Developments in Nottingham's Sandstone Caves

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Abstract: The sandstone caves cut beneath Nottingham are part of the city's heritage, and the recorded list of them is growing steadily. Most but not all of the partial cave roof failures are related to water input or tree root growth. Intact sandstone forms arches successfully for 11m across the largest single cave room under the city, though it is being given extra support following a small roof fall. Weathering of the sandstone inside caves is greatest in those with free air circulation through open doors, and survival of the fine carvings in the Park caves may be dependent on new doors being fitted in their entrances.

The many hundreds of artifically excavated caves beneath the streets and buildings of Nottingham are now a well-established part of the city's structure. Their existence is due to geological factors, in that the Triassic Sherwood Sandstone is such an ideal tunnelling medium — easily excavated due to the low rock strength, but then stable over an underground void due to the high rock mass strength. Beyond this influence, the nature and distribution of the caves were largely determined by man's needs for a little more space in a once crowded town (before Nottingham became a city).

Nottingham's caves were described earlier in the pages of the *Mercian Geologist* (Waltham, 1992). That paper was published as a separate booklet, until it was replaced by the new book on the caves (Waltham, 1996b), also published by the Society. The book is a more user-friendly presentation designed for the wider audience, and therefore has less detail on some pure and applied aspects of the cave geology. This short paper reviews some recent events, developments, discoveries, research and literature that are more relevant to the ethos of the Society.

The changing face of the caves

Most of the caves lie beneath the city centre of Nottingham, where continuing redevelopment of the commercial buildings is the main means by which previously unsuspected caves are revealed, perhaps for the first time in many hundreds of years. Consequently, the latest map of the caves (Fig. 1) has numerous additions to the data recorded on the earlier map, published in the *Mercian Geologist* in 1992, but equally it will be outdated in future years.

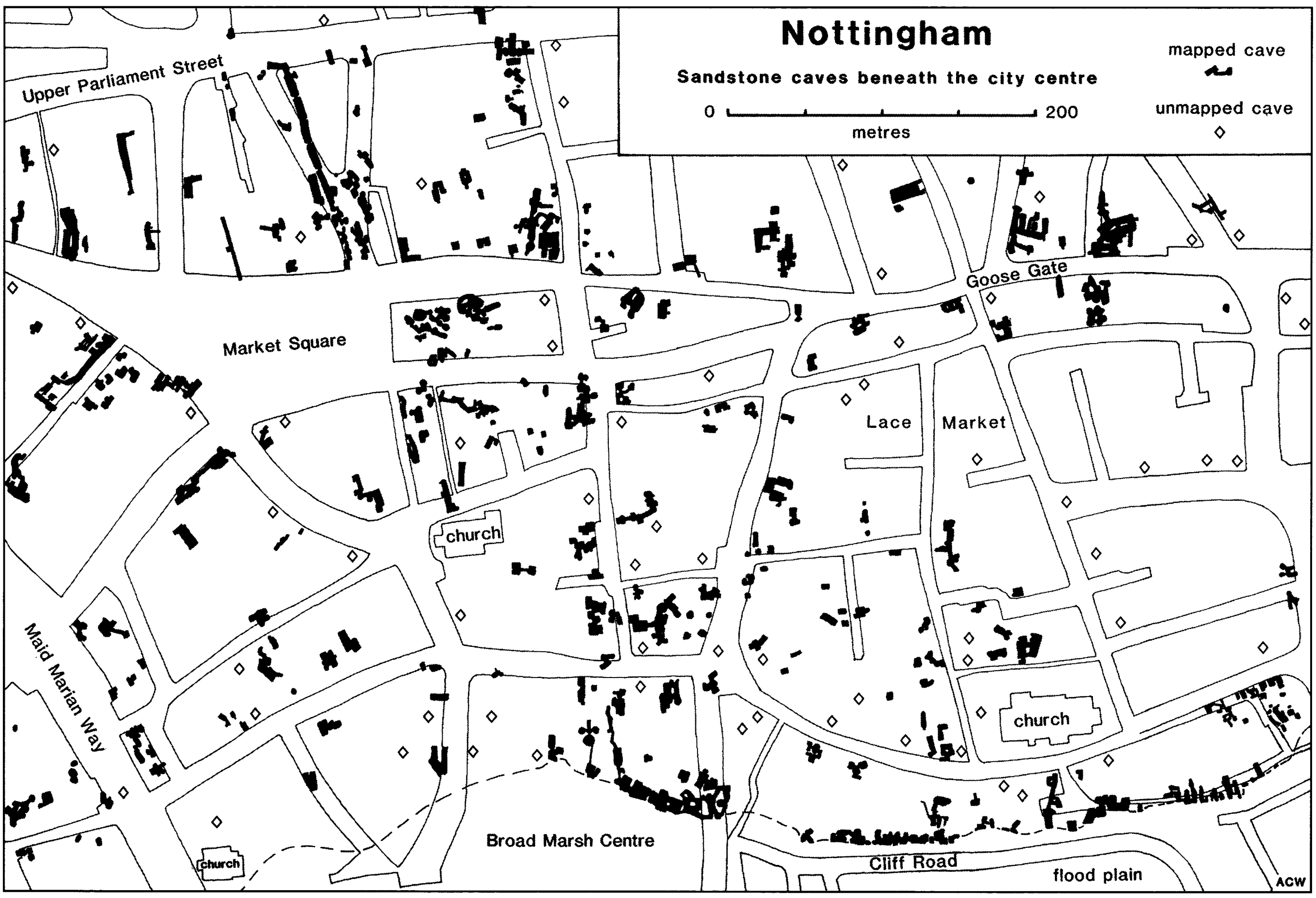

Fig. 1. Map of the caves known under central Nottingham in July 1997.

Most exciting of the recent discoveries was the complex group of caves, named after the bygone Black's Head Inn; these were found in the section of sandstone cliff now tucked away behind the Broad Marsh Centre. Pub cellar caves, a malt kiln cave and a cave tannery were all found literally on top of each other, when the upper caves partially collapsed into the lower caves, to the detriment of the buildings above (Waltham and MacCormick, 1993). Furthermore, the caves also yielded some fine pottery fragments, a slate tool from the tannery, and a pair of gold coins.

Recent cave discoveries also include the remains of two more malt kiln caves, bringing the total to twenty within the city. One of the new ones lies beside Huntingdon Street, and is therefore the first one outside the old town limits. In the cliff below Malin Street, the bricked-up caves were briefly re-entered, and proved to be a series of old beer cellars that had also seen various other phases of use. A complex group of caves and passages on two levels, found behind brick walls beneath the old Shire Hall (now the Galleries of Justice), include one room 7 metres wide and another smaller round cave that appears to have been an ice house.

The sand mines along the Mansfield Road have been a little better understood, and another site of old sand mining was recognised across the road from Rouse's well known mine (Waltham, 1994). Large amounts of loose sand within Rouse's mine probably originated from the excavation of the two air raid shelter exists up to Peel Street; members of the Nottingham Historical and Archaeological Society have recently cleared a new route that loops through the old air raid shelter. New office blocks have been built above the mine; they were positioned carefully with reference to the mine pillars, so that there was no need for disturbance within the galleries. Similar shallow mines in the Permo-Triassic sandstones have required extensive concrete filling beneath housing developments at Castleford (Baldwin and Newton, 1988) and at Redcliffe in Bristol, but the Nottingham mines are fortunately more stable than both these sites.

Activity related to the 1996 Christmas landslide at Nottingham Castle (see this volume, pp. 53-57) provided the opportunity to inspect parts of Castle Rock from a crane bucket. A cave found on a thin, ivy-clad ledge 5m below the footings of the old walls proved to be natural. It is just 4m long, though only about 700mm high and wide, except at its flare onto the cliff face. The cave has formed where a bed of pebbles and mud flakes is intersected by one of the main set of vertical joints aligned just west of north; its enlargement has been by frost action and granular spalling, aided by groundwater seepage (though it is now dry), and perhaps by loose sand being brushed off the walls by the foxes who now visit it. This appears to be the longest natural cave in Nottingham at present; it probably indicates the style of many small fissures and natural caves in the sandstone cliffs all along the south side of Nottingham, before the artificial caves were cut and the cliffs were repeatedly cut back by man.

While new sites add to the inventory of Nottingham's caves, there have also been some losses. A cave system beneath shops on Goose Gate was reported to be quite extensive, but was just one of a number of caves whose entries were bricked up before they could be properly mapped, photographed and documented. The city's twentieth malt kiln cave was found close to Broad Street, but only half the kiln remained and even this has since been filled. On the Mansfield Road frontage, a new office block has been built partly over the extensive caves that date from the old Nottingham Brewery. Only a few metres of cave were totally filled and lost, but there are some massive partial fills of concrete where columns were founded on bases above the caves. These were the cheap option, but the shuttered fills are larger than they needed to be, producing results that are seriously unsympathetic to the city's heritage. Bored piles into the caves, similar to those supporting the adjacent York House, were not used because their added costs were too high for a very tight budget.

Greater publicity and wider knowledge about the caves have raised their profile within Nottingham. The benefits are slow to mature, but caves are being preserved, or at least documented, where they may have been lost in the past. The best publicity of all has derived from the commercial development of the caves under the Broad Marsh Centre. Now known simply as The Caves of Nottingham (James, 1995), the site offers an excellent presentation of the caves to visitors from Nottingham and farther afield. The informal guided tours that used to run in the Broad Marsh caves have now been displaced to Rouse's sand mine (often known as the Peel Street caves), where some sand clearance has made a better route through the section fitted up as the air raid shelter. The register of caves published by the British Geological Survey (Owen and Walsby, 1989) remains the key source of documentation; one of its authors, Jenny Walsby, is still at the BGS, where she fields enquiries and also aims to produce a register supplement when time and funding permit.

Instability and failure of the caves

Though many of Nottingham's caves have remained intact for over 500 years, there are various ways in which failures can occur. Simple cave roof failure due to imposed loading is a permanent threat where new buildings are placed over old caves, but the hazard is minimised by careful adherence to loading limits. A critical zone can be recognised within the ground beneath any foundation (Fig. 2), where caves have to be searched for and then either avoided or provided with appropriate support.

Research at Nottingham Trent University has investigated the dimensions of the foundation critical zone, by destructive test loading of numerous scale models of caves and also one full-size cave

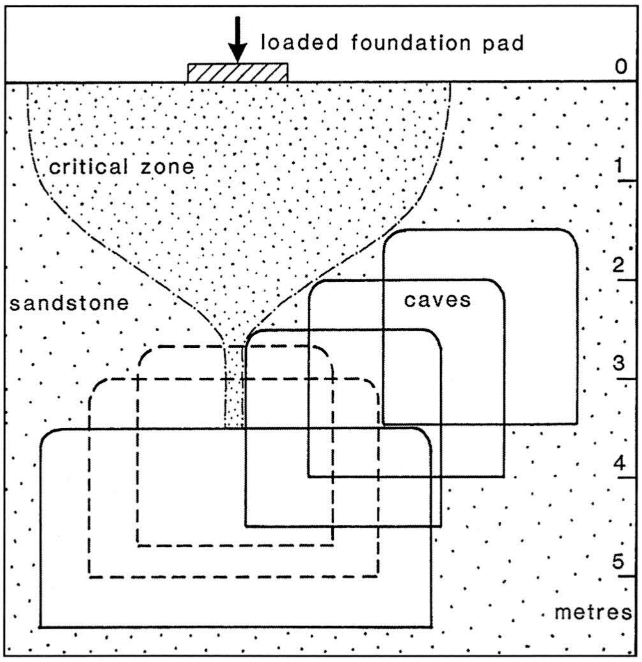

Fig. 2. Cross section showing caves in Nottingham's sandstone, which are acceptable below a foundation pad. Sound rock has to be proven within the critical zone to avoid the threat of a punching failure, except where the caves shown with broken lines are stable due to their modest widths. Caves wider than 4 metres are uncommon, and may require a greater cover to ensure stability.

(Waltham, 1992; Froggatt, 1992; Lonsdale, 1995). Failure occurs by punching, where a plug of rock bounded by shear planes is pushed into the cave; only very thin cave roofs are seen to collapse as beam failures. Results have broadly justified the 3m of sandstone cover required in general foundation design for Nottingham buildings; they have also justified some flexibility in design with respect to caves where shapes and passage intersections render strict guidelines difficult to apply. Mathematical modelling of cave failures by finite element analysis (Roodbarkay *et al.*, 1994) is being employed to cross-check the results from the physical modelling; when this programme is complete, a comprehensive overview of all the test results will be published, to succeed the interim review (Waltham, 1996a).

Many cave roof failures have been a consequence of water reaching the rock, usually from a broken drain or pipeline. The sandstone loses 40-80% of its strength when saturated, and the normal result is therefore the progressive failure of the roof beds, perhaps through to the surface as a typical crown hole (Waltham, 1993). Any drainage failure, and saturation of the rock, can cause progressive cave roof failure regardless of any load imposed by a surface building. The saturated and overstressed sandstone breaks into beds, each typically 10-40mm thick, and upward stoping and cavity migration occurs when single beds fall away consecutively. A

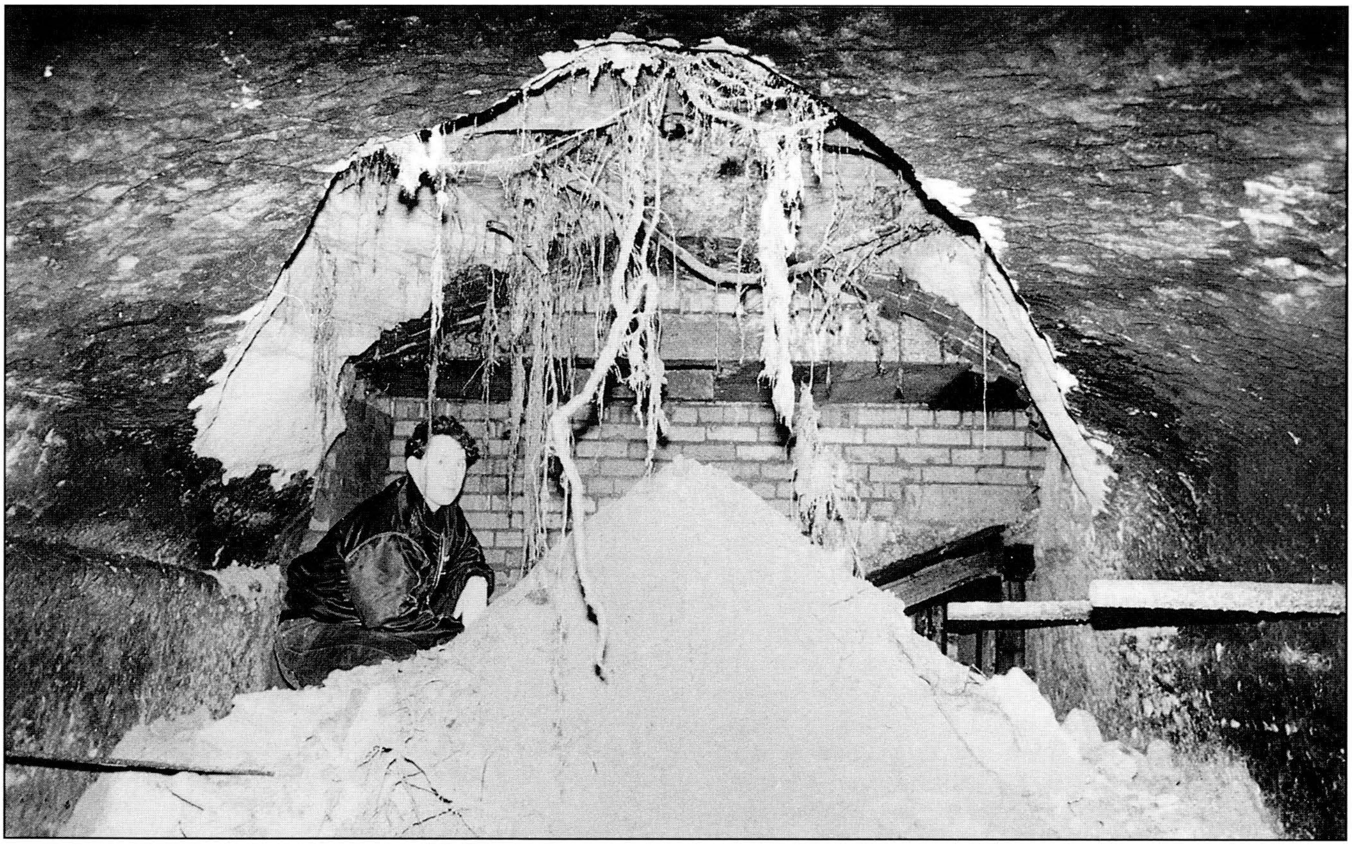

Fig. 3. Tree roots hang from the failure zone where a crown hole developed beside North Sherwood Street. The roof sandstone was little more than 1 metre thick, and tree roots had grown into it from a thin soil cover. The fallen debris on the floor is broken blocks of sandstone capped by a cone of completely weathered sand and soil. The brickwork in the background is not related to the failure (photos by Tony Waltham).

cave 4m wide with a gently arched roof is likely to develop a stable arched profile after about 2m of sandstone has fallen away in the centre; no arch or failure rising more than 1.3m has yet been observed. Though the local building design guidelines are based on a cover of sound and dry sandstone over a cave, the 3m requirement does therefore also protect against crown hole failures in saturated rock.

Water may be the dominant factor in cave roof collapses, but some failures in dry rock have had other causes. Tree roots are a significant factor in many roof failures in the caves. Roots cannot penetrate the unjointed sandstone, but they find their way into even the narrowest of fractures. Their growth then forces the joint faces apart and may cause lateral extension of the initial fracture; the rock deformation also opens up bedding plane weaknesses and creates new fractures in massive sandstone. Fine root ends hanging into a cave are fair warning of an incipient failure, and rather thicker roots are commonly exposed by a failure (Fig. 3).

The caves cut into the foot of the cliff along Castle Road have experienced a number of roof falls over the years, all near the cliff face where tree root growth has been active. The single most unstable piece of rock became detached above a steeply dipping joint that intersected the cliff face at its toe (Fig. 4). This joint was being heaved wider at a rate of 1mm per day in the summer growing season, and

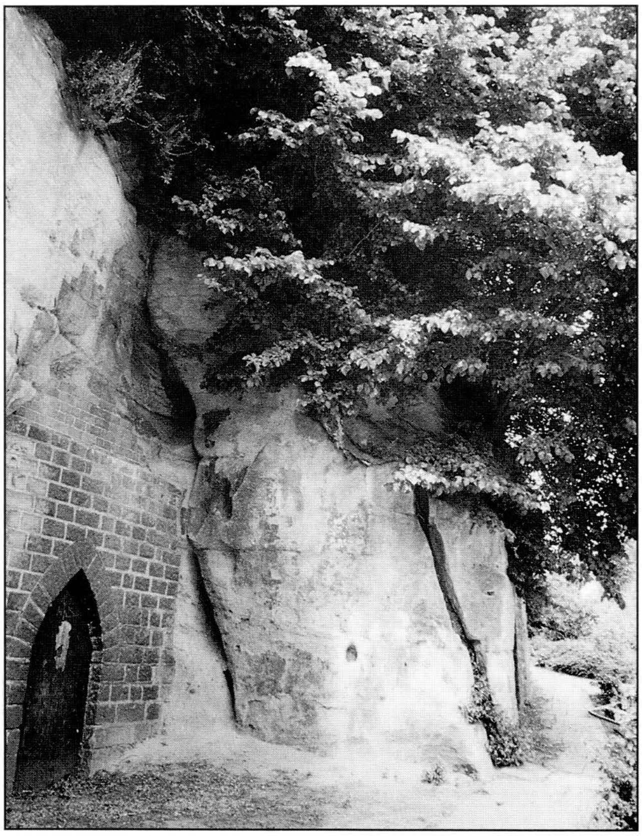

Fig. 4. The widening fissure beneath the unstable sandstone slab beside Castle Road, before the trees were removed and the rock was bolted.

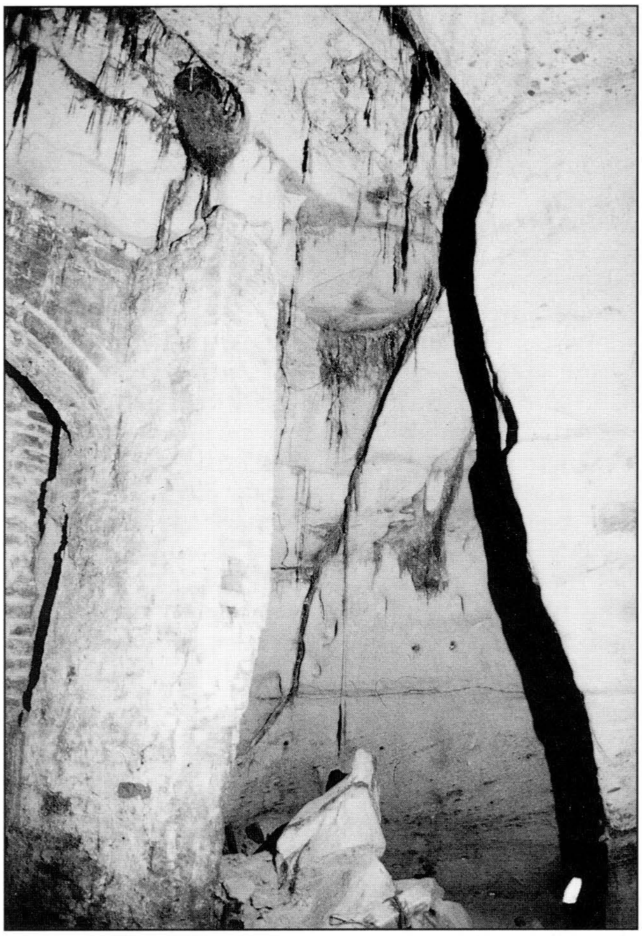

Fig. 5. Interior of the cave beside Castle Road, with the fissure seen in Figure 4 descending diagonally towards the left. The fine tree roots which hang from many bedding planes and joints have caused the roof falls whose debris lies on the cave floor.

it cut obliquely through the entire thickness of the wall and roof of a cave immediately inside the rock. Tree roots hung down inside the cave, while blocks were falling away into the cave, and the whole arch of the wall and roof was disintegrating (Fig. 5). The tree has now been removed and long dowels reinforce the thin sandstone wall. In January 1997, all the trees were cut down along these cliffs; this should eliminate any further deterioration of the caves, as long as the roots are completely killed and any subsequent regrowth is prevented.

While most cave roof failures can be attributed to water ingress or tree root expansion, there have been other events unrelated to either of these factors. A slab of sandstone, over a metre across, fell away from the roof of a cave under the north frontage of Goose Gate, where the rock remained dry and there were no trees. The fallen slab broke away from a bedding plane which had been 150mm above the cave ceiling. Long-term deformation of cave roof beds has not yet been measured, but hundreds of years of creeping sag of an unsupported bed of sandstone could cause de-lamination at a bedding weakness; the consequent loss of all tensile strength at the bedding plane would then hasten a failure.

The Brewhouse Yard caves are part of the museum visitor route, and have had numerous very small falls of roof sandstone, mostly where bed edges have broken back to their overhead bedding planes. In May 1996, a larger slab of sandstone fell away from the roof immediately in from the entrance arch, but this was a different style of failure. Within the cave roof, a vertical tension fracture developed parallel to the vertical maximum stress; as a feature of stress relief, this opened by about 3mm, as the rock moved towards the exposed cliff face, which receives no support or restraint from the museum building. The fissure opened only within the rock above the roof bed, so that it was not visible within the cave; its western end ran into a shaft, which was yet another weakness within the roof rock structure. The roof bed immediately above the cave did not move, so that bedding plane shear separated it from the moving block above (Fig. 6). The outer section of the roof bed was therefore held only in cantilever, until it failed completely. Initial deformation of the rock may have been aided by sagging across the span of the cave entrance, and this would have accelerated opening of the bedding plane.

The whole cave roof has now been reinforced by an array of 42 dowels. Holes 720mm deep were carefully bored into the cave roof, using a rotary drill to avoid vibration disturbance; steel bars, 700mm long with a load capacity of nearly 4 tons, were then inserted into each hole and cement grouted over their whole length. Grout covers the bar ends, and there is no face plate, so that the dowels are not easily seen. The reinforced unit of rock, 700mm thick, now acts as a coherent entity. Tensile strength of the Sherwood Sandstone is low perpendicular to the bedding, and is negligible across significant bedding planes, but the dowels effectively prevent bed de-lamination within their length.

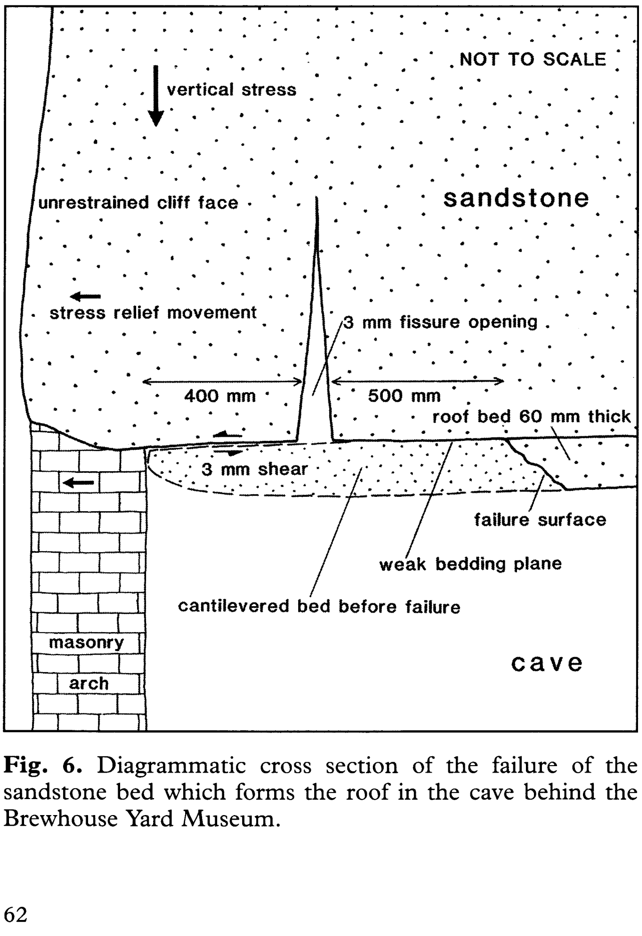

Fig. 6. Diagrammatic cross section of the failure of the sandstone bed which forms the roof in the cave behind the Brewhouse Yard Museum.

The Wollaton Street cave

Early in January 1997, a partial roof failure drew attention to the largest cave room in Nottingham. The cave's length of over 20m is not exceptional, but its width varies from 8 to 11m, and it is a full 3m high (Fig. 7). No other cave approaches the width of this unsupported span; the walls are curved into a partially arched profile, but the flat section of the roof is 6 to 7m wide (Fig. 8). The cave lies directly beneath the traffic lanes of Wollaton Street, and its huge roof span is probably just less than 3m thick. The original purpose of the cave is in doubt, though it may have been a wagon maker's workshop (Nix, 1984b), cut behind an old building on Derby Road, which was at a lower level in the eighteenth century. It is unrelated to Wollaton Street, which was an old sunken trackway cut down to its present level in 1852. The garage caves above the eastern end of the large cave were probably excavated in 1870 as store rooms, also reached by a shaft up to the rear of buildings on Talbot Street.

The size of this cave puts it beyond all known empirical data on stability assessment of the Nottingham caves. Structural analysis of the cave roof is hindered by not knowing the exact fracture patterns within the sandstone — which remain obscured until they are revealed by collapse. The roof gains strength through its part that is arching and is therefore in compression, yet it suffers weakness through lateral tension in the underside of the flat section, which behaves as a beam. The unknown balance of the components makes it difficult to estimate a reliable safety factor. The cave roof is also weakened by a drain trench through practically its whole thickness (Fig. 7).

In the recent roof fall, a slab of sandstone nearly 5 by 3m, tapering from 20 to 200mm thick, broke away from a pebble bed horizon that dips gently eastwards to pass just above most of the flat cave roof. No water or tree roots were involved, and the failure can only be ascribed to long-term de-lamination and creep of the roof bed; this may have been accelerated by traffic vibration. The main fall was probably triggered by the collapse of a wall on the north side of Wollaton Street, when the debris fell down the rock cliff and landed almost above the cave. After the main failure, small chunks of sandstone continued to fall away from the broken edge of the unsupported bed beneath the weak bedding plane. All the fallen rock has been from the zone of the roof left in tension, beneath a theoretical arch in compression; it is clear that the arch must be the mechanism that provides integrity in the cave roof, so the loss of rock from beneath the arch causes no direct reduction of the stability.

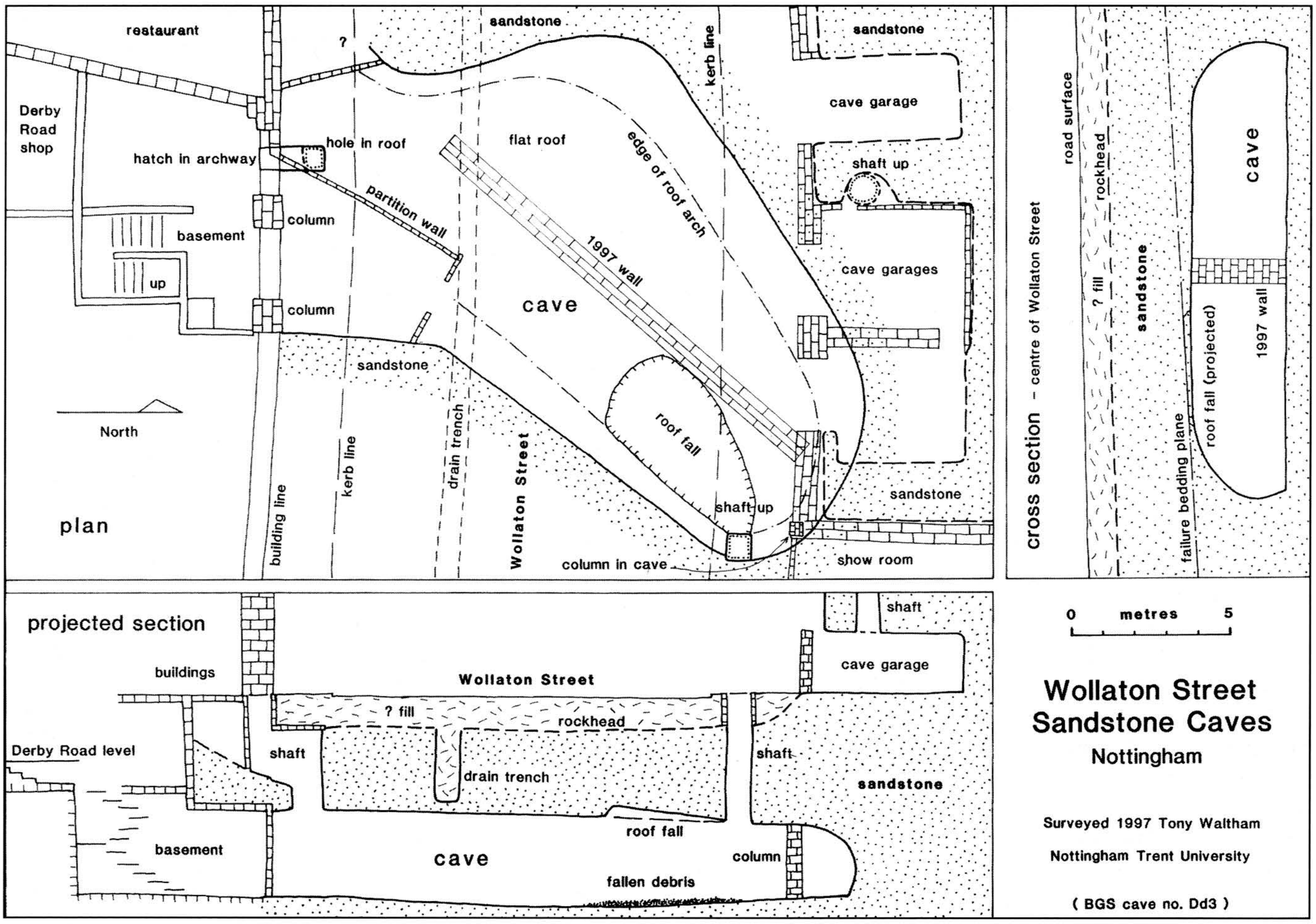

Fig. 7. Plan and profiles of the large cave beneath Wollaton Street.

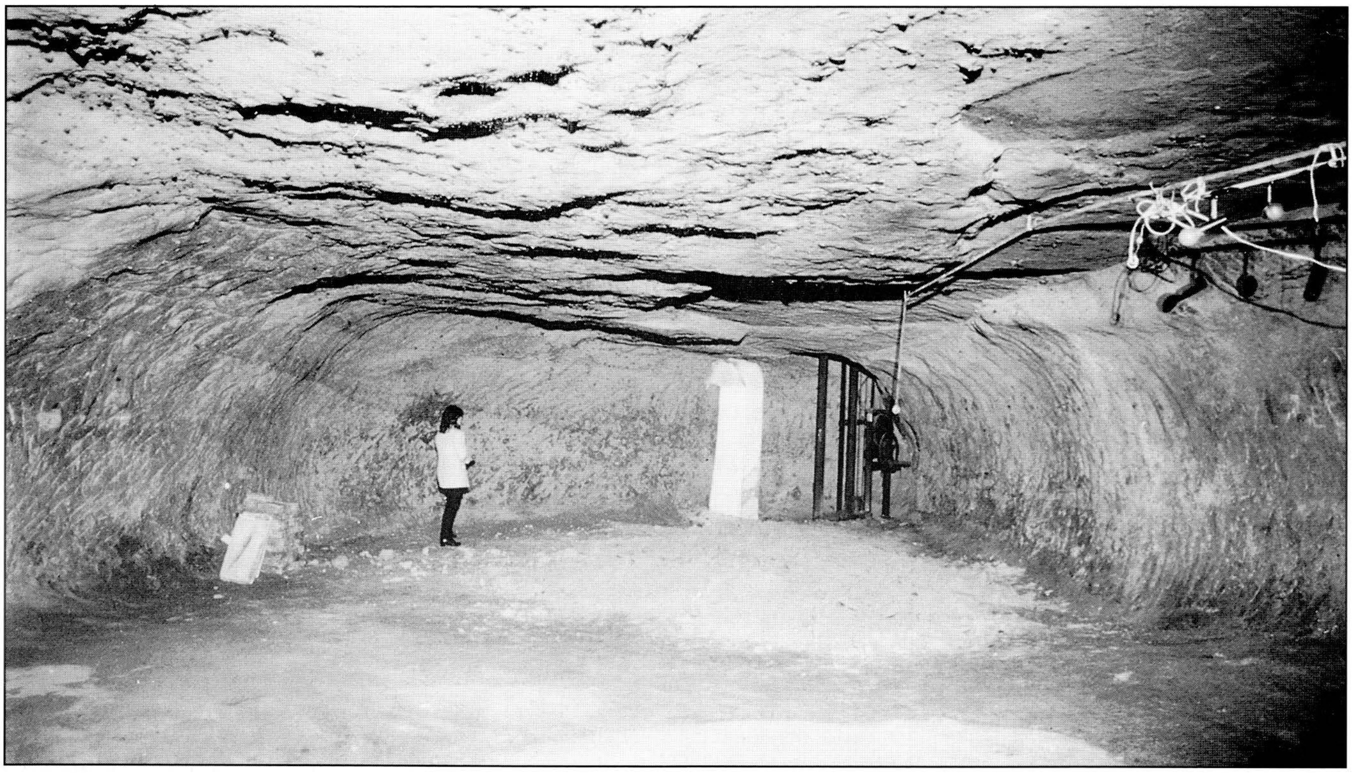

Fig. 8. Part of the Wollaton Street cave, looking towards the northeast, before construction of its central support wall. Beyond the light patch of concrete in the foreground, the low pile of debris is the sandstone which fell from the roof early in 1997.

Fig. 9. The statues of Daniel in the Lion's Den, in their cave within The Park. All surfaces are losing sand grains due to weathering, and unswept loose sand is visible at the foot of the two columns. The view is from the open cave entrance.

A consensus of opinion on the cave was that it was only marginally stable. Consequently, temporary internal supports were installed in March, before a load bearing wall was built along the centre of the cave in April 1997 (Fig. 7). This eliminates any threat of total collapse, and Wollaton Street is now safe from its unseen hazard. Meanwhile, concern may be directed to the possible existence of any other equally large caves, as the current building guidelines (Fig. 2) are based on caves up to about 5m wide.

Sandstone weathering inside the caves

Most of Nottingham's caves are entered by stairways that lead down from the basements of buildings. Their microclimate is therefore very stable, and weathering of the sandstone walls is negligible or absent. In contrast, caves that are open to the outside may experience cyclic changes of temperature and humidity within their atmosphere. This may cause weathering of the rock, irrespective of any effects due to moisture movement through the sandstone. Caves that have open entrances, and are not regularly swept out, are distinguished by the miniature scree banks of loose fallen sand grains along the bases of their walls (Fig. 9). Closed caves lack these scree slopes. Additionally, many closed caves that are damp have a layer of mould on their walls, and this appears to further prevent weathering, as loose grains on the surface cannot fall away.

This scale of weathering rapidly destroys any detail or features carved into the sandstone. The caves that have suffered most are those excavated at the behest of Thomas Herbert, and which contain the splendid statues carved into the underground bedrock (Nix, 1984a; Waltham, 1996b); they now lie within The Park. Daniel in the Lion's Den is the finest of the statues (Fig. 9), and it is steadily shedding sand grains, thereby losing much of its finer detail. Rates of wall decay have been measured by catching the fallen sand grains at the foot of the cave walls, and up to 20 grams of sand per week have been collected in trays just 700mm wide (Cubby, 1997). This translates into a mean rate of wall retreat of over 0.3mm per year. The wall disintegration varies in different parts of the caves (Table 1), and the mean retreat rate at the statues is about 0.1mm per year. Under uniform conditions during the 160 years since they were carved, in about 1837, the bare rock surfaces of the statues would have retreated by about 16mm.

cave	*3m in*	*14m in*	*worst site*	*at statues*
Daniel's	0.057	0.029	0.354	0.110
Fishpond	0.014	0.019	—	—

Table 1. Mean weathering rates in the sandstone caves over four months, November 1996 to February 1997. Rates are expressed in millimetres per year of wall retreat, based on fallen debris collected in trays. Daniel's Cave is open to the weather, but the Fishpond Drive cave is closed by doors and windows. Measured sites were 3 and 14 metres in from the entrance of each cave, and also at a notably weathered zone beside the statues in Daniel's Cave.

Caves carved into the more conglomeratic facies are distinguished by resistant quartzite pebbles which protrude from the walls where the matrix sandstone has weathered back (Fig. 10). Mean pebble protrusion in the area around the Daniel statues is 22mm, and the unweathered zone at the rear of Daniel's Cave has pebble protrusion of about 7mm. The latter figure may represent the cave wall profile as it was originally cut, in which case subsequent weathering has removed about 15mm from rock surfaces in the statues area; this value for wall retreat matches closely that calculated from current rates of wall degradation.

Microclimates are being monitored at various points inside these carved caves, and also in caves that have comparable front entrances in the gardens of houses along Fishpond Drive; some of these are like Daniel's Cave, with open entrances, but the monitored cave has doors and window glazing, which reduce or prevent air circulation.

Air temperatures inside the caves fluctuate in response to external changes, but the ranges of temperature fluctuation decrease further into caves, and are lower on caves without open entrances. Across the different sites within the various caves, weathering rates correlate broadly with the ranges of temperature variation (Table 2). The reduction of temperature variation and weathering within the less ventilated caves indicates the benefits of doors and windows on their entries. Periods of freezing and frequency of freeze and thaw may be expected to influence weathering, but during the programme of monitoring, freezing conditions have not reached even to the measured sites which lie only 3m inside the caves with open entrances.

location	*Temperature range, °C*	*Weathering mm/year*
outside	9.5	—
3m into Daniel's Cave	6.1	0.057
14m into Daniel's Cave	5.3	0.029
3m into Fishpond Cave	2.6	0.014
14m into Fishpond Cave	2.0	0.019

Table 2. Temperature ranges recorded at sites during December 1996, correlated with the mean rates of weathering (in millimetres per year) measured over a period of four months. The temperature range at 14 metres into the Fishpond Drive cave is only approximate, as it is based on fewer readings.

Fig. 10. The heavily weathered wall of the Herbarium Cave, which has its unprotected entrance in The Park close to Daniel's Cave. Pebbles protrude from the rock due to the loss of weathered sand grains, some of which are still banked along the foot of the wall.

The role of water in the weathering of the cave walls is not yet clear. The monitored caves lie beneath open ground with just a thin soil cover and discontinuous garden paving, yet weathering rates show no recognisable correlation with overall rainfall patterns (Table 3). Individual storm events may have an impact if the rock becomes saturated, but this has not been identified. Water does not drip into either of these caves, even though the Fishpond Drive cave intersects several fissures. Humidity inside the caves is always high, and contrasts between the monitored sites have not been recognised. Moisture contents of the sandstone surface layer in the cave walls have been measured approximately with an electric probe dampmeter (originally designed to measure moisture in timber). Moisture values show very little variation deep inside the caves. The greatest variation was found in the rapidly weathering zone in Daniel's Cave, at the same time that moisture levels were found to be closer to constant both farther inside the cave and nearer to the entrance.

Preliminary results from the monitoring programme do suggest that the fitting of good doors and windows on all the entries should be an effective way of prolonging the survival of the splendid Daniel statues. It appears that, without new doors, the statues will be lost sooner rather than later. There is however a possible disadvantage to such action; in a more stable cave environment, the statues may eventually acquire a covering of mould and lose their very clean appearance. Waterproof sealing of the sandstone above the caves would be expensive, and the potential benefits appear to be minimal. Modern methods of preservation of stone statues are based on injection with some form of resin or silicate gel; this would prove difficult and expensive for the Daniel and the Lions statues, due to the fragile nature of their remaining sandstone.

Geological variations are among other factors that influence weathering in the caves. Some beds and zones of the sandstone weather at higher or lower rates than the mean, but susceptible areas do not just follow the bedding, are not visually identifiable (except by their weathering rates), and the material is not available for sampling. In contrast to the zone within Daniel's Cave which has the highest weathering rate, the Summerhouse Cave, adjacent to Daniel's, has almost no deterioration by weathering of its carvings in the sandstone. This cave now lies beneath the protective umbrella of a house, but this has only been there since 1968, and the cave has probably had open doorways and windows for nearly as long as has Daniel's Cave.

Rainfall, mm/day		1.5	1.7	2.2
Daniel's	3m in	0.034	0.087	0.048
	14m in	0.003	0.022	0.053
	worst	0.328	0.385	0.235
Fishpond	3m in	0.004	0.025	0.013
	14m in	0.004	0.040	—

Table 3. Variations of rates of weathering of the cave walls (in millimetres per year) at various sites within the caves, correlated with mean daily rainfall over three periods, each of 4-6 weeks, in differing weather patterns.

While weathering is a significant problem in the open caves, the sandstone is also prone to slow disintegration within almost any cave; this is well known to drinkers in the Trip to Jerusalem bars, where beer mats are best placed on top of the glasses to protect the amber nectar from the rain of sand grains. The adjacent Brewhouse Yard caves are suffering from numerous small roof falls, mostly of a few hundred grams of sandstone at a time. These cannot be stopped, as the surface zone of the rock is just too weak; probably the only response is to clean the cave roofs by picking them over lightly with a bar and chisel, to create a new stable profile in better sandstone, but this raises conservation issues in the older caves.

At exposed sites, the sandstone weathering may contribute to an even larger scale of roof deterioration, and eventual cave collapse. The admittedly incomplete historical records do indicate a disproportionate number of collapses in the caves along the cliffs reaching from Castle Rock, past Broad Marsh and onto Sneinton Hermitage, where more caves were open to the cliff instead of being protected under buildings. Nottingham's caves may be regarded as part of the urban heritage, but it does appear that not all of them can survive into perpetuity.

Acknowledgements

Research on the caves forms an ongoing programme at Nottingham Trent University, and part of this work was within a degree project for the second author. Both authors gratefully acknowledge the following for their generous support: Alan MacCormick, Keeper of Antiquities at Brewhouse Yard Museum, for his endless assistance and cooperation; Judy Edgar, Michaela Butter and Ernie Rothery for hospitality at the caves of Castle Rock; Graham and Maria Brown, and Maisie Stamper for repeated access to their caves in The Park; Jenny Walsby, Alan Forster and David Lowe of the British Geological Survey for many discussions and contributions; the Civil Engineering Department at Nottingham Trent University for logistical and technical facilities; and Geoff Matthews, Ken Brand, Alan Freebury, Kate Pudney, Paul Alcock, Paul Zablocki, Michael Preston, Michael Long, Barry Liggott, Glen Mayfield, Doug Gilbert, the late Gordon Partington and many others who have helped in and under Nottingham.

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