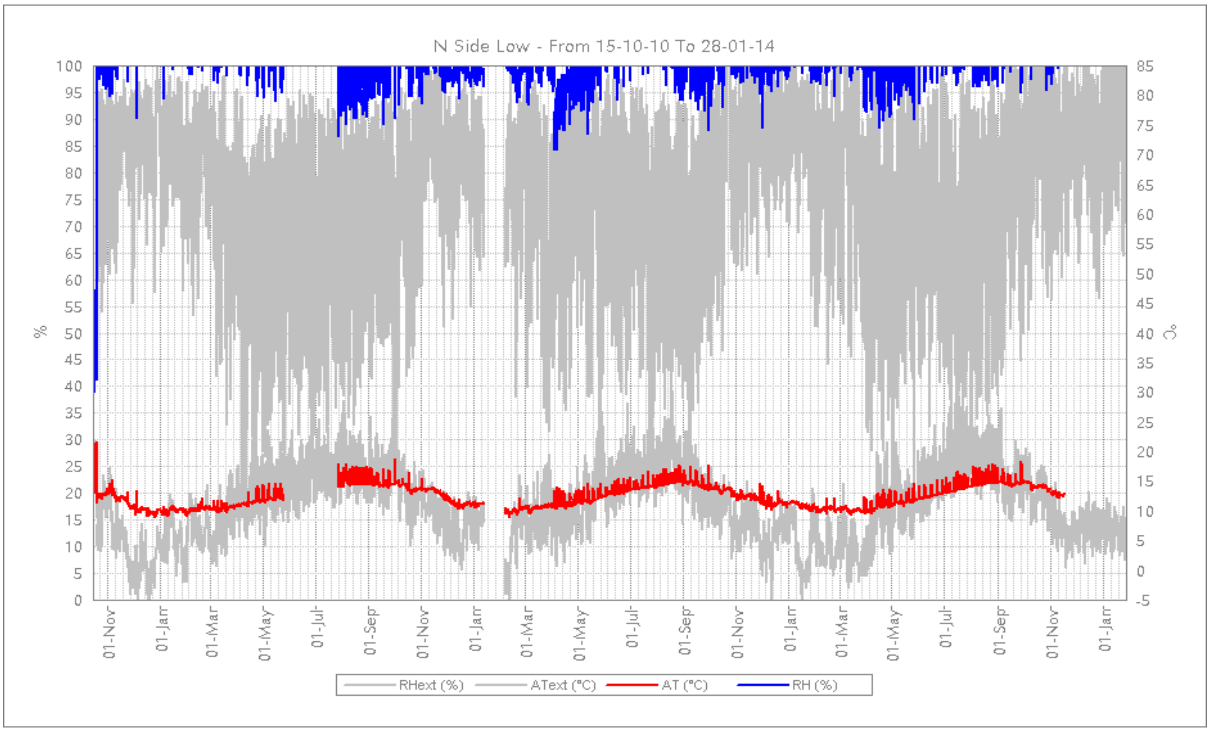


Figure 34. AT/RH data for the lower monitoring position inside the cave and external conditions (2011-2013).

The AH is normally stable with a minimum and maximum of 8.6 gm^{-3} and 14.9 gm^{-3} and an average of 10.9 gm^{-3}. Figure 23 shows that, as with the temperature changes, the AH increases with greater visitor numbers in the cave rather than following external conditions. Open days in the cave are clearly visible, due to the peaks in AH and AT from visitors. This is likely to arise from the sensor being located nearer to the visitors at a height of 1.35m, therefore, their presence has a greater effect on the microclimate recorded locally.

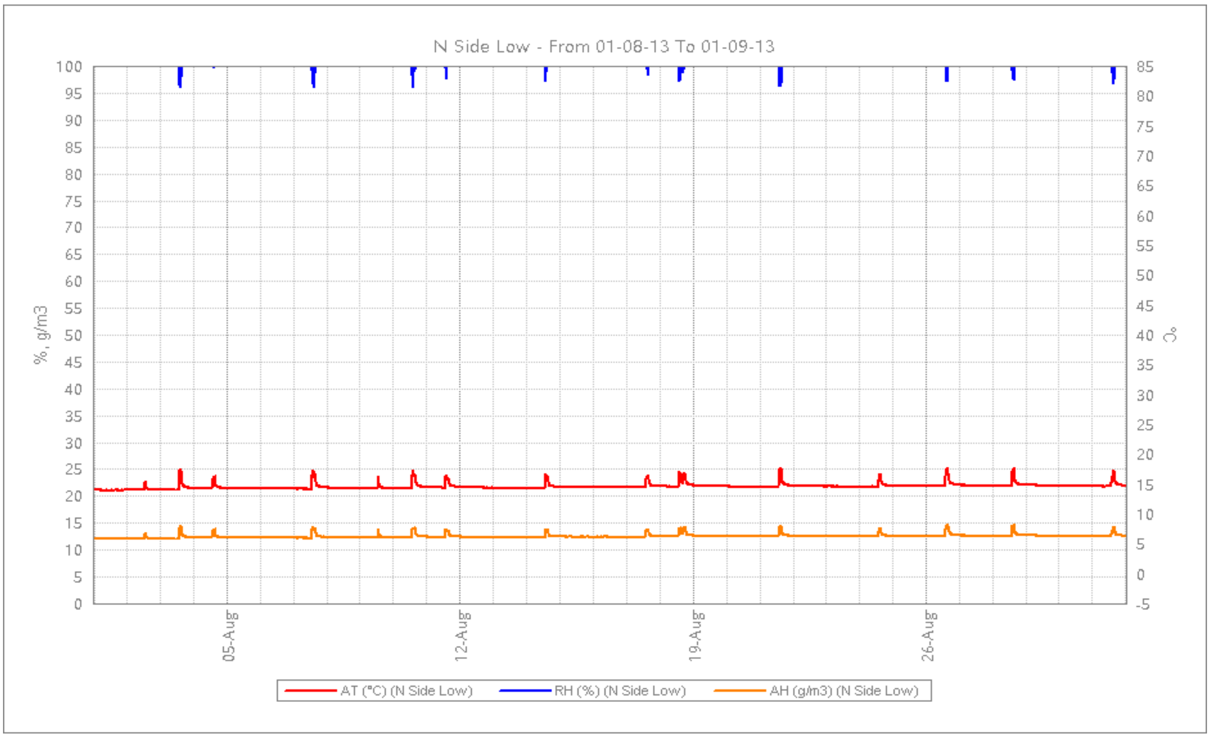


Figure 35. Detail from August 2013 showing the effect of visitors on AH, AT and RH at the lower level of the cave.

High level conditions

In contrast to the lower sensors, the high level north side conditions are similar to those at the top of the stairs sensors and are affected primarily by external conditions. The chalk still provides thermal buffering limiting the differences between the summer and winter internal temperatures, compared to external conditions. The temperature minimum was 7.3°C, the maximum was 20.3°C and the average was 21.6°C, which are not too dissimilar to the lower sensor. However, more short term daily thermal changes are often recorded compared with lower in the cave. Unlike the lower height sensors, clear patterns of visitors cannot be seen in the data. As the high level north side sensor is placed at a height of approximately 6.2 m within the cave, this is not surprising.

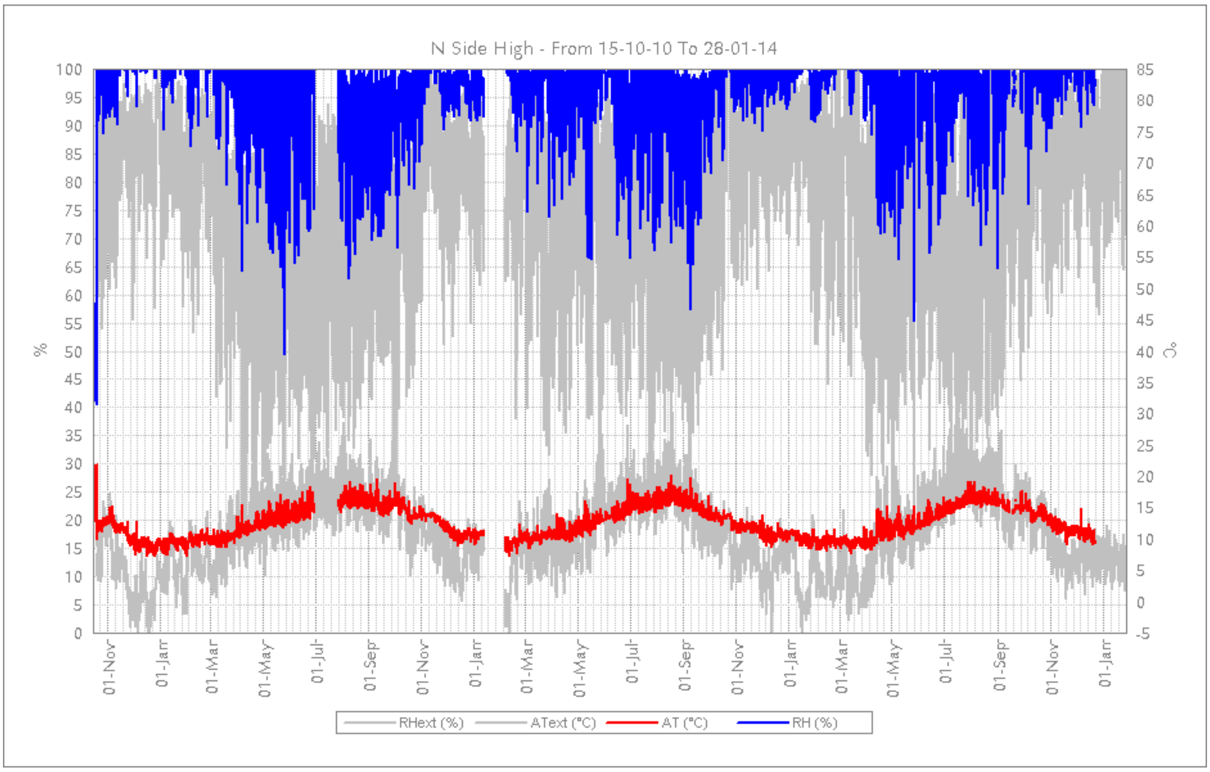


Figure 36. AT/RH data for the higher monitoring position inside the cave and external conditions (2011-2013).

During winter months the RH varies very little in comparison to the summer, remaining close to 100% at the high level north side. From the spring to autumn the daily RH variation is much larger (<40% RH but with relatively regular daily fluctuations of >20% RH) and closely follows external variations. While the average RH is 96.7% (relatively similar to the lower sensor), the minimum is 49.4% and the maximum is again 100%, showing a wider RH range. The AH closely tracks the higher peaks in AH externally, and follows a similar general trend. However, the internal AH rarely drops to the same extent as the external conditions, with summer decreases in AH never matched. Here the average is similar to the lower sensor 10.8 gm^{-3}, however the minimum (6.7 gm^{-3}) and maximum (15.8 gm^{-3}) again give a wider range. During the winter months the AH remains significantly above external conditions (often twice the external value) and remains relatively constant.

5.5.4 Surface temperatures

Surface temperature has been recorded at both the high and low levels of the north side of the cave. These show that, in both locations, there is little difference between the dew point and surface temperatures throughout the year. In practice this means condensation is likely to be occurring, almost daily, particularly during the summer months when the risk of condensation is greatest.

At the higher level of the cave (the surface temperature sensor is at 3.8 m) the risk of condensation in the summer is greater than at the lower level. The high frequency of condensation events means these surfaces may remain wet for extended periods of time, potentially up to 3 months or more.

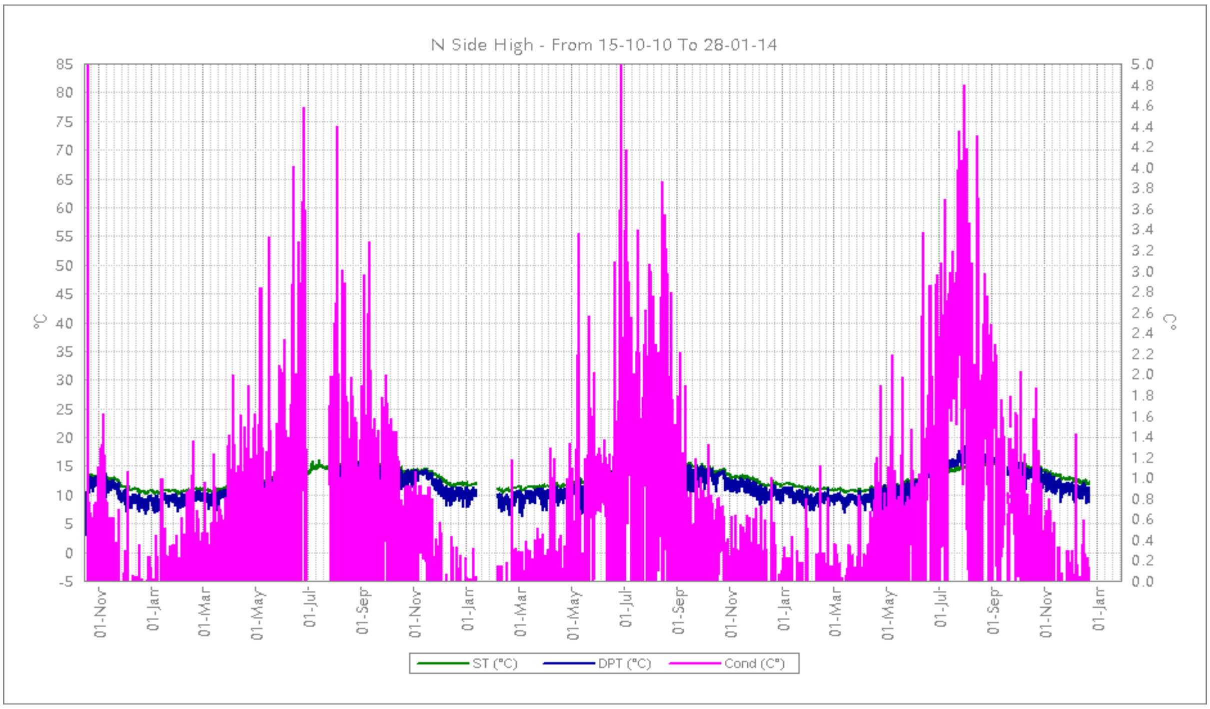


Figure 37. ST, DPT and condensation data for the higher monitoring position inside the cave (2011-2013).

There is less data for the surface temperature sensor at the top of the stairs. However, this shows that condensation is less likely during the summer months where the difference between the surface temperature and dew point temperature is greater. Generally the likelihood of condensation at the top of the stairs increases during the autumn, is greatest in the winter and decreases in spring, showing the opposite trend to that within the cave.

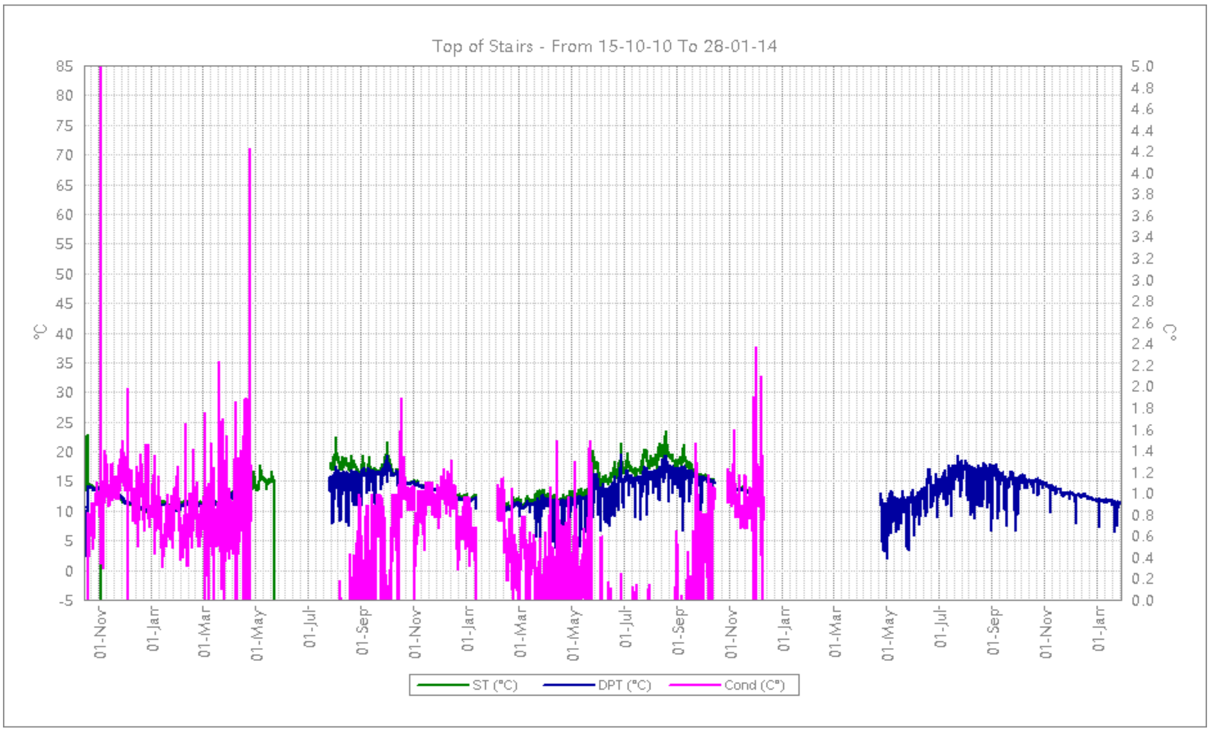


Figure 38. ST, DPT and condensation data for the top of stairs monitoring position inside the cave (2011-2013).

5.6 Air Exchange and Carbon Dioxide

The Stage I condition report[1] indicated the instability in the microclimate may be due to air infiltration from the vent in the cave ceiling. As a result attempts were made to reduce the air infiltration from outside by sealing the ventilation grille in the pavement above. An additional benefit of this measure would be to reduce water and dirt infiltration via the vent.

Figures 39 & 40. Initial tests with complete closure of the vent.

In order to assess the effect that treatment of the vent might have on carbon dioxide (CO_2), monitoring has taken place since January 2012. Prior to sealing the grille in June 2012, CO_2 levels in the cave were generally between 500-600 ppm when unoccupied and rose to 1500-2500 ppm during visits, depending on visitor numbers and visit lengths.

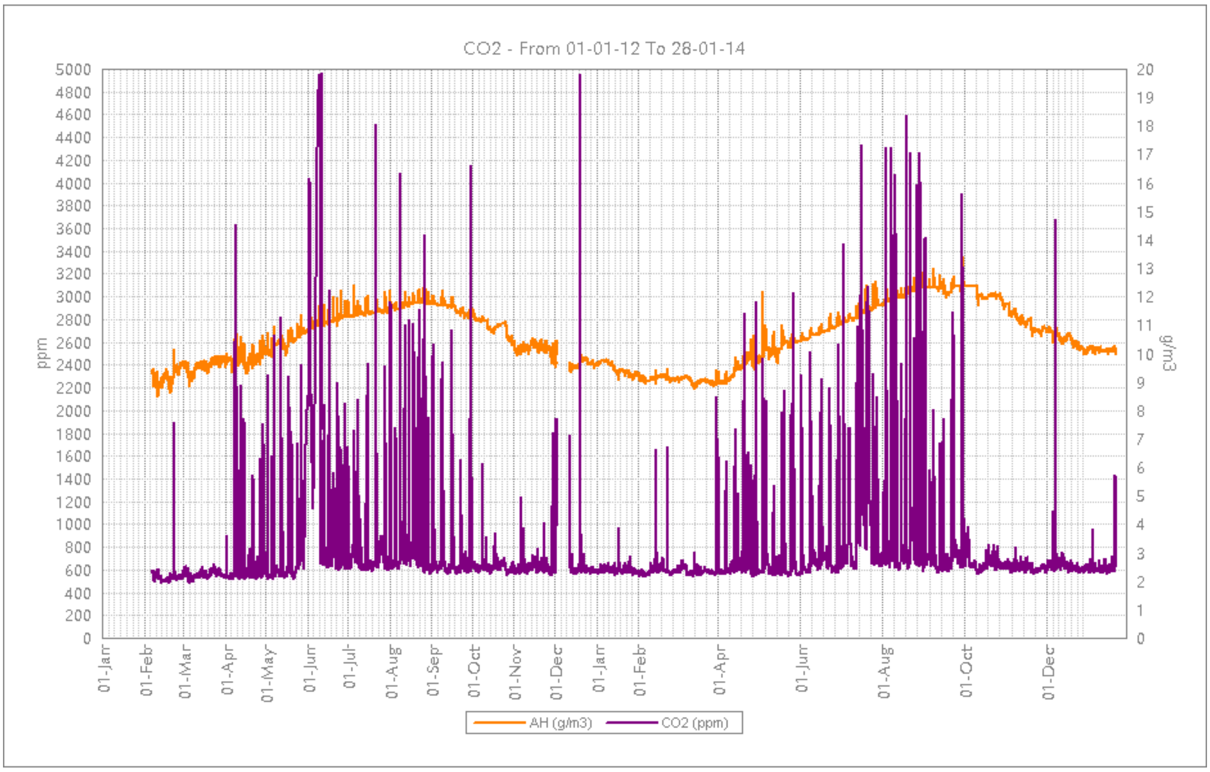


Figure 41. AH and CO_2 data for the CO_2 monitoring position inside the cave (2012-2013).

Once the grille was sealed the CO_2 levels rose to 3800 ppm over the first week and then to 5000 ppm (the sensor limit) in the second week. The long-term workplace exposure limit (8 hour reference period) is 5000 ppm, whereas the short-term exposure limit (15 minute reference period) is 15000 ppm[34]. Therefore, although it was unlikely to be dangerous, as expert advice on health and safety issues was not available, the grille was reopened and CO_2 values fell to previous levels. [35]

As a result of removing the seal it was recommended that a plate be placed beneath the grille to prevent water and rubbish infiltration but allow sufficient air exchange. This would then have to be cleared, probably on a regular basis to remove any accumulated material. As an alternative in April 2013 a filter was added to the vent, consisting of a section of open cell reticulated polyether foam placed over a thin steel wire support.[36] While this will reduce the amount of large debris falling into the cave it should not affect CO_2 levels. However it is still recommended that any debris is removed from the filter regularly to prevent blockages from occurring. The filter has the disadvantage of still allowing water ingress via the ventilation grille, but preventing high CO_2 concentrations is more critical in this instance.

Figures 42 - 45. Installation of the vent filter in April 2014.

The larger CO_2 peaks (>1000ppm) correlate well with the small rises in AH seen on open days, as visitors are contributing both CO_2 and moisture to the cave's environment. When the AH is compared to the AT and RH for the CO_2 sensor position the peaks in AT match those in AH. Similar to CO_2 and moisture levels, this is because the increased heat is coming from the visitors. Days when the cave is open, compared to closed ones, are noticeable due to the increases in CO_2, AH and temperature. However the increases in AT and AH are both relatively small and the microclimate near the CO_2 sensor is generally very stable.

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[34] http://www.hse.gov.uk/carboncapture/carbondioxide.htm (accessed 30th January 2014).

[35] Tobit Curteis Associates LLP has no expertise in health and safety matters and can offer no expert advice with regard to these matters. Comments on this report relate simply to CO_2 values observed and the public advice provided by the HSE. This is in general terms only and does not relate to cave environments or other non-standard locations. For information regarding specific health and safety matters in this case, it would be necessary to seek advice from a qualified specialist.

[36] 10 pore per inch reticulated polyether foam supplied by Maidenhead Aquatics at Scotsdales (Cambridge) but widely available.

The increases in temperature noticeably reduce the RH. However the reduction in RH is limited by the increase in AH, caused both be visitors expiring water vapour and by vapour evaporating from the walls as a result of the temperature increase.[37]

Figure 46. Detail showing the effect of visitors on CO_2, AH and AT levels at the CO_2monitoring position.

In general CO_2 levels are lower over the winter closed period with occasional peaks, whereas during the open period, from April to September, CO_2 levels generally increase with visitors. Visitors generate CO_2 when they are inside the cave, therefore on days with higher visitor numbers there are greater CO_2 levels. For example using the figure above, on 7th August 2013, 73 people visited the cave, at 4pm the CO_2 levels reached 4308 ppm. However, the visitor number records do not include the length of visits, which will also affect the CO_2 levels, e.g. on 18th August 2013 CO_2 levels reached 4595 ppm, yet the visitor numbers were 32.

The higher recorded levels of CO_2 can be used to calculate how quickly the CO_2 is dissipating from the cave, giving the air exchange rate for the cave[38]. These calculations show that sealing the grille had little effect on the air exchange rate, in part as it is already very low. This would also suggest that air infiltration from outside is not the main cause of microclimate instability inside the cave. However this is at odds with the environmental data recorded higher up on the north side and at the top of the stairs.

One possible reason for this difference is that temperature stratification occurs within the cave. During the summer period temperatures measured by the north side high sensor can be as much as 5°C warmer than those measured by the CO_2 sensor, with a 3°C difference common for most of the summer. This will lead to the air within the cave stratifying into layers of different temperatures. The cooler air in the lower parts of the cave will stay there, along with the denser CO_2 gas, forming a stable environment and low air exchange rate, as measured by the CO_2 dissipation. However higher up in the cave, closer to the grille, the warmer air will form a separate layer.

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[37] People tend to expire moisture at a rate of approximately 50g/h in a resting state. See Camuffo, G. et al, 'The Conservation of Artworks and Hot Air Heating Systems in Churches: Are They Compatible? The Case of Rocca Pietore, Italian Alps', *Studies in Conservation*, Vol 44, No. 3, London (1999), p. 211
[38] See Appendix VIII for full details.

As seen from the monitoring higher up in the cave, this more closely follows external conditions and the environment is much more unstable. One way to determine whether this is occurring would be to measure AT and CO_2 levels at 1m intervals up the height of the cave during the open periods to determine whether stratification and trapping of CO_2 is taking place.

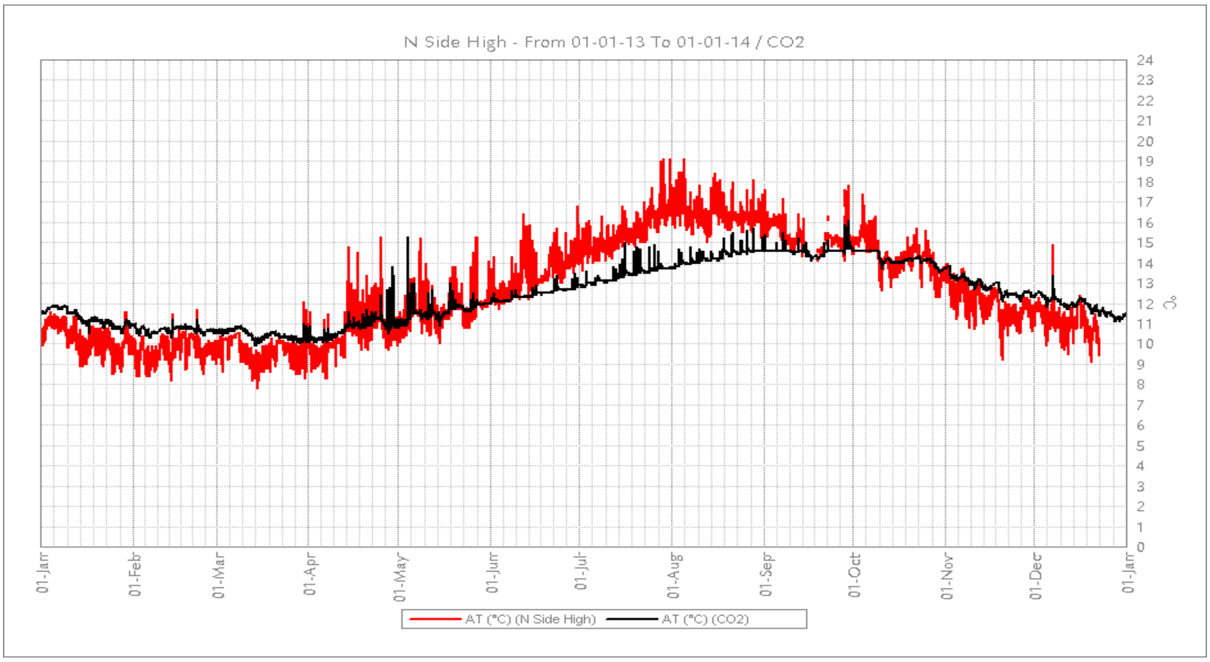

Figure 47. Detail showing the AT difference between the CO_2 monitoring position and the higher location (N side high) inside the cave during 2013.

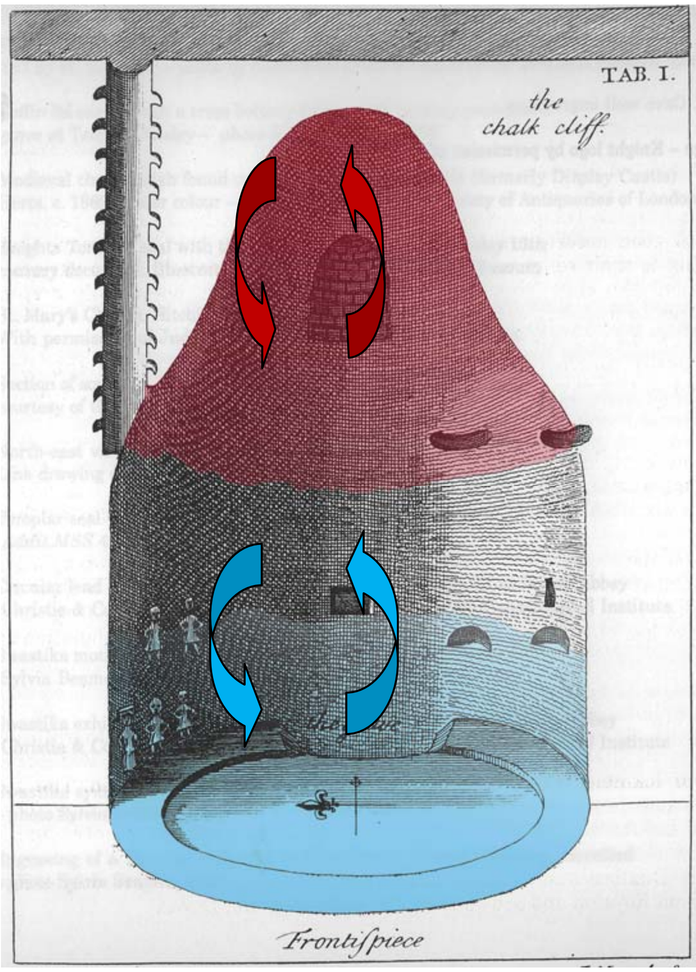

Figure 48**.** Illustration of thermal stratification within the cave with cooler air (blue) trapped at the bottom compared to the warmer air (red) at the top.

A further factor which may be affecting CO_2 increase in the summer months is the increases in AT and AH. There is a temperature difference of 4.5°C between March and August, and a 3.2 gm^{-3} difference in AH. An alternative reason for the CO_2 levels seeming to grow during the open season might be the increase in moisture and temperature. There is little research on buildings or caves in this area, but within oceanography it is reported that, as water temperatures increase, its ability to absorb CO_2 is reduced. This may mean that as the AT and AH in the cave increases towards July and August the CO_2 is not absorbed to the same extent as when it is cooler earlier in the year. Oceanographic studies have shown that increases in CO_2 absorption lead to more acidic water. Therefore, if water on the surface of the chalk is absorbing CO_2, this may be decreasing the pH locally, risking further damage to the carvings. However, to understand these processes would require substantially more knowledge about the effects of CO_2 absorption in underground environments and is outside the scope of the current project.

6.0 DISCUSSION AND RECOMMENDATIONS

6.1 Stage II Outcomes

6.1.1 Dating

The research into the costume and armour as possible sources of dating information for the carvings provided a relatively wide date range (1350-1650). However, the author suggested that a date close to the start of this range is most likely, which would mean the carvings date from the mid to late 14th century, based primarily on the costume, sword, crucifixion and crown imagery.

6.1.2 Deterioration rate

Large-scale deterioration and loss appears to have decreased in rate since the middle of the 20th century. This may be associated with the construction of the bypass and the rerouting of the major traffic load from the road above the cave. It was not possible to assess the short-term deterioration rate by collecting chalk debris; however periodic laser scanning, as part of a condition survey undertaken every 5-10 years, will show the current rate of material lost from the surface. Understanding this will help determine whether the deterioration rate has been slowed by the interventions undertaken during this project.

6.1.3 Vibration

Vibration monitoring demonstrated that background levels from traffic are relatively low, even when lorries or buses travel overhead. At current rates this appears unlikely to cause severe damage to the carvings. However, the vibration levels from unloading vehicles, or major impact in close vicinity to the cave, were found to be significantly higher. It has been recommended that unloading should be prevented, or methods adapted to limit vibrations, for 25m either side of the top of the cave. Although the vibration levels are low it was suggested that, where micro-cracks exist, the vibration could be sufficient to contribute to the chalk surface failing and the carvings collapsing.

Remedial conservation treatment to consolidate the cracks will limit this effect, but preventive measures combined with regular condition monitoring are recommended. Any changes to traffic management (alterations to the design of the traffic lights or the inclusion of traffic calming measures) or work on the surface above the caves should be carefully assessed and mitigation measures taken in order to prevent vibration related damage.[39]

[39] It is understood that the cave is now listed so that the council is alerted if specific work is being undertaken in the immediate vicinity. Pers. comm. Susan Thornton Bjork

6.1.4 Conservation treatment

Existing cracks and vulnerable surfaces from previous losses have been readhered or consolidated during the Stage II works. The conservation treatment focussed on stabilising small, vulnerable areas to prevent further losses to the carvings. This was undertaken with lime based mortars and nano lime dispersions, both to ensure compatibility with the carvings, minimal variations in porosity and similar visual appearance of materials. Further remedial treatments may be required in the future to prevent further losses to the carvings. This will depend on the stability of the microclimate in the cave in the future.

6.1.5 Worm and microbiological control

Identification of both the larger purple and smaller translucent worms has enabled control methods to be implemented. For the larger purple worms this meant removal of the soil from the base of the cave and internal ledges, to limit their habitat. The translucent worms have been identified as the larvae of the fungus gnat, the adult of which looks similar to a mosquito. A safe treatment method could not be identified; however a UV lamp was used as a control solution to attract the adult flies, removing them from the cave, and limiting the breeding cycle. The lamp now operates on an 8 hour timer to minimise any algal growth nearby. This treatment appears to be successfully reducing the larvae and fly numbers and should be continued.

Microbiological activity has been assessed and found a limited number of fungal and bacterial species. It is understood that none were human pathogens. Limiting lighting will minimise activity by photosynthetic organisms.

6.1.6 Microclimate and liquid water issues

Environmental monitoring data indicated that the microclimate at the top of the cave is unstable due to air exchange with the exterior. By contrast, conditions in the lower part of the cave, near the carvings, are comparatively stable. Nevertheless, small fluctuations do occur at low level and, while this continues, it is likely that slow deterioration will take place. As a result, the carvings will need infrequent, but occasional, treatment.

It is less simple to suggest ways of limiting the occasional floods that occur within the cave. Over the last 100 years many things locally will have changed that may have led to increased deterioration of the carvings. This includes changes to the number of access routes into the cave, changes to local drainage and water courses, changes to the road surface increasing the impermeable areas above the cave, or loss of vegetation, such as trees above, reducing the amount of water removed by plants. These will all potentially have impacted on the cave, but the extent of any individual event would be difficult to determine.

Where the source of leaks can be identified, i.e. sudden water in the cave following road or pipe works, these will still need to be reported to the various water companies to ensure repairs take place. However it will be difficult to prevent all water ingress via the chalk and the bedding planes it contains, and so it should be accepted that some level of water penetration will always occur in this type of subterranean sight.

6.2 Conclusions and Recommendations

The present environmental control should be continued to maintain the current stable microclimate at the floor of the cave, which provides suitable conditions to limit the deterioration of the carvings. While the major floods have been significantly reduced by relining the pipes, localised small leaks will continue to require managing and any substantial water ingress should be followed up with the water companies. The recent, small leaks have been limited to the entrance corridor and pose minimal risk to the carvings.

The filter in the ventilation grille of the cave ceiling is allowing sufficient natural ventilation to dissipate visitor-generated CO_2 levels, while preventing large debris from entering the cave. In order to prevent blockages the debris will need to be regularly cleared from the filter. A formal programme should be put in place to do this and to make sure that there is no risk of the filter becoming blocked and CO_2 level becoming raised.

The UV lamp has been successful in removing the adult gnat flies, limiting the population of the larvae and reducing their damage to the carvings surfaces. The UV lamp is used overnight for 8 hours to prevent any microbiological growth from occurring and this schedule should be continued. As the species of gnat fly which was identified is common to caves, recolonisation could occur should the UV lamp be discontinued. Regular checking and replacement (as required) of the sticky board behind the UV lamp, alongside replacement of the UV bulbs (as necessary) is recommended. All electrical equipment, including the UV lamp, should be checked by a suitably competent electrician on a regular basis.

Environmental monitoring has demonstrated that the CO_2 levels rise on days when visitors are present in the cave, sometimes significantly. It would be sensible to continue to check CO_2 levels during the open season, especially on busy days to ensure levels remain below the recommended levels. An environmental health specialist should be consulted with regard to visitor use of the cave.

A condition review should be undertaken on a five yearly basis to assess any deterioration or changes to the carvings and their environment. This could be complemented, possibly on a 10 yearly basis, by repeating the 3D scanning of the cave to identify any areas where material or details have been lost from the chalk surface. Additionally regular condition surveys would highlight whether interventive conservation treatment is required to ensure micro-cracks are stabilised before major fractures or significant losses take place.

A conservation management plan should be put in place, in order to record the risks and mitigation strategies which have been developed both as a result of the current research, but also more generally as a result of the experience of the cave managers. This will allow continuity of care of the cave as responsibilities are passed to other parties in the future.

In summary therefore the following measures should be implemented or continued:

- Maintain the current environmental controls, with similar levels of external ventilation
- Check and clean the pavement filter on a regular basis in order to prevent blockage
- Continue the use of the UV biocide lamp to maintain a low gnat population
- Remove any build up of debris to minimise habitat for larger worms
- Carry out periodic checks for CO_2 levels during the open season
- Seek the advice of an environmental health expert on the management of the cave
- Carry out periodic condition surveys, and laser scans, in order to assess the ongoing rate of deterioration
- Periodic minor remedial conservation treatment may be required to prevent further loss
- Prepare a conservation management plan for the cave

7.0 LIMITATIONS

This report draws together information from a number of fields where specialist research has been undertaken. While the authors provide an overview of the results received, we cannot comment on the accuracy of the individual areas of research, relying, rather, on the expertise of those undertaking that research. All matters relating to the health and safety of those engaged in the management of the cave and visitors should be referred to the relevant environmental health and safety experts, and advice should be sought from them. Tobit Curteis Associates cannot offer and advice with regard to health and safety matters and comments in this report on issues including gas concentrations are made as they relate to conservation issues and published management guidelines. Comments on the stability of the chalk relate to the conservation of the internal surfaces and issues regarding the overall stability of the cave should be referred to the structural engineer.