The formation and sedimentary infilling of the Limeworks Cave, Makapansgat, South Africa

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The remnant cavern of the Limeworks australopithecine site has a number of special features. Firstly, unlike Swartkrans and Sterkfontein, which developed in relatively flat relief, the Limeworks Cave developed as part of a mountain karst. Then upon abandonment by its formative river, there formed a unique, conjoined series of tall stalagmites and columns arranged in an irregular arc against the walls of the cavern. This arc had the effect of dividing up the space into a central volume and several lateral alcoves. The spaces were separated from each other, so that, when the cavern began to unroof, each came to be filled by its own surficial deposits or, in some cases, not at all. At only one level is it possible to show that a gap existed between two adjacent repositories so as to produce common, contemporaneous deposits. This turns out to be the hyena den layer known as the Grey Breccia, and a connection was made possible with the centre by spaces that existed at local roof level for a limited period. The Grey Breccia appears to be about contemporaneous with the white bone breccia at the back of the cavern, whereas the black bone breccia in the Main Quarry is slightly younger than these two. The recognition of distinctive depositional horizons has allowed us to reconstruct a stratigraphic section for all deposits from the known base to the known top on the western side of the site. This section can be used for magnetostratigraphic purposes to construct a firmer chronology that includes the Grey Breccia; but further work is required to tie in the eastern side.

Keywords: Makapansgat, *Australopithecus,* Grey Breccia, stratigraphy.

INTRODUCTION

The Limeworks Cave, Makapansgat, in the Northern Province, South Africa (Fig. 1), is well known for its finds of *Australopithecus africanus.* Currently the chronology of the site is believed to lie somewhere between at least 4 and 2 Ma. However, as the question of sequence stratigraphy is not settled this, in turn, has cast doubt on the chronology as determined by faunal correlation and by magnetostratigraphy (McFadden *et al.* 1979; White *et al.* 1981; Partridge and replies 1982; McFadden & Brock 1984) and, hence, the age of the bone breccia layers is uncertain. All workers now agree that, within the cavern, there were separate repositories rather than just one overarching sequence. An important task now, therefore, is to study the stratigraphy of these repositories to see whether, and how, they are linked. Part of the problem in understanding the deposits of the Limeworks is that the formation of the original cavern is not sufficiently well understood. So the first part of the paper presents simple, karstic, hydrogeological concepts of cave formation in order to explain the origin of the cavern before surface erosion and unroofing took place. Only then can the description of the deposits be presented with the interpretation of the phases of infilling and the processes that operated. Some of this work has been presented in Latham *et al.* (1999) and in Partridge (2000). As the work at Limeworks Cave is ongoing and forms part of a project to study afresh the magnetostratigraphy, this paper represents our current understanding of the configuration and origins of the Limeworks Cave deposits.

Note on nomenclature. For convenience, and where applicable, we refer to the main sedimentary layers on the west side by the Member names given by Partridge (1979, 2000). We have also followed the advice of Maguire *et al.* (1980, 1985) in giving informal names to distinct repositories and to other specific areas. For reference, these names are marked on the plans and sections presented in this paper (Fig. 2 *et seq.*).

THE LIMEWORKS CAVE AS A FORMER RESURGENCE

An understanding of how the cave formed aids an understanding of its deposits. In this regard, the evidence and arguments that the Limeworks Cave was once part of a large river cave recapitulate parts of a paper on the nearby Cave of Hearths (Latham & Herries, in press).

Neither the Cave of Hearths – Historic Cave (CoH-HC) – complex nor the Limeworks Cave formed as a single isolated cavern under a watertable, as has sometimes been assumed. To begin with, watertables do not form in impermeable limestone or dolomite except where the rock body is highly fractured. Unlike more porous and permeable rocks such as sandstone, dolomite and limestone are too impermeable to allow groundwater to follow Darcy's law of diffuse flow except, possibly, in the very early stages of inception when the protoconduits are less than about 1 mm wide (Ewers 1982) or when the rock body is highly fractured. Laboratory experiments, modelling and field observations show that caves form in limestone by the integrated connection of one set of protoconduits that successfully competes over others (see Ford *et al.* 2000). The winning connective set of conduits is that which provides the least overall resistance to flow from source to resurgence. That set then enlarges rapidly over the alternatives until the whole of the flow is captured. The protoconduits form initially along bedding partings, cracks and faults so that the overall route from source to

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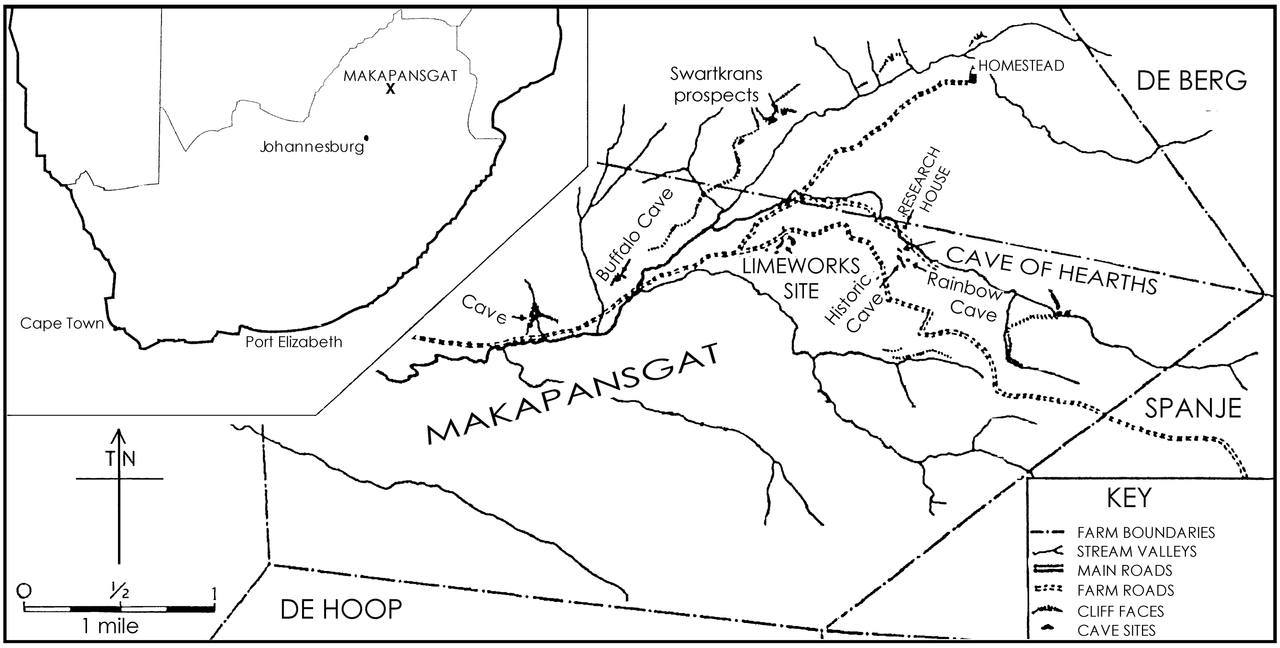

Figure 1. Location map of Makapansgat, the Cave of Hearths and related features (after Wells & Cooke 1957).

sink is seldom the shortest straight-line distance. Once sufficient flow has been established it is no longer possible for the maintenance of any continuous piezometric surface. For example, it is quite common, in karst worldwide, to find waterlogged passages lying above air-filled passages in the same cave system. It is therefore inappropriate to talk about a saturated zone since this term applies only to rock having connective porosity, that is, having permeability. Although it is not uncommon to find 'watertable' as a working concept in the literature, Jennings (1985) presents a list of observations to demonstrate why watertables only exist in limestones exceptionally. See also Bögli (1980) and various papers in Klimchouk *et al.* (2000).

In mountain karsts, such as at Makapan, the underground drainage creates just one set of connected passages. More complex systems occur when there are multiple inputs. Later incision of the valley provides an opportunity for the establishment of rerouting to a newer spring at a lower level and this results in the abandonment ('fossilization') of upper cave passages. (By contrast, those caves that are formed on the fault zone of the Zwartkrans valley, such as Peppercorns, Ficus and Katzenjammer, demonstrate a hydrological behaviour more like that appropriate to the watertable scenario. The present-day water levels of these caves are connected and rise and fall together.)

In the case of Makapansgat, a large fault near the Red Cliffs (Fig. 3) has brought the host Malmani dolomite into contact with the stratigraphically lower Black Reef quartzite and this would have presented a zone of entry for water draining off the upper catchment. The Limeworks Cave must therefore have acted as the resurgence for the system, conducting water from this uplands catchment out to the Zwartkrans valley. Fig. 3 shows this putative cave system overlain on the present lower valley (the Mwaridzi valley). It seems that, at some stage in the formation of the river cave, new passages developed to shift the system to the north leaving CoH-HC as an oxbow. It is possible that streams occupying what is now the northern flank of the Mwaridzi valley, corresponding perhaps to the modern House, and Bee Rock, Gulleys, initiated this shift. The system thus developed a second, later outlet into the Zwartkrans valley some 1 km to the north of the Limeworks resurgence. In the Mwaridzi section, the cave river was able to incise its bed until it reached the contact with the basal shale units and Black Reef quartzite. It is probable that downcutting was arrested in favour of undermining of the dolomite sides and, with help from surface dissolution, the roof eventually collapsed. Further flank erosion and dissolution of dolomite rubble over two to three million years resulted in the present canyon-like cross section. The modern Mwaridzi valley as far as the Red Cliffs thus occupies the position of the final river cave, and the Limeworks represents the bevelled remnant and infill of the earlier resurgence.

The possibility of an old connection to the Limeworks from the CoH–HC complex is discussed in Latham & Herries (in press).

The size and shape of the original cavern

Figure 2 shows the main features of the excavation and the position of the dolomite walls of the original cavern as outcrops. Prior to speleothem mining, the centre of the cavern was occupied by breccia and layered sediments and, to the sides, by huge masses of speleothem; most of the central breccia, referred to subsequently as the Central Debris Pile, was left intact. The cavern lies on the northwest flank of a low ridge sloping roughly east to west, and its deposits have been eroded away as part of the bevelling of the surface from the ridge (Fig. 3). It can be assumed, fairly safely, that the present land surface in which the cavern lies has maintained approximately the same form for the last 3 to 4 millions of years. There does not appear to have been much catchment potential above the cavern for runoff to develop beyond the size of small

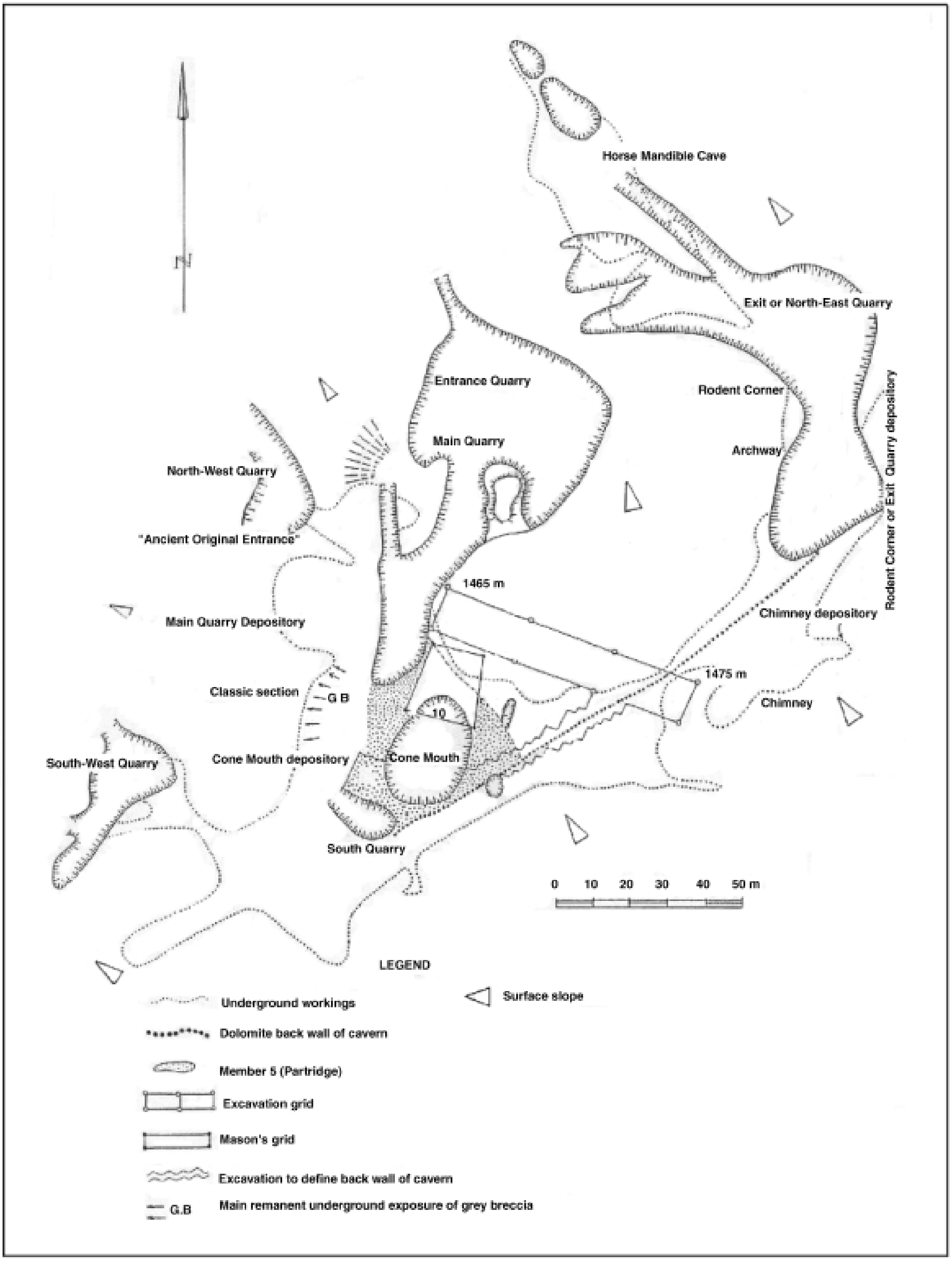

Figure 2. Map of the Limeworks site (after Maguire *et al.* 1980). The dotted area represents Member 4, the sediments winnowed from the Central Debris Pile and which were emplaced under an existing roof (see text).

streams and, consequently, there does not appear to have been any surface stream capture to, or from, any adjacent catchment. Thus, most of the erosion and later infill of the cavern was probably due to direct action of rainwater and surface runoff.

The configuration of the present floor of the cavern is discernible in places by the presence of large dolomite blocks that have fallen from the roof and, under the Central Debris Pile, by spot heights from bore cores drilled in 1993 (see Partridge 2000). It is not known what the configuration of the original floor was before block fall. The Main Quarry and the Exit Quarry appear to have formed along faults and, judging by its straightness, this may also be true of the back wall of the cavern (Partridge 1975).

What was the form of the resurgence in its early active phase? Between the Cone and the Exit Quarry, the walls rise vertically some 20 m to the present surface and show no signs of having suffered significant rock breakdown. In other words, the rear walls most certainly reflect the last stages of solution of this part of the cavern when the emerging water filled it. This strongly suggests that, in its

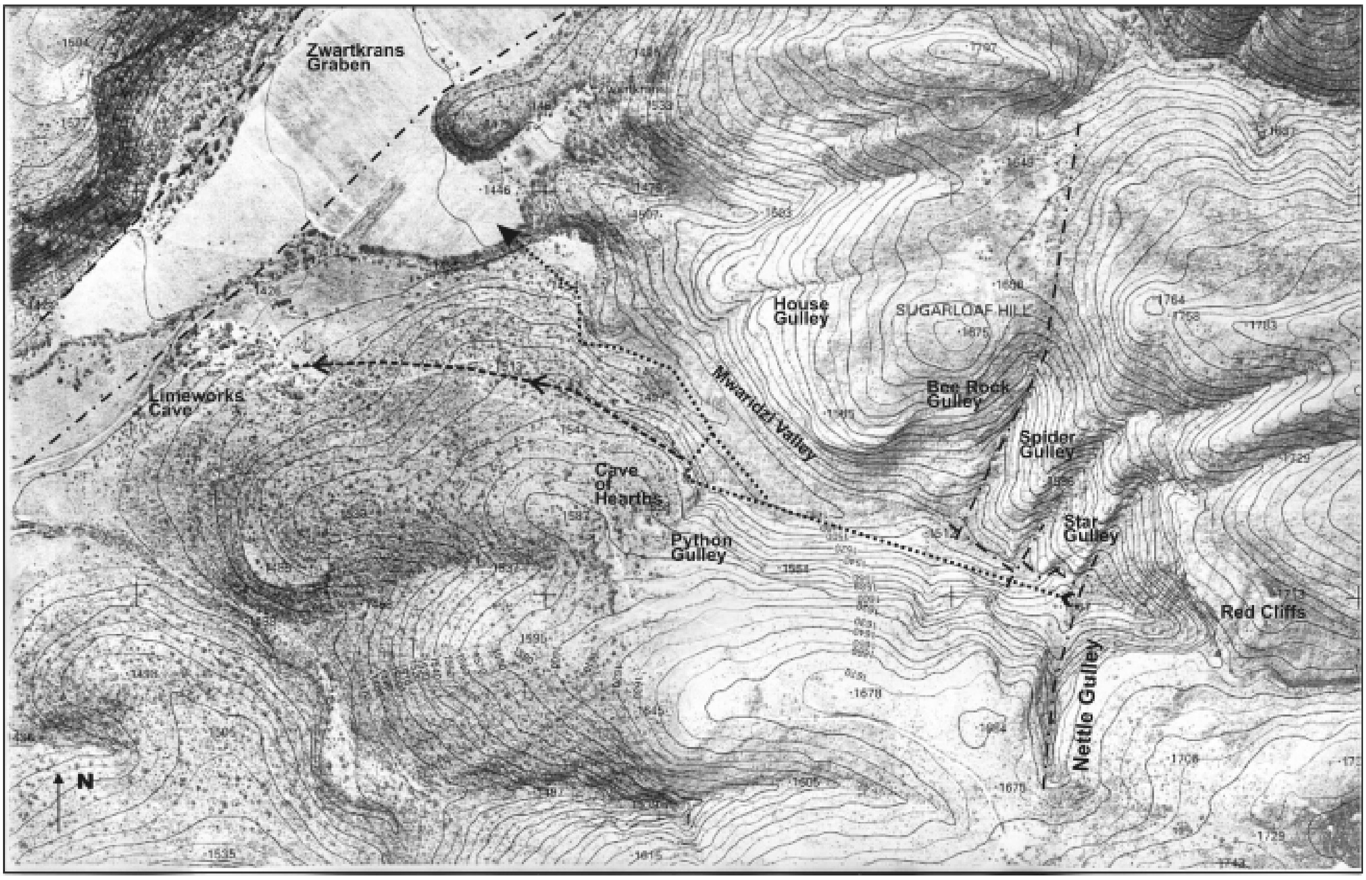

Figure 3. The Zwartkrans and Makapansgat (Mwaridzi) valley area, with contours at 5-m intervals. The dot-dash lines represent some of the main faults at the head of the Mwaridzi valley and the approximate positions of the Zwartkrans graben fault zones. In Nettle Gulley, the dolomite, to the west, is downthrown and brought into contact with the Black Reef Quartzite to the east; the Red Cliffs are in the Black Reef Quartzite. The dotted line marks the reconstructed former plan position of the active cave in Miocene times and the dash line with arrows is the earlier putative underground connection between the Historic Cave – Cave of Hearths and the Limeworks Cave. The Historic Cave fossil remnant passages probably occupy positions of former oxbows (adapted from 1:10 000 aerial photo sheets of Makapansgat, 2429AA14, and Button Kop, 2429AA15, of Surveys and Land Information, Mowbray, Pretoria)).

formative phase, the resurgence was of the Vauclusian type in that stream water rose from depth as a deep spring. The active outlet into the former Zwartkrans valley must therefore have been at least as high as the present surface in the Cone area.

There are stalactites and curtain-form speleothems embedded in the eroded surface of the breccia in the west side of the Cone Mouth, some of which appear to be *in situ.* This means that the roof of the cavern, from which the stalactites hung, was considerably higher than the present surface (Latham *et al.* 1999). The mined hole at the surface known as the South Quarry consisted mostly of speleothem that must have hung down as a huge stalactite mass partly attached to the dolomite back wall. By projecting the curvature of some of the overhanging walls around the Cone area in section, we estimate that the original height of the cavern was some 20 m or more above the present surface in this area. The original Limeworks Cave would have approached in volume some of world's largest caverns of today (see Courbon *et al.* 1989 or Ford & Williams 1989).

On the western and northwest sides of the cave are two upward ascending exits, the one to the west being dubbed 'Original Ancient Entrance' (OAE). This entrance is artificially mined but outcrop traces show that it is part of a larger passage that probably acted as exit for stream water into the valley. Evidently, as the Zwartkrans valley floor became lower, new lower exits formed leaving the upper part of the cavern abandoned. It is probable that the part of the complex known as Horse Mandible Cave also once functioned as a lower stream exit out to the valley.

STRATIGRAPHIC NOMENCLATURE OF THE LIMEWORKS

The member system devised by Partridge (1979, 2000) is fairly well known, and various studies related to the Limeworks have referred to it. It is still possible to apply this member system, to some extent, to the repository of the west side of the Limeworks. The repositories on the east side such as the Exit Quarry Chimney repository or the Rodent Corner deposits cannot, however, be related with certainty to the deposits in the west side and cannot therefore be assigned with certainty to the member system. The deposits of the Central Debris Pile are certainly time transgressive.

Using the Member notation of Partridge (1979, 2000) the main western deposits are:

M1. Subaerial massive speleothem, now removed, originally in huge volumes up to 15 or even 30 metres wide in places, reaching 30 or more metres high. It was mined mainly from an irregular arc (Speleothem Arc) stretching from the Entrance Quarry out to the Exit

Quarry and beyond.

Unassigned. Mainly subaqueous, mammillary speleothem layers, ubiquitous to all parts of the system including Horse Mandible Cave.

M2. This member consists of 5 m of mostly red-purple silts in the Classic Section overlying and abutting against Member 1.

M3. The Grey Breccia in the Classic Section is a dense bone breccia with a matrix of yellow, buff silts cemented by secondary calcite. At the wall it is about 50 cm thick but in other places it had been as much as 2 m thick before mining. It is graphically described by Eitzman (1958) from his recollections of 1925.

Unassigned. In a dolomite overhang of the wall of the Classic Section, the bone layer is succeeded firstly by a compact white flowstone with holes (vugs) in it, and then by an undulating banded flowstone. The two together are about 40–60 cm thick, and are local to this section.

M4. This is the cemented breccia of the central area containing massive (>2 m) to small angular dolomite blocks. The matrix is made up of pink, or red, silts and is up to 20 m thick. It occupies most of the Central Debris Pile. It is likely to be time transgressive, and younging not only upwards but also, irregularly, from the front (north) to the rear (south) of the cavern.

M4 (Formerly Member 5 in the Partridge (1979) notation). This is a conglomerate-breccia with cobbles or clasts, smaller than those in Central Debris Pile, grading into finer stratified lenticular silts and sands. In parts of the Cone area, it is unconsolidated and this condition was responsible for the collapse and formation of the Cone following mining of massive stalagmite from below. It is up to 10 m thick.

THE BROAD SEQUENCE OF EVENTS AT THE LIMEWORKS

The main events and phases of deposition are:

Abandonment

Faunal studies, summarized by Maguire *et al.* (1985), and magnetostratigraphy (McFadden *et al.* 1979), suggest that the Limeworks cavern must have been abandoned by the Makapansgat river well before 4 Ma (see below). This suggests that the system was forming, and active, before the end of the Miocene at 5.1 Ma.

The fall of dolomite blocks

The oldest recognized deposits are large, fallen, dolomite blocks, and they are present in the Main Quarry, under the Central Debris Pile, around the back of the Cone on its east and west sides, in the Exit Quarry and outside the Original Ancient Entrance. There is, as yet, no evidence for the kind of basal, allochthanous sediments that might have originated from transport by the original river. For example, there do not appear to be any sedimentary coatings on fallen blocks or walls before the deposition of speleothem. We suggest that if such sediments are extant then they ought to contain a component of sand from the Black Reef Quartzite.

Main period of speleothem deposition

Speleothem remnants and their negative impressions in sediment show that stalactites, stalagmites, columns and massive flowstones were precipitated mainly as an irregular speleothem arc from the Main Quarry and Entrance Quarry to the back of the Cone Area, where it was joined to the back wall to various heights, and thence to the Exit Quarry.

In the Main Quarry these deposits formed two main spines or bosses reaching to the roof and walls, and each about 20 m wide (Fig. 5). The more northerly boss was deposited onto massive fallen blocks of dolomite. Brain (1958) suggested that, 'probably a structural weakness in that part of the roof caused first the blocks to fall – and then allowed large quantities of water to pass through the roof at that point, which on dripping to the floor, deposited the travertine. Similarly [elsewhere].'

In any event, the impression overall is one of fairly rapid deposition of speleothem that points, firstly, to a thinning roof and, secondly, to a fairly high rainfall. Voluminous deposits such as these are found mainly in tropical to sub-tropical karst areas such as Borneo, Central America and south China. The increase of temperature and especially humidity as a major control of speleothem deposition has been highlighted by Corbel (see references in Jennings 1985). By contrast, with an annual rainfall of 700 mm today, the rate of speleothem deposition in the caves of the area is very low.

Sub-aqueous speleothem

Subaqueous speleothem layers coat fallen dolomite blocks in many places. Brain (1958) noted a good example to the east of the Cone where a large block has fallen and split into two pieces, coated by a 5–10 cm uniform layer of what he termed 'floor travertine'. It is in fact mammillary form speleothem. This kind of deposit is subaqueous and it precipitated from pools saturated with calcium carbonate. As CO_2 outgassed from the water's surface, mammillary speleothem was deposited onto existing submerged speleothems, as in the Main Quarry west wall, and onto other surfaces below the pool surface. Mammillary speleothem coats the walls around the Southwest Alcove, the East Quarry and below the Chimney Repository. It appears to have coated a shelf of rock in the tunnel area near Rodent Corner, as was noted by Maguire *et al.* (1985). Subaerial stalactites later hung from it. Mammillary speleothems formed in the lower reaches of Horse Mandible Cave. Drill core samples extracted from the base of the Central Debris Pile also show that 'flowstone' (probably mammillary speleothem) was deposited inside the Arc (Partridge 2000).

At the base of the breccia on the east side of the Main Quarry some layers of subaerial speleothem of the central 'boss' cover the mammillary forms (Fig. 4). The question of which type preceded which cannot now be discerned in some areas because mining has removed much of the evidence, but these alternations in stratigraphic order strongly suggest that the carbonate-rich pools originated from a high rate of percolation from the surface that, in effect, fed both the subaerial, and subaqueous, speleo-

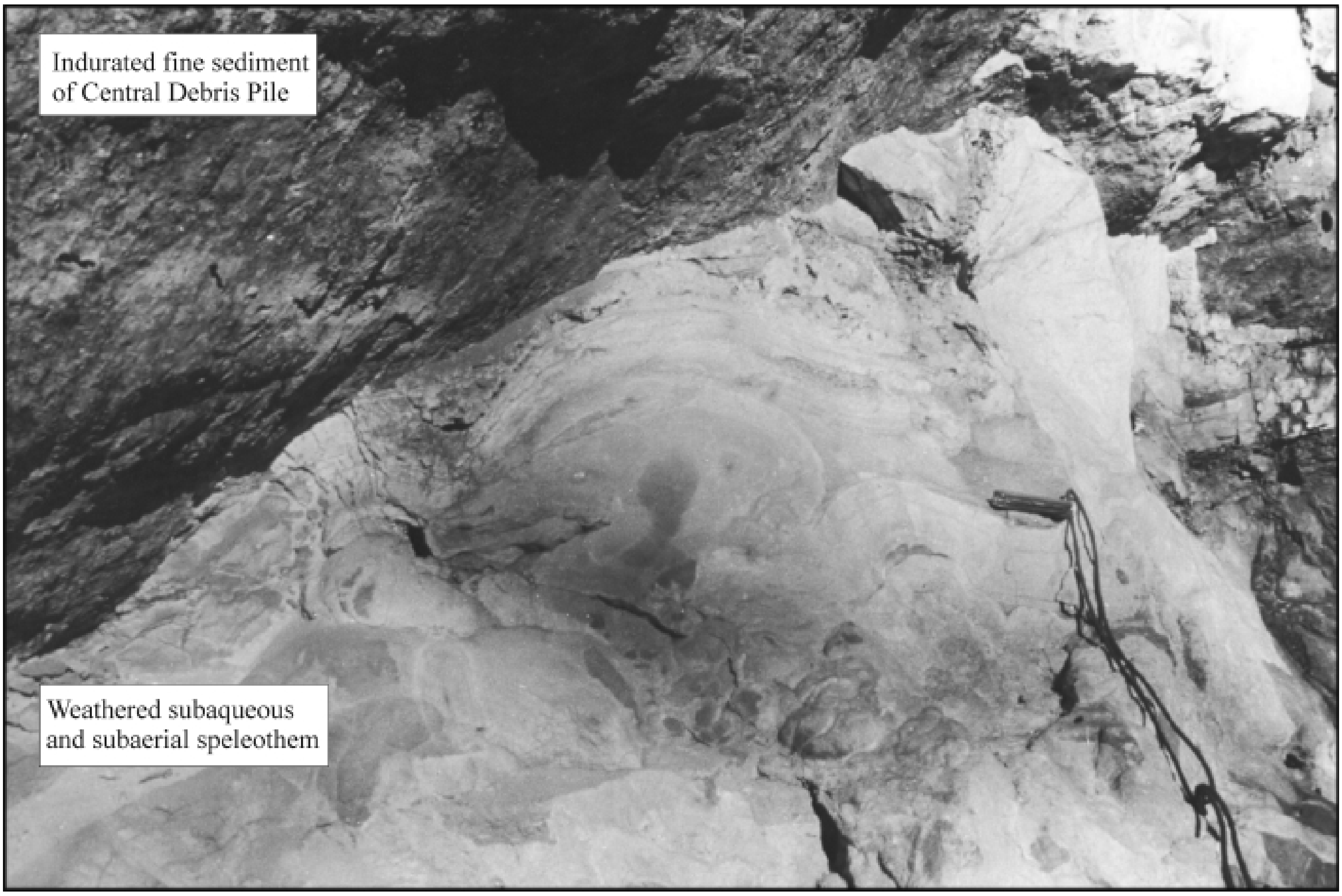

Figure 4. Photograph of eroded speleothem of the Main Quarry boss on the east side. The speleothem is a mammillary flowstone coating over a dolomite block that is in turn overlain by subaerial flowstone. The near wall of Central Debris Pile abuts against the inner truncation of the speleothem layers and shows that they were eroded before, or at the time, the fine sediments were emplaced. The fine sediments may represent a channel between the speleothem and the clast-dominated Central breccia.

thems more or less at the same time; the pools that formed from the high-flow seepage water fluctuated in level at various times.

There is also good evidence in the Main Quarry, Classic Section and Ancient Entrance to show that stalagmites and flowstones continued to form as later sediment entered the cave. This qualifies the strict, sequential two-stage M1A and M1B presented in Latham *et al.* (1999). There is evidence in the OAE that there were two phases of deposition of sub-aqueous speleothem, the first of which probably corresponds to the mammillary layers seen throughout the whole site.

Rodent Corner sediments

The Rodent Corner sediments in the Exit Quarry are so named for the red sediments containing the many rodent bones that appear to have resulted from owl roosts. These sediments and the underlying water-lain grits and sands, containing cave pearls, postdate mammillary speleothem; the sediments were laid down between stalactite curtains in the tunnel area (Maguire *et al.* 1985). It would probably be misleading to relate these sediments to the member system, which was constructed chiefly from repositories in the west side of the Limeworks. Among the rodent bones are those belonging to a rat, *Mystromys darti,* which is found in the Langebaanweg deposits and dated to between 7 and 4 Ma (Maguire *et al.* 1985).

Original Ancient Entrance sediments

Just inside the mined entrance, a short series of red-mud contaminated flowstones, which comes to resemble a mud-calcite breccia, lie at floor level and originate from outside the present OAE. As this series lies between two sub-aqueous layers, they are among the earliest deposits in the west side of the Limeworks. This unit is not assigned to the member system.

Collapse and infill of clastic sediments

Breccia Member 4 occupies the centre of the site and this phase represents cavern roof stoping and unroofing either together with, and certainly followed by, hillwash of red sediment and soil. The Central Debris Pile occupies the main part of the cavern and probably formed over a long period of time, beginning in the Miocene at the down valley, northern end, of the site. It is a fairly safe conjecture that the earliest clastic deposits of the Central Debris Pile were emplaced between the Entrance Quarry and the Exit Quarry and Horse Mandible Cave. This is because, from the slope of the bevelled surface, this is the most likely place for unroofing to have begun.

Sedimentation rate increases in the Original Ancient Entrance

In the OAE, the red silts of Member 2 include small dolomite blocks and bone fragments as a breccia but, by the time the sediments wash into the Classic Section, they are free of large rock clasts. This period appears to represent retreat of the OAE cave brow.

Induration of breccia and other sediments

The surface of these deposits is now indurated except for vegetation root holes (known locally as makondos). When open to the rain and to surface runoff, the redistribution of carbonate from the dolomite debris has cemented the clasts and matrix into a hardened breccia. According to Brain (1958), samples of hardened breccia on the north side of the Cone contained about 95% carbonate cement. On the southwest side, dolomite overhangs may have prevented this kind of induration and so the deposits remained unconsolidated. An analogous situation obtains in the modern debris of the surrounding hill slopes. Debris consisting largely of dolomite clasts are indurated by carbonate cement whereas debris of non-carbonate rock are unconsolidated.

The eastern half of the roof of Horse Mandible Cave consists of hardened breccia with stalactites in several places. It seems that, at some stage in its history, loose breccia and sediment has been removed from underneath indurated breccia, allowing stalactites to form on the newly created roof. The existence of the competent breccia roof and of its stalactites thus doubly testifies to the induration process by carbonate cement.

Watertables or winnowing

The concept of fluctuating watertables has been invoked to explain deposition of the more horizontally bedded sediments in the Limeworks such as the rhythmites of Rodent Corner (Brain 1958; Rayner *et al.* 1993). This second usage of watertable concept was criticized by Latham *et al.* (1999) who showed that it was much more likely that such sediments resulted from the periodic inflow or winnowing of sediments. Repeated formations of mud cracks in the Original Ancient Entrance, in Member 2 of the Classic Section and at Rodent Corner elicit a picture of periodic flood events each followed by desiccation. It is tempting to think of each cycle as being seasonally driven.

THE SPELEOTHEM ARC: THE KEY TO THE REPOSITORIES

Because of its apparent continuity, the body of flowstones and stalagmites that constitute the Speleothem Arc caused several large alcoves at the sides and rear of the cavern to be isolated from each other and from the centre of the cavern. Visitors to the Limeworks walk chiefly where the purer speleothems existed prior to mining (Fig. 5). The width and height of the body of the Arc varied from a few metres to tens of metres and it was continuous all the way from the Entrance and Main Quarries round to the Cone and back out to the Exit Quarry. Eitzman (1958) stated that 60 000 tons of lime had been removed by 1937, which converts to about 180 000 m^3. Owing to the irregularities of the present cavities it is difficult to make a precise estimate of the mined volume between the Entrance and Exit Quarries but a rough calculation puts it somewhere between 250 000 and 350 000 m^3. Some of the material was dumped as unusable including breccia, sediment and impure calcite. Contacts and remnants show the speleothem mass was joined to the adjacent walls, overhangs and roof in many places. Brain (1958), Maguire *et al.* (1985) and others also noticed that remnants of massive flowstones near the Cone showed that they had suffered re-solution; flowstones were cracked, fallen away in blocks, and growth layers were truncated (Fig. 6). In fact, there are weathered remnants and weathered surfaces of speleothem in several places testifying to the likelihood that eroding streams had flowed past them or that they experienced direct rainfall. On the western side of the Cone Mouth there is a huge fallen block of speleothem that appears to have dropped off a nearby massive boss and both are now embedded in the finer sediments. Both remnants are now part of the cemented roof breccia left by the miners.

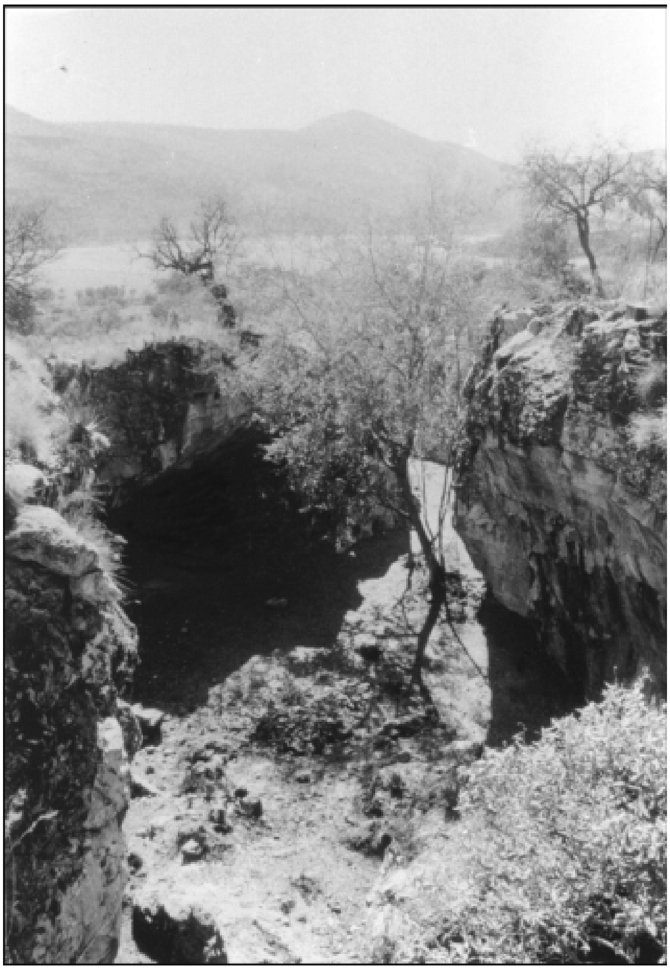

Figure 5. The Limeworks Main Quarry looking northeast. The dolomite roof and wall, to the left, contain the Classic Section (underneath, not visible) and the adjacent North and West alcoves. The central stalagmite boss, which was probably weathered before it was mined out, occupied the space. The wall to the right is the Central Debris Pile consisting of large dolomite blocks that came to lie against the (now mined) stalagmite. The negative imprint is in finer sediments that are probably channel fill deposits. Figure 4 was taken to the right behind the small tree in the foreground.

What this shows is that, before unroofing, the speleothem mass was even more voluminous than the amount the miners had access to. As the cavern eroded away,

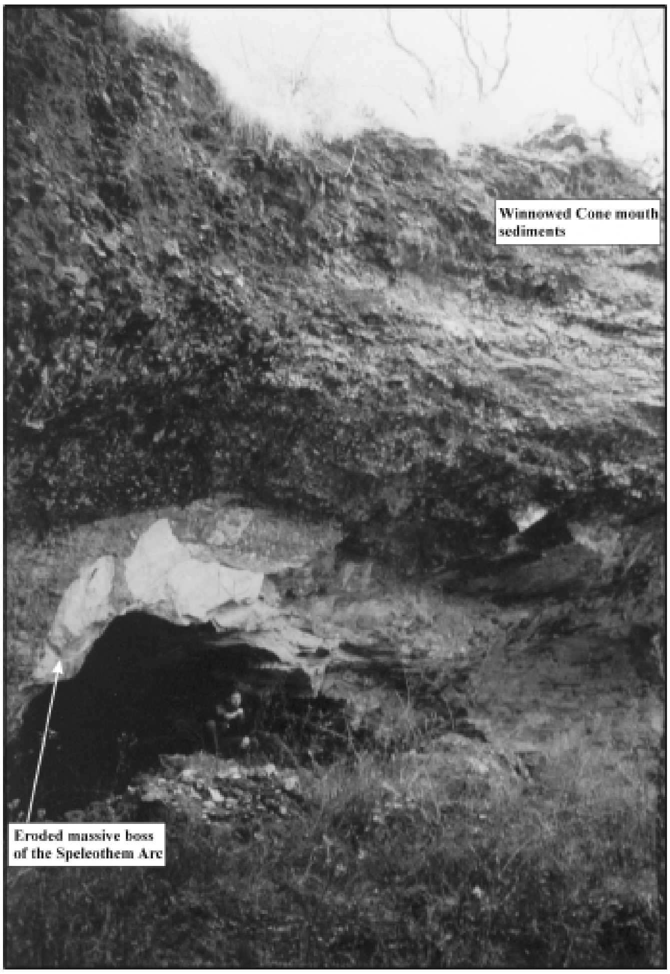

Figure 6. The southeast side of Cone Mouth taken from the collapsed Cone sediments. The dark space, behind the person, was originally occupied by massive flowstone speleothem, remnants of which are embedded in the breccia now acting as roof. This speleothem was truncated by weathering and had cracked apart before the emplacement of the breccia. Progressing from east to south (left to right), the breccia contains angular, subangular, subrounded and rounded cobbles in layers of gravel to silt, which suggest that streams swept underneath an extensive cave roof. Some parts of the sediments are calcited together whereas, to the south, the sediments are much less indurated.

some of the speleothem fell in and other parts of it were dissolved and eroded by water falling in from the slopes above. The important point to note is that it is this Speleothem Arc that later promoted separate repositories. That is, as the cavern unroofed upslope, the Arc acted as a barrier to prevent winnowed sediment from the Central Debris Pile from reaching some lateral alcoves, and alcoves were isolated from each other.

Given the importance of the Speleothem Arc to understanding the Limeworks repositories, we now focus attention on the Central Debris Pile and the areas around the Original Ancient Entrance, the Classic Section and the Cone. The reasons are that; (1), the areas include three bone breccia horizons, one of which is the Grey Breccia, Member 3, (2) several of the layers can be correlated across the western side of the site and, (3), together they encompass layers from the lowest, earliest, phase to the topmost, on the western side, and thus provide the greatest potential for magnetostratigraphy. Rodent Corner and the Exit Quarry Repositories have been discussed by Turner (1980), Maguire *et al.* (1985) and Pocock (1985, 1987) and will not be discussed further.

THE CENTRAL BRECCIAS AND SEDIMENTS: MEMBERS 4 AND 5

Clearances of vegetation on the surface of the Central Debris Pile show that the area between the Main Quarry, the Exit Quarry and the Cone Mouth is dominated by large blocks of dolomite, typically up to 3 m on a side, some up to 20 m (Partridge 2000), often in contact with each other, between which is a matrix of fine sediment containing much smaller clasts and occasionally pieces of speleothem. This clast-supported breccia, Member 4, stretches to the Main Quarry, over to the Exit Quarry and is evident at the surface to within 3–5 m of the edge of the Cone Mouth. By contrast, the sediments around the Cone Mouth down at the base consist of matrix-supported breccia, conglomerates and stratified, lenticular, gravels grading into sands (Partridge 1979). The sediments grade from cobble layers to massive, dark-red, sandy-mud, layers toward the back of the cavern and against the dolomite wall (Fig. 6).

Partridge (2000) represented the interior breccia as matrix-supported material falling onto a central point and rolling away from it. As the large blocks are in contact with each other, however, the breccia must be clast-supported, This suggests that, at that time, roof-fall was occurring faster than the inwash of surficial material and that the finer sediments were being winnowed out from the block clasts. In the base of the cavern on the north side of the Cone, it is observed that the matrix-supported debris, with its partly rounded quartzite cobbles and pebbles, actually extends under the Central Debris area more than 10 m away from the base of the Cone. The dolomite blocks appear to lap onto the conglomerates and winnowed sediments. Such a configuration points strongly to the likelihood that the dolomite blocks represent progressive stoping and unroofing in an uphill direction (Fig. 7).

Where stoping of the roof preceded actual unroofing to daylight, the dolomite blocks preceded the finer matrix sediments that later came to lie within the pile. Once most of the roof had been removed and blockfall ceased almost entirely, the deposits came to be dominated by reworked surficial deposits. The finer sediments of the Cone that were deposited to the sides of the breccia represent the winnowing of the breccia matrix.

These events are additionally supported by the following observations:

1. Under the hanging calcified sediments to the west of the Cone there is a water-worn remnant of massive speleothem against which lies the underside of about 10-m long arcuate deposit of sediment that is U-shaped, 0.5–1 m deep, and up to about 1–2 m wide (Fig. 8). This feature contains negatives of mud cracks and clearly operated for some time as a substantial channel. There is no clear indication of the direction of flow but it was probably away from the back of the Cone and toward the Main Quarry.
2. Though not so clear, there is the underside of another channel, going away from the Cone on the north side

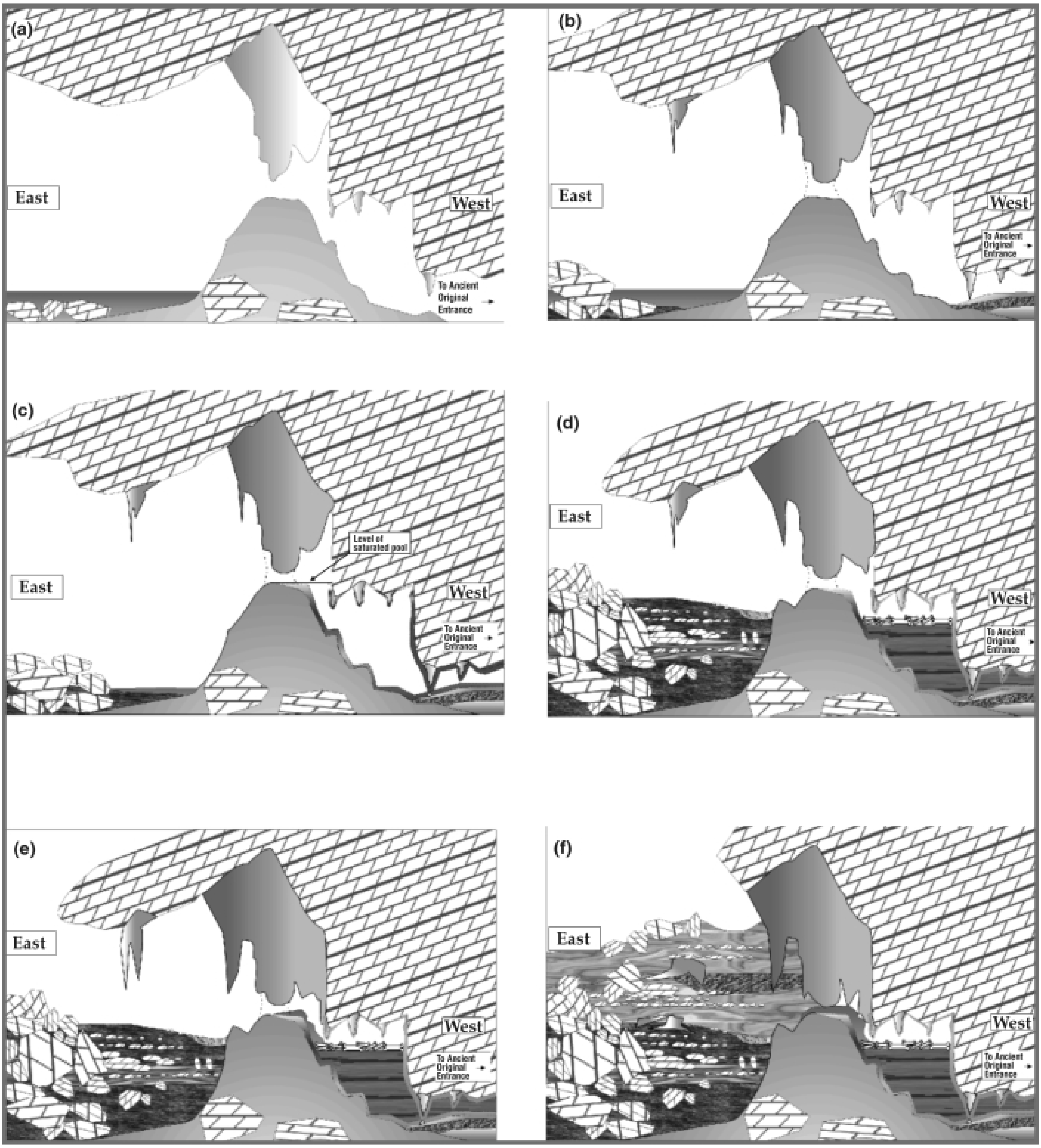

Figure 7. Interpretative diagrams to illustrate the main stages of deposition and erosion of the western side of the Limeworks site. **(a)**, begins with blockfall and deposition of massive speleothem to form the speleothem arc. Between the Cone (East) and the lateral Classic Section (West) there is a gap that is not 'plugged' until after M3 times. **(b)**, shows the start of unroofing to the southeast and the beginning of the build-up of the Central Debris Pile, M4. Carbonate-saturated pools allow coatings of sub-aqueous speleothem; subaerial deposition of speleothem continues to be deposited. On the western side of the Speleothem Arc, sediments wash in from the direction of the OAE. **(c)**, in addition to carbonate-saturated pools in the Central Debris Pile, a pool develops between the OAE and the Classic Section. Mammillary speleothem is deposited on all surfaces. Initially it is pure but becomes increasingly contaminated with fine mud leading to a mud calcite breccia and a second sub-aqueous layer. **(d)**, Sediment of M2 times is deposited from OAE to the Classic Section. Animals are able to enter from OAE to den near the Main Quarry. Eventually deposition ceases as the low dolomite roof in the OAE area obstructs sediment ingress to the Classic Section. The Central Debris Pile continues to grow, and run-off winnows the sediments to the Cone area; channels form round the inside of the Speleothem Arc. Deposition at the rear of the cavern reaches a level where animals can gain access to the Classic Section. Bone breccias are created in the Classic Section (M3) and at the rear of the Cone together with more phases of flowstone. **(e)**, speleothem deposition and then sediment seals the gap between Central Debris Pile and the Classic Section. The roof continues to retreat with the destruction of some of the massive speleothem stalactites and columns. **(f)**, in the Cone Area, winnowed fluvial sediments continue to build up to higher than the present day surface. Lateral alcoves at the rear of the cavern and part of the Classic Section remain unfilled.

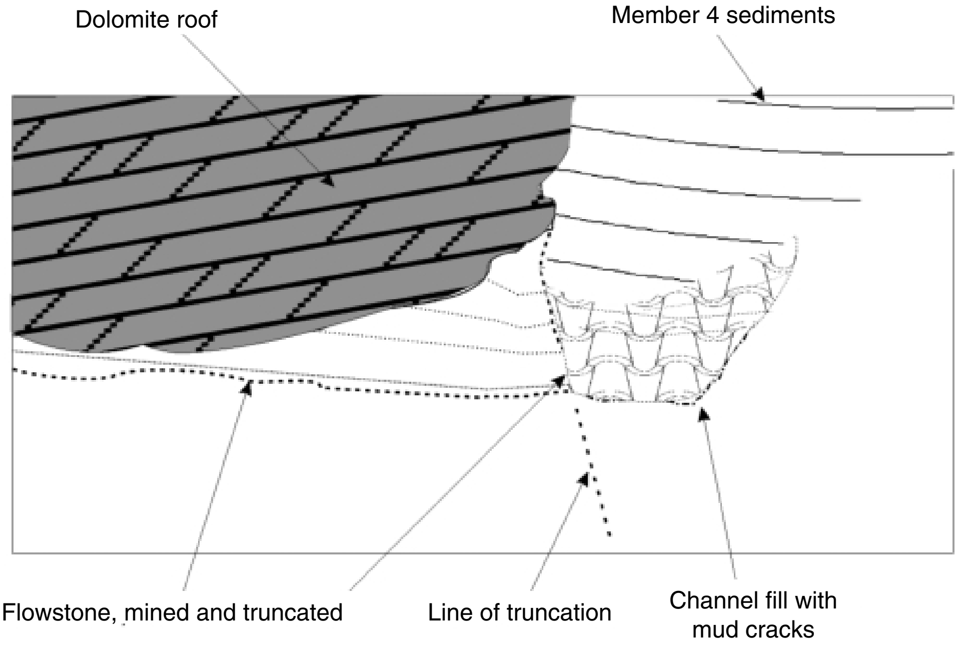

Figure 8. Simplified section of stream channel fill against the roof and remnant flowstones under the southwest side of the Cone Mouth. The channel contained mud cracks that were later filled in by calcite. The flowstones were evidently weathered by flowing water before sediments were laid down. The channel is at about the level of Member 3, the last traces of which are seen about 3 m to the west. Bat guano is also evident in these sediments.

and into the base of the Central Debris Pile.

3. Similarly, in the east side of the Main Quarry, from the present floor level to about 2 m above it, truncated mammillary and subaerial speleothem clearly shows that it has been re-dissolved by flowing water (Fig. 4). It is interesting to note that, whereas the breccia surface immediately above this area contains large dolomite clasts, the sediment against the sides of the speleothem is virtually clast-free. We infer that this part of the Speleothem Arc acted from time-to-time as the western barrier of a drainage system.

Throughout the history of infilling, there must have been a number of channels through and round the mounting Central Debris Pile to drain the water from the back of the cavern out to the valley. The presence of mud cracks indicates periods of desiccation between periods of rainfall, though that in itself cannot tell us whether any periodicity was daily or seasonal.

ORIGINAL ANCIENT ENTRANCE (OAE) TO THE CLASSIC SECTION

The section most likely to provide a long magnetostratigraphic record is the area from the OAE to the Classic Section and the Cone Mouth. Hence the stratigraphy of these sections is now dealt with in more detail.

Partway through the OAE deposits, a well-defined 4–8 cm thick subaqueous layer of mammillary speleothem formed on all available surfaces from the OAE to the Classic Section reaching as high as the roof above the Grey Breccia. Fine red-brown silts, grading laterally into a mud-calcite breccia, followed this mammillary layer. Then followed another sub-aqueous layer though not reaching quite as high as the first. These two sub-aqueous layers negate the normal superposition principle and lead to locally inverted stratigraphy. But otherwise, both

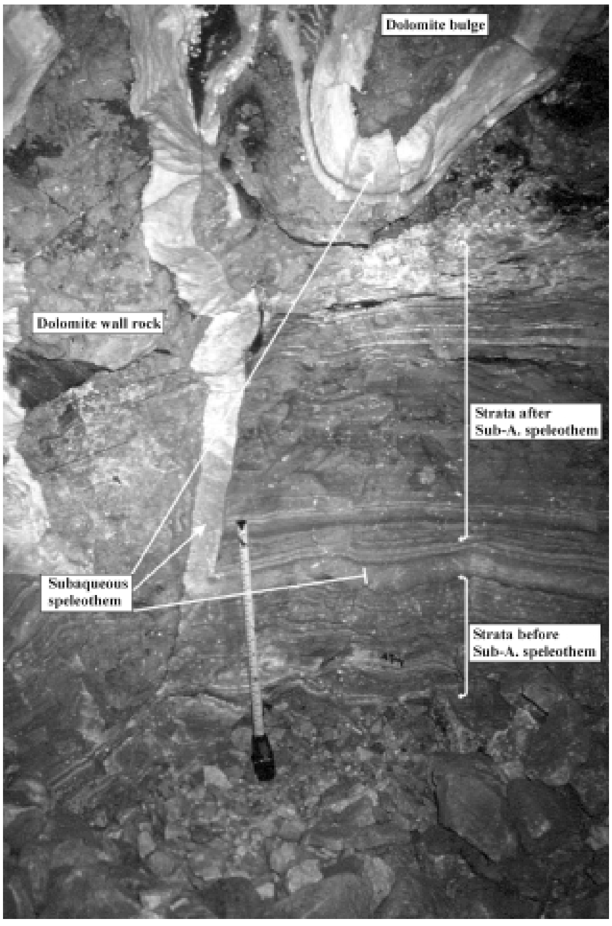

Figure 9. The early layering inside the mined Original Ancient Entrance. The visible sequence is 20–30 cm of fine calcite-indurated sediments intercalated with flowstones. A 6–10 cm thick mammillary layer covered these sediments, wall and roof to be followed by increasingly mud-contaminated speleothem. This was followed by a calcite–raft breccia in mud. The mammillary layer is ubiquitous to the whole area from the OAE, to the North Alcove as far as the Main Quarry, and to the top of the Classic Section reaching higher than Member 3.

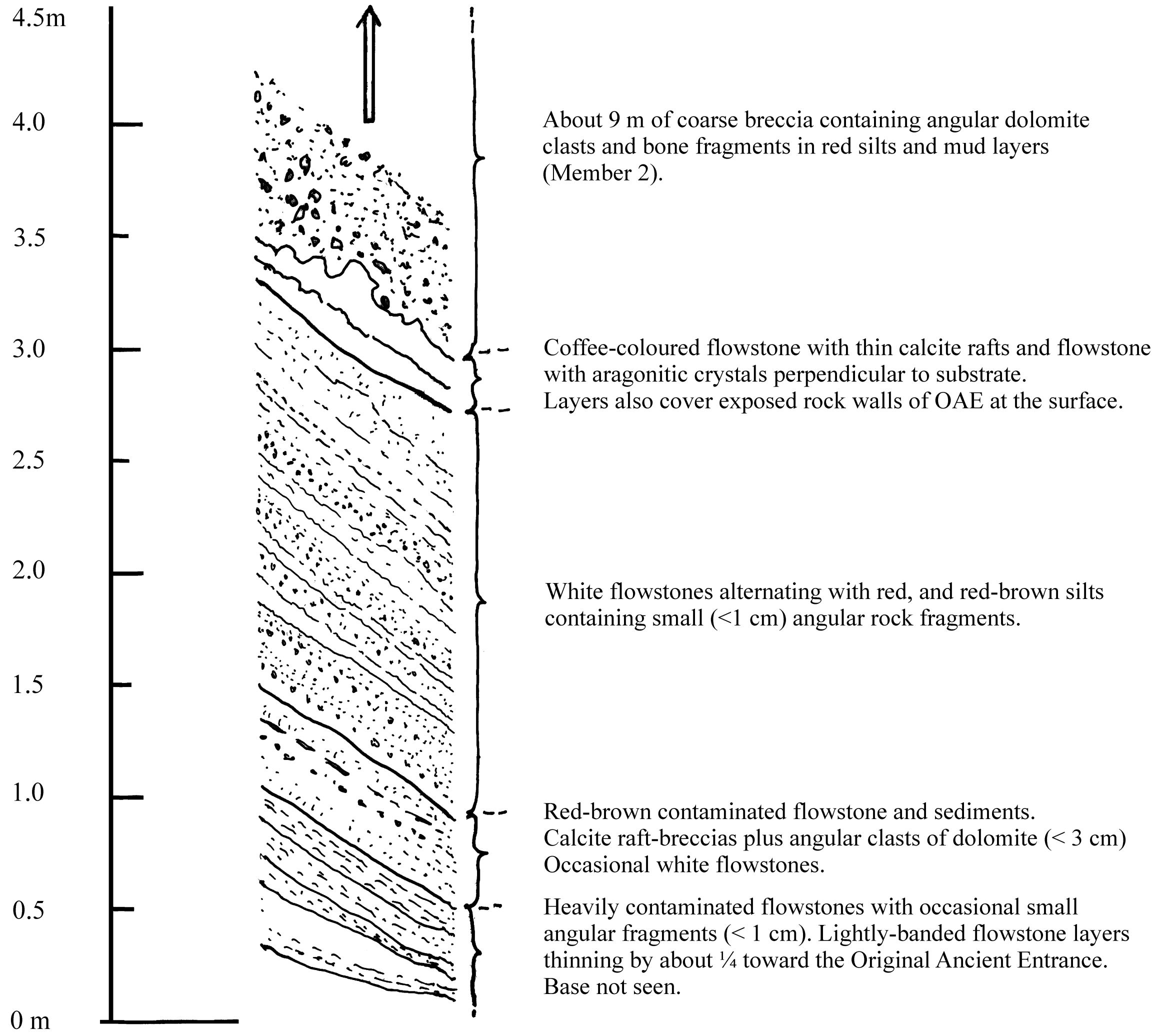

Figure 10. The stratigraphy on a section 8 to 15 m outside the Original Ancient Entrance. The OAE is down and to the right of the section. The arrow points to the top surface of bevelled (eroded) Member 2 (about 3 m above), which begins at the coffee layer. The coffee speleothem and overlying purer flows are the equivalents of the mammillary speleothem under the OAE and out to the Classic Section. There are bone fragments in Member 2 immediately overlying the coffee layers.

sub-aqueous layers make useful chronostratigraphic markers for all of this area (Fig. 9).

North Sequence

A clear sedimentary sequence can be recognized in the section from outside the OAE, up under the North Alcove, to the black bone breccia in the overhang of the Main Quarry northwest wall and to the Classic Section. It begins in the North Alcove with a large 3 m high stalagmite boss. About 40 cm of contaminated flowstones, which originated from the OAE, abut against the boss. Outside the OAE, all sediments dip down into the opening itself at about 30° (Fig. 10). The impure flowstones are followed by the sub-aqueous layers, which have coated all existing surfaces including the roof and walls above Grey Breccia Member 3. In the alcoves the mammillary speleothem grades into calcite-raft clasts in fine mud. This very distinctive and unusual mud and calcite breccia deserves a separate treatment and will be discussed elsewhere.

It is clear that most of the mass of the two speleothem bosses in the Main Quarry and the smaller boss under the North Alcove had already formed before the mammillary speleothem and raft-calcites were emplaced. Toward the Main Quarry, the steeply dipping surfaces of more massive Member 1 flowstone shows that it represents the lower shoulder or apron of the Main Quarry stalagmitic bosses. Flows continued to form during the emplacement of early Member 2 sediments and, stratigraphically, therefore, these later flows have to be placed within Member 2. Member 1 also made a more-or-less continuous contact with the dolomite overhang of the cavern, resulting in the isolation of the alcoves from the Central Debris Pile.

In the Main Quarry, the manganese-blackened long bones and other remains occur on top of the shoulder of later flows from the Main Quarry boss. They appear to have resulted from a period of animal denning partway through the deposition of Member 2, the denning animals having gained access via the OAE. Most importantly, from its higher altitude (by several metres), and its higher stratigraphic position, this bone breccia would appear to postdate the Grey Breccia.

In the depositional basin inside the OAE, the red silts, which constitute most of Member 2, progressively contaminate the subaerial flowstone layers of Member 1 or alternate with it. Finally, red sediment becomes rapidly

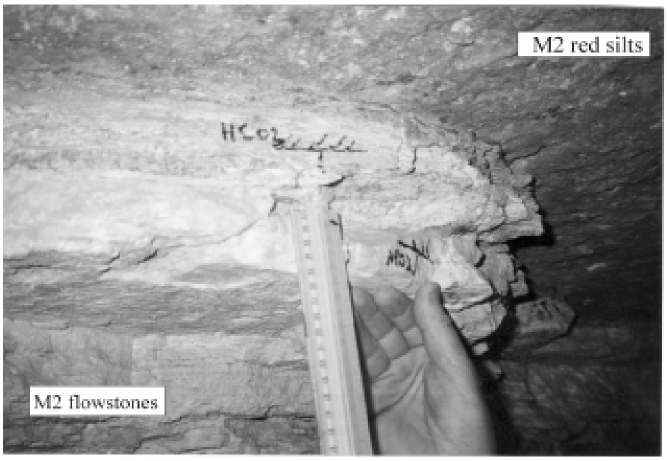

Figure 11. Underneath the Classic Section at the junction between M2 contaminated flowstone and M2 red sediments. The magnetic polarity changes from reversed to normal in the flowstones a few centimetres below the disconformity.

dominant with fewer and fewer thin calcite bands. Outside and above the OAE this takes the form of 9 m of 20–40° dipping, red sediments with rock clasts and bone fragments.

Classic Section

Following the sub-aqueous layers there are contaminated flowstones in the Classic Section that probably belong to Member 2. The Member 2 red silts cover the next 5 metres and are conformably overlain by the bone dense, Grey Breccia, Member 3 (Figs 11 & 12). A white, compact flowstone 30 cm thick, with small holes, is followed immediately by 20–30 cm of a banded red-brown flowstone (see also Plate 3.1 of Maguire *et al.* 1985). Out in the roof and toward the Cone, the bone breccia lies between partly rotted stalactites that were earlier coated in mammillary speleothem (see also Figs 3 and 4 of Maguire *et al.* 1980). The remains of stalagmite contacts with the wall at the end of the Classic Section clearly show that the massive, subaerial central flows of the stalagmite boss were close to sealing off the Classic Section space, leaving a gap of about 1 metre between it and the roof. If, as seems most likely, the hypothesis of hyaena denning is used to explain the presence of bones in the Grey Breccia, then this gap demonstrates how it would have been possible for these animals to gain access from the direction of the Cone at a time when this part of the cavern was not yet filled.

THE SEDIMENTS OF THE CONE MOUTH

The miners removed a large speleothem boss joined to the south, rear, wall of the Cone Mouth and this eventually resulted in the collapse of the overlying, winnowed sediments, now the Cone, only part of which had been indurated. The weathered surfaces of extant speleothem and contact relationships show that these sediments were laid down against the rear wall from a height that is just above the level of Grey Breccia. Unlike the Grey Breccia, however, these Cone sediments were deposited inside the Speleothem Arc. The section thus begins with speleothem attached to the lower dolomite wall, up through about a metre of white bone breccia and some fossil guano deposits.

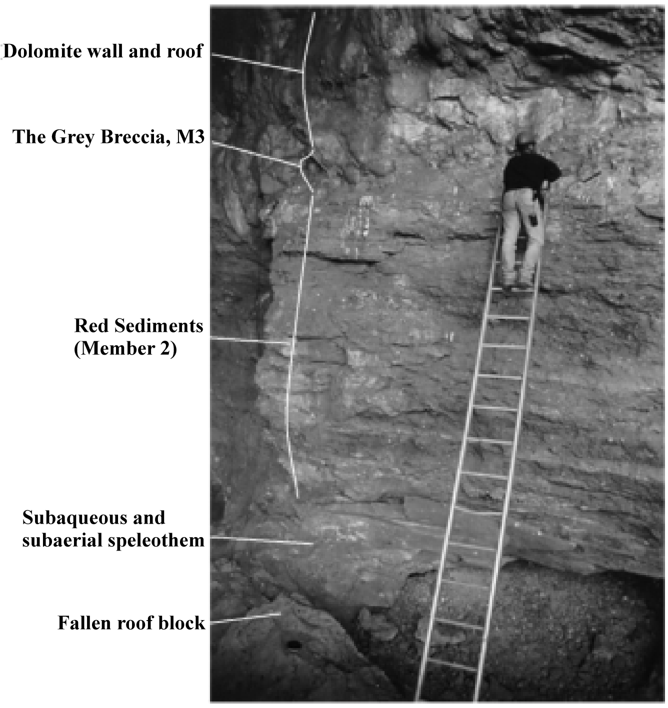

Figure 12. The Classic Section with the Grey Breccia. Under the base and into the West Alcove, the walls contain calcite rafts and mammillary speleothem. The fallen block contains mammillary and subaerial speleothem as an apron of one of the bosses. M2 red sediments continue into the Grey Breccia with no discernible hiatus, as does the banded flowstone above (at the level of the head of the person).

The bones in this breccia have a more chalky appearance than bones in the Grey Breccia or in the Main Quarry. They are followed by 2–3 metres of partly calcited breccia, and then 15m of silts up to the present surface.

The bone breccia on the rear wall is at about the same height as the Grey Breccia. It is unfortunate that much of the intervening sediment at roof level between the Grey Breccia and the Cone bone breccia has been removed. The Grey Breccia can, however, be traced about two thirds of the way from the Classic Section to the rear wall, and so it is not unreasonable to suppose that these two bone breccias resulted from hyaena denning at about the same time. There thus seems little doubt that a connection existed for a while between Grey Breccia and the Cone area and that stratigraphic continuity, perhaps with some overlap, exists between the Classic Section and the Cone Mouth section.

THE RECONSTRUCTION OF REPOSITORY SEQUENCES: DISCUSSION

Apart from the presence of sub-aqueous speleothem, the principal of superposition and younging upwards allows us to reconstruct a stratigraphic order for each of the repositories (Fig. 13), and affords a basis for correlation between sections.

In contrast to the Classic Section where the M2 red sediments are followed by the M3 bone breccia, the area at the back of the Cone shows that the white bone breccia precedes the Cone sediments. Whereas the Classic Section was on the outside of the Arc, the back of the Cone was on its inside. And whereas Member 2 sediments in the

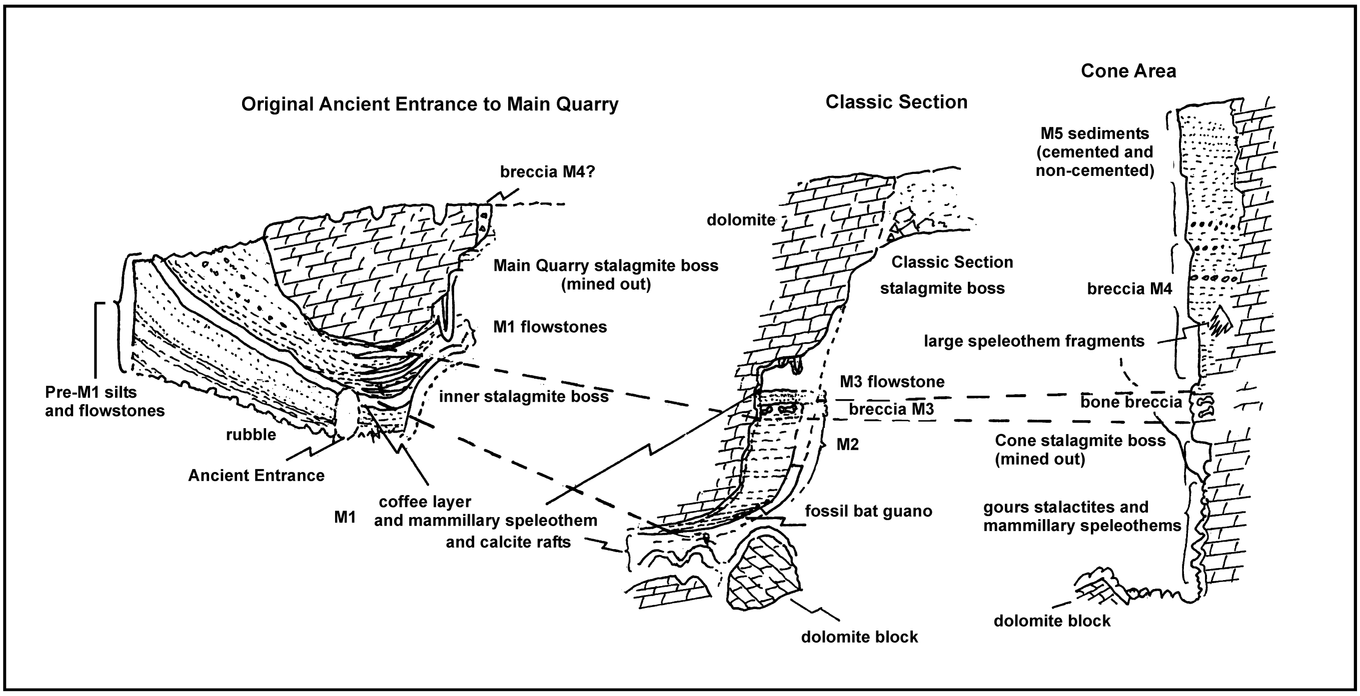

Figure 13. The correlation of stratigraphy across the three repositories, Original Ancient Entrance, Classic Section and Cone Mouth. The diagram is not exact in vertical section but is intended to be illustrative of the main stratigraphy and features.

Classic Section came from the Original Ancient Entrance, the Cone originated from the Central Debris Pile. If, as argued here, hyaenas occupied the area of Member 3 only when the sediments inside the Arc had reached a sufficient level for access, then the lowest layers of red sediment at the front of the Cone area predate Member 3. This implies that the lower layers of these sediments might be roughly contemporaneous with Member 2 and that all sediment above the Cone Mouth bone breccia postdates Member 3.

The clastic sediments are continuous to the top of the Cone Mouth without hiatus so that, in effect, the sequence from the rear, base of the Cone represents the history of sediment deposition for the Limeworks from M3 times onwards. No hiatuses or erosional features have been detected in the Cone clastic sediments.

As magnetostratigraphy at Limeworks Cave requires a sampling of both chemical and clastic sediments, the question of relative rates of deposition is obviously important. In some speleothems, the visible sediment banding is probably due to seasonal flooding and they often show that contamination increased with time. The observation that Member 2 red sediment is partly calcified and has calcite horizons, and that Member 3 is overlain by flowstones, shows that speleothem deposition did not cease in this area. However, in all areas to the west of the Main Quarry, clastic sedimentation eventually out-competed speleothem deposition. It is therefore probable that when unroofing was underway, the deposition of winnowed sediments was faster than the precipitation rate in most places. It is important to note possible relative rates of deposition in this regard because any magnetostratigraphic record will be stretched and compressed in various places and magnetic reversal chrons and subchrons of differing duration could be wrongly identified.

SUMMARY

The reconstruction of the infilling history of the Limeworks Cave is made possible by the recognition of a number of major depositional features. Early infilling was dominated by dolomite block fall from the roof, and this continued sporadically until the roof itself opened to daylight when the process speeded up. At about the same time, massive subaerial speleothem in the form of stalactites, stalagmites and flowstones were deposited mainly around the outside of the cavern. The huge masses of speleothem are probably good evidence that, during Member 1 times, the area enjoyed a climate that was significantly more humid than that of today. In time, speleothem formed a more-or-less continuous arc that became joined to walls and roof in several places so as to isolate various alcoves from each other and from the centre of the cavern. The result was that when erosion began to remove the roof, these alcoves were either filled by sediment from directions other than the centre or were not filled at all. The Classic Section was filled by sediment coming from the Original Ancient Entrance. The Cone, on the inside of the Speleothem Arc, was filled firstly by the winnowing of matrix sediments from the Central Debris Pile, and then by the reworking of colluvium falling from the surface as the cave brow continued to retreat upslope.

Thickening bands of contamination in flowstones indicate increasing sedimentation with time so that in many places clastic sediments came to replace the precipitated flowstones. This means that any attempt at magnetostratigraphic dating based on the sequence will have to take these relative rates of deposition into account.

The white bone breccia at the rear of the Cone is at about the same level as Grey Breccia. In the repository that includes the Classic Section and the Main Quarry, the bone breccia in the Main Quarry is stratigraphically higher than the Grey Breccia and thus postdates it, but probably not by much. Given that the Grey Breccia is on top of the first few metres of Member 2 sediments and the Main Quarry bone breccia is also in Member 2, then these two bone breccias may be separated in time by, at most, just a few tens of thousands of years. Faunally, therefore, all three breccias would seem to be about the same age. Bone fragments belonging to Member 4 or other breccias are, however, likely to be much different in age.

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REFERENCES

BÖGLI, A.1980. *Karst Hydrology and Physical Speleology.* Berlin, Springer-Verlag.

BRAIN, C.K. 1958. The Transvaal ape-man-bearing cave deposits. *Transvaal Museum Memoir* No. 11. Pretoria, Transvaal Museum.

COURBON, P., CHABERT, C., BOSTED, P. & LINDSAY, K. 1989. *Atlas of The Great Caves of the World.* St Louis, Mo, Cave Books.

EITZMAN, W.I. 1958. Reminiscences of Makapansgat Limeworks and its bone-breccia layers. *South African Journal of Science* **54**, 177–182.

EWERS, R.O. 1982. *Cavern development in the dimensions of length and breadth.* Unpublished PhD thesis, McMaster University, Hamilton, Ontario.

FORD, D.C., EWERS, R.A. & LAURITZEN, S-E. 2000. Hardware and software modelling of initial conduit development in karst rocks. **In**: Klimchouk, A.B., Ford, D.C., Palmer, A.N. & Dreybrodt, W., *Speleogenesis: Evolution of Karst Aquifers,* 175–183. Huntsville, Alabama, National Speleological Society.

FORD, D.C. & WILLIAMS, P. 1989. *Karst Geomorphology and Hydrology.* London, Unwin Hyman.

JENNINGS, J.N. 1985. *Karst Geomorphology.* Oxford, Blackwell.

LATHAM, A.G., HERRIES, A., QUINNEY, P., SINCLAIR, A.S. & KUYKENDALL, K. 1999. The Makapansgat australopithecine site from a speleological perspective. **In**: Pollard A.M. (ed.), *Geoarchaeology: Exploration, Environments, Resources,* 61–78. Geological Society Special Publication No. 165, Geological Society.

LATHAM, A.G.& HERRIES, A.I.R. 2004. The formation and sedimentary infilling of the Cave of Hearths and Historic Cave complex, Makapansgat, South Africa. *Geoarchaeology* **19**(4), 323–342.

MAGUIRE, J.M., PEMBERTON, D. & COLLETT, M.H. 1980. The Makapansgat Limeworks grey breccia: hominids, hyaenas, hystricids or hillwash? *Palaeontologia africana* **23**, 75–98.

MAGUIRE, J.M., SCHRENK, F., & STANISTREET, I.G. 1985. The lithostratigraphy of the Makapansgat Limeworks australopithecine site: some matters arising. *Annals of the Geological Survey of South Africa* **19**, 37–51.

McFADDEN, P.L., BROCK, A. & PARTRIDGE, T.C. 1979. Palaeomagnetism and the age of the Makapansgat hominid site. *Earth Planetary Science Letters* **44**, 373–382.

McFADDEN, P.L. & BROCK, A. 1984. Magnetostratigraphy at Makapansgat. *South African Journal of Science* **80**, 482–483.

PARTRIDGE, T.C. 1975. Stratigraphic, geomorphological and palaeoenvironmental studies of the Makapansgat Limeworks and Sterkfontein hominid sites: a progress report on research carried out between 1965 and 1975. Conference report on *Recent Progress in Later Cenozoic Studies in Southern Africa,* Cape Town, 17 pp.

PARTRIDGE, T.C. 1982. Dating of South African hominid sites. *South African Journal of Science* **78**, 300–302.

PARTRIDGE, T.C. 1979. Re-appraisal of the lithostratigraphy of the Makapansgat Limeworks hominid site. *Nature,* **279**, 484–488.

PARTRIDGE, T.C. 2000. Hominid-bearing cave and tufa deposits. Chapter 7, **In**: Partridge, T.C. & Maud, R.R. (eds), *The Cenozoic in Southern Africa.* Oxford Monographs on Geology and Geophysics No. 40. Oxford, Oxford University Press.

POCOCK, T.N. 1985. Plio-Pleistocene mammalian microfauna in southern Africa. *Annals of the Geological Survey of South Africa* **19**, 65–67.

POCOCK, T.N. 1987. Plio-Pleistocene fossil mammalian microfauna of southern Africa – a preliminary report including description of two new fossil muroid genera (Mammalia: Rodentia). *Palaeontologia africana* **26**, 69-91.

RAYNER, R.J., MOON, B.P. & MASTERS, J.C. 1993. The Makapansgat australopithecine environment. *Journal of Human Evolution* **24**, 219–231.

TURNER, B.R., 1980. Sedimentological characteristics of the 'Red Muds' at Makapansgat Limeworks. *Palaeontologia africana* **23**, 51–58.

WHITE, T.D., JOHANSON, D.C. & KIMBEL, W.H. 1981. *Australopithecus africanus*: its phyletic position reconsidered. *South African Journal of Science* **77**, 445–470.