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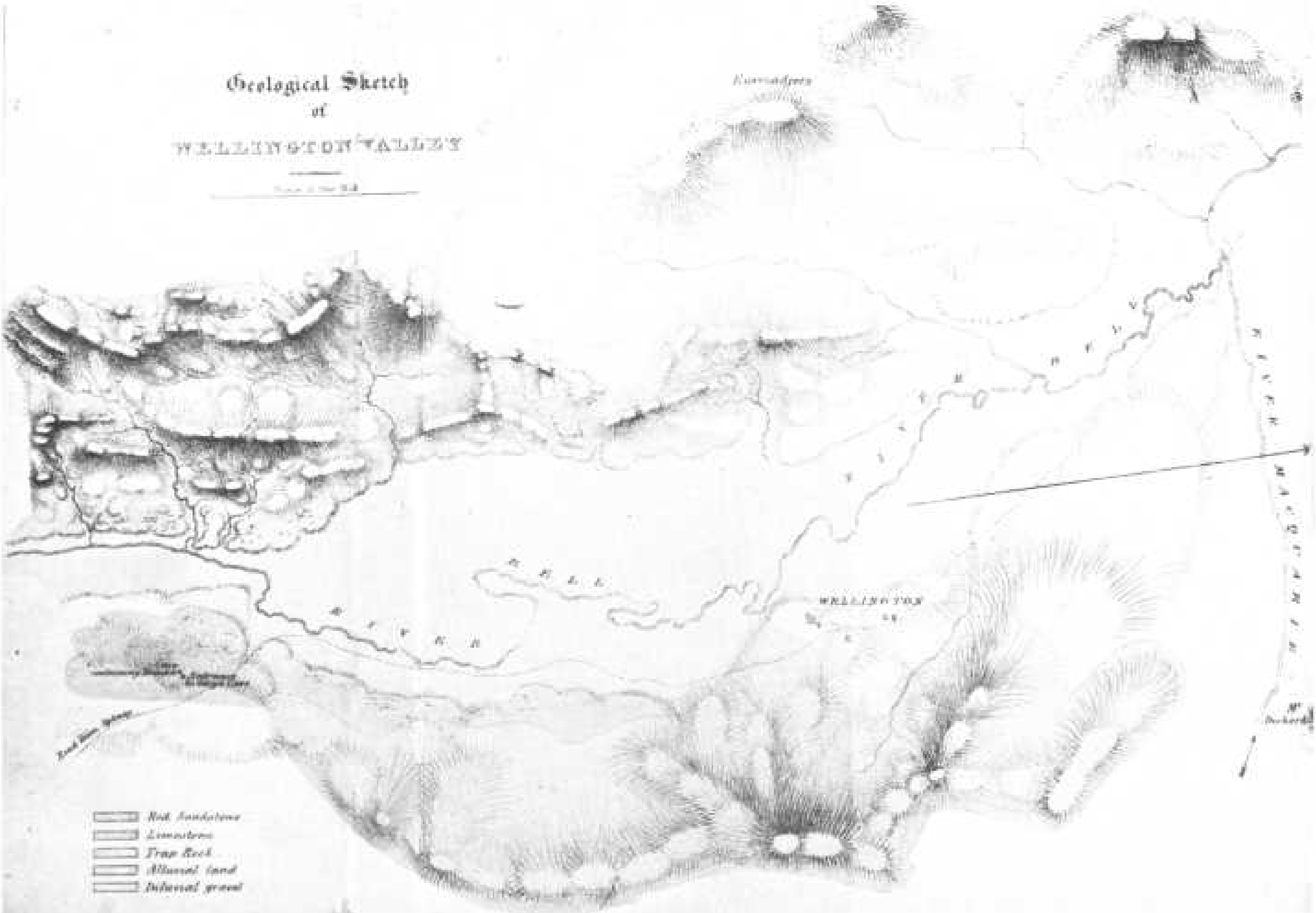
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



First map showing location of the Wellington Caves, N.S.W., published in 1838. See page 2.

"HELICTITE"

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COVER PICTURE

First published map ("Geological Sketch of Wellington Valley"), showing location of the Wellington Caves, New South Wales. The original plate was hand-coloured, the wash showing the rock types as shown bottom left of picture. The cave reference, the legend and the words "Road from Sydney" are difficult to read even on the original. The cave reference states (left) "Cave containing Breccias" and (right) "Entrance to large Cave". The map was published as Plate 42 in Volume 2 of Three Expeditions into the Interior of Eastern Australia, by Major T.L. Mitchell, T. and W. Boone, London, 1838. This plate was copied from the first edition. A second, revised edition of "Three Expeditions" was published in 1839. - E.A.L.

A B S T R A C T S

SEASONAL VARIATION OF POLYCHROMOPHILUS MELANIPHERUS (SPOROZOA : HAEMOPROTEIDAE) IN THE BENT-WINGED BAT MINIOPTERUS SCHREIBERSII (CHIROPTERA) IN NEW SOUTH WALES. By (The Late) Barbara B. Dew and B. McMillan. Parasitology, 61, 1970 : 161 - 166.

Gametocytes of a polychromophilid parasite infecting the bent-winged bat Miniopterus schreibersii in New South Wales are morphologically indistinguishable from those of Polychromophilus melanipherus infecting the same species in Europe and other countries. Blood from bats in several caves and mines in New South Wales was sampled, but with emphasis on the Bungonia-Wombeyan Caves population. In bats of this population there is marked seasonal variation in infection and density of parasitaemia. This variation is the reverse to that found in M. schreibersii in the northern hemisphere. The infection rate is lowest (0%) in April amongst juveniles in the nursery colony at Drum Cave, Bungonia, but highest (up to 82.7%) when bats congregate for mating and hibernation in Fig Tree Cave, Wombeyan. It is suggested that absence of gametocytes in juveniles is due to a prepatent period of over three months. Infection and density of infection rise to a peak after the bats congregate and it is at this time that vector-parasite contact would be optimal.

Nycteribiid flies are the likely vector of Polychromophilus, probable vector species in N.S.W. being Penicellidia oceanica and Nycteribia parilis.

M. schreibersii at Naracoorte Caves, South Australia, and Eptesicus pumilis from Rockhampton, Queensland, were also infected with Polychromophilus. Several other bat species in N.S.W. were negative when examined for the parasite. - G.S. Hunt.

THE CLASTIC SEDIMENTS OF THE WELLINGTON CAVES, NEW SOUTH WALES

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Introduction

The Wellington Caves are about 8 km south of the town of Wellington, New South Wales. They were discovered in the 1820s and their long and varied history as a vertebrate palaeontological site began about 1830. Most of the early fossil collections were made by the explorer and surveyor-general, Major T.L. Mitchell, from an upper stratigraphic unit exposed in Mitchell's Cave and Cathedral Cave. Such venerable palaeontologists as Cuvier, Pentland, Jameson and Owen examined the material. Phosphate mining operations in the early 1900s exposed additional sedimentary sequences and most of the later vertebrate collections have come from these mines. A history of the discovery and exploration of the caves, as well as of the more important palaeontological aspects, is given by Lane and Richards (1963).

A number of theories on the origin of the caves, and especially on the depositional environment of the bone-bearing sediments, has been offered and some of these are summarised by Lane and Richards (1963). Most of these were conceived before 1900, none of them are detailed and they are generally speculations presented as minor portions of other articles dealing with a broader subject.

General Geology

Steeply dipping, meridionally folded Silurian and Devonian rocks and flat-lying Tertiary sediments are exposed in the vicinity of the Wellington Caves (Basnett and Colditz, 1946). The Silurian rocks consist of shale, limestone and slate, and volcanics composed of interbedded lavas and pyroclastics with small limestone lenses. The lavas are mostly andesites and the pyroclastics include tuffs, breccias and agglomerates. The Devonian rocks are limestones, shales, sandstones and conglomerates. The Tertiary outcrops are small and consist of basalts and river gravels. Some of the gravels are overlain by the basalts and others occur as lag deposits as on the limestone hill above the caves. In addition, Quaternary alluvium is abundant along the stream courses and forms prominent terraces in places.

The Limestone

The Wellington Caves are formed in the Devonian Garra Formation, a massive bedded pelletal, oolitic and algal calcarenite (Strusz, 1965). In addition to the predominant massive beds there are occasional thin beds which in some places have been highly folded. The general strike is north-south and the dip ranges from about 45^{o} to 80^{o} to the east or west.

Three partial chemical analyses given by Carne and Jones (1919) list $CaCO_3$ ranging from 90.71 to 99.00%, $MgCO_3$ from 0.57 to 0.97%, $MnCO_3$ from trace to 0.01%, Fe_2O_3 and Al_2O_3 from 0.12 to 1.25% and gangue from 0.15 to 6.90%. Examination of the insoluble residues of the limestone show that quartz is by far the most abundant skeletal grain. The quartz grains are single crystals with straight extinction, subangular to subround, contain few to moderate numbers of vacuoles and more than half are euhedral. Other skeletal grains include microcrystalline chert and dolomite. The clays include 2M illite and well-ordered kaolinite plus a small amount of chlorite.

Physiography

The climate in the Wellington area is semiarid with a mean annual temperature of 17^{o}C and with a seasonal range of about 15.5^{o}C. Average annual precipitation is about 630 mm with a slight winter maximum. Potential evaporation is approximately 1625 mm annually but during the winter months is only about equal to precipitation. The area falls within the category DA' (semiarid megathermal) according to the classification of Thornthwaite and Hare (1955).

The caves are in an area of moderate relief with an altitude ranging from 300 to 450 m. Relief on the limestone is considerably less than on the adjacent Palaeozoic sandstones and volcanics. It is generally about 50 m, whereas the sandstones of the Catombal Range, immediately west of the limestone outcrop, rise 150 m above the valley floor. The limestone extends along the river for about 9.5 km and is about 2.5 km wide, but much of it has been drowned in alluvium so that only isolated patches are exposed ranging from a few square metres to a few square kilometres.

The caves occur in the north end of one of the larger of these outcrops, a 40 to 50 m high hill that extends for about 3 km to the south and is about 1.5 km wide. At the southern end, the limestone is in contact with Silurian volcanics. Alluvial terraces of the Bell River delimit it to the west and north. On the east side an alluvial filled corridor parallels the Bell River for 5 km with the limestone hill forming an interfluve between. The corridor is about 30 m higher than the Bell River and connects with the river valley at both ends of a straight stretch of the river. A tributary of the Bell, Catombal Creek, joins the river at a sharp right hand bend at the downstream end of the straight stretch and forms a straight southerly extension of the main river valley. Patches of quartz and sandstone lag gravel occur on the high parts of the limestone hill at about 50 m above the level of the Bell River and are within 700 m of the most southerly cave entrance, Gaden Coral Cave. These lag gravel deposits are part of Colditz' (1943) Pliocene erosion level.

Collectively, the evidence suggests that the Bell River has been captured by its tributary, Catombal Creek, sometime during the Late Pliocene or Early Pleistocene and the following sequence of events seems the most probable.

During the Late Pliocene (according to Colditz) the Bell River was flowing on the limestone within about 700 m of the caves area and at least 9 m higher than a level now occupied by the highest cave entrance. It then shifted about 1 km to the east to flow through the area now occupied by the alluvial filled corridor. At this time it had a parallel tributary, the ancestor of Catombal Creek, which flowed on the west side of the caves area and joined it a short distance north of the caves area. The hill in which the caves now occur was part of the interfluve between the Bell and Catombal Creek. The creek, or one of its tributaries, then captured the Bell River about 5 km south of the caves area and the Bell River now occupies this old valley of the ancestral Catombal Creek. Matheson (1951) and Colditz (1943) have also suggested on separate evidence that the Bell River at its junction with the Macquarie a few kilometres north has migrated in a westerly direction.

Downes and Sleeman (1955) have mapped the soils in the vicinity of the Wellington Caves as red loams which include terra rossa and red solodics. The soil developed on the limestone at the caves is a red-brown earth according to the classification of Stephens (1962). It is chiefly sedentary with a shallow, brown A horizon and a B horizon containing calcite nodules. The texture varies from a slightly pebbly, fine sandy mud near the top, to a slightly granular, fine sandy mud near the bottom*. The thickness varies from a few centimetres to about 1.5 m. Median grain size is $< 2\mu$ and extreme range is from $< 2\mu$ to about 6 cm. Sorting is moderate to poor with an increasing degree of bimodality towards the top due to increasing amounts of calcite nodules in the upper part of the B horizon. Kaolinite, illite and montmorillonite make up about 60% of the soil. Detrital calcite and quartz make up most of the remainder. The quartz is mostly single crystals with straight extinction. Calcite nodules and microcrystalline chert also are present.

In addition, a terra rossa, probably colluvial, is exposed by erosion gullies a few hundred metres northwest of the caves. The total exposure is about 3 m. No bedrock is exposed. The soil consists of a thin, red-brown A horizon and a dark red B horizon which becomes more clayey and blocky with depth. The texture is a clay with just enough silt in the top part for it to be classified as a mud. Median grain size is $< 2\mu$ and the extreme range is from $< 2\mu$ to about 4 cm. Sorting is moderate and unimodal. Kaolinite and illite make up about 60% of the soil in the A horizon and 80 to 90% in the B horizon. Quartz and microcrystalline chert make up almost all of the

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* Terminology for textural classes of soils, detrital sediments and precipitates is from Folk (1961).

skeletal grains. The quartz is mostly single crystals with straight extinction. Traces of orthoclase, microcline, plagioclase, hematite and tourmaline are also present.

THE CAVES

The Wellington Caves (Figure 1) are concentrated in an area of less than 50,000 m^2 on the northern brow of the limestone hill. There are at least five natural caves plus about 400 m of mine tunnel through cave fill. In addition there are several mined vertical shafts from 1 to 15 m deep that have been excavated in fill and limestone and there are numerous shallow grikes and a few small solution pits.

Gaden Coral Cave

The Gaden Coral Cave (Figure 2) consists of an inclined fissure about 60 m long, 22 m deep and sloping to the west at an angle of about 45°. In general the hanging wall is bedrock, covered with speleothems in places, and the foot-wall is breakdown or externally derived sediments. It is broken up into passages and rooms because the fill of the foot-wall reaches the hanging wall in places. This has been emphasised by some rearrangement of the fill during commercialisation.

The entrances have been excavated entirely in fill. At the bottom of the main entrance steps the cave opens out into a natural cavity and the passage leads off to the left and to the right. The left passage goes down over breakdown and soil-derived material for about 25 m where it ends in a breakdown wall. Flowstone caps the breakdown and soil-derived material in most places and stalactites, stalagmites, coral and other speleothems are abundant.

The passage to the right from the bottom of the main entrance steps leads down over the same kind of fill, though with noticeably fewer speleothems, until it reaches the bottom of the slope at X-section GC-2. The floor then levels off in the direction of X-section GC-3 and is composed of finer material with no breakdown. The walls and ceiling in this part have an abundance of speleothems, mostly coral. The limestone of the hanging wall, or ceiling, along this entire passage is generally smooth and the erosional forms have large radii of curvature. There are three small domes with vertical long axes that extend into the ceiling for about 1 to 2 m. The one at X-section GC-1 is corkscrew shaped.

A partially excavated tunnel leads off from near the beginning of the flat floor of the right passage. Most of the passage into which it leads has been partially or entirely excavated, or the fill has been rearranged, so that it is difficult to determine what the natural cavities were like. At the lowest part of the passage, near X-section GC-7, a pit containing CO_2 drops about 2.5 m to an unexplored, horizontal, natural passage.

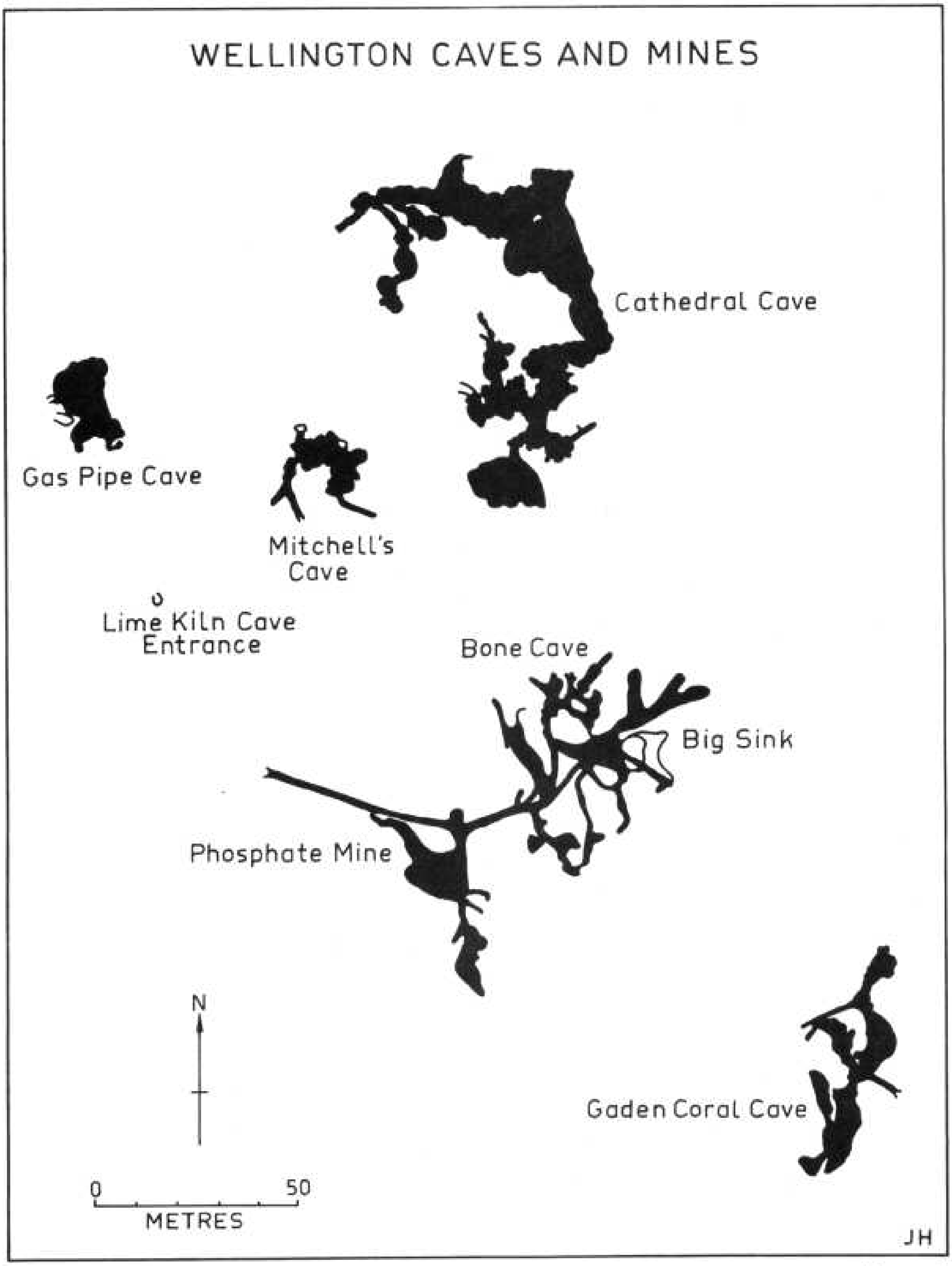

WELLINGTON CAVES AND MINES
Cathedral Cave
Gas Pipe Cave
Mitchell's Cave
Lime Kiln Cave Entrance
Bone Cave
Big Sink
Phosphate Mine
N
Gaden Coral Cave
0
50
METRES
JH

Figure 1

Cathedral Cave

Cathedral Cave (Figure 3) is the largest of the accessible natural caves. In contrast to Gaden Coral Cave, the walls and ceilings are virtually devoid of speleothems. Most of the floor is covered with soil-derived red earth, though breakdown is prominent near the entrances. Pits dug in the big room near X-section C-4 by Ramsay (1882) show that the fill is from 3 to 10.5 m deep and becomes gradually deeper towards the far end. The cave has not suffered a great deal of historic excavation as the others have, but commercialisation and 140 years of visitation have altered the floor deposits such that they bear little resemblance to the earlier descriptions given by Mitchell and others. The walls and ceiling are domed and cuspate so that concavities are smooth with large radii of curvature and convexities are sharp with small radii of curvature (Plate 1).

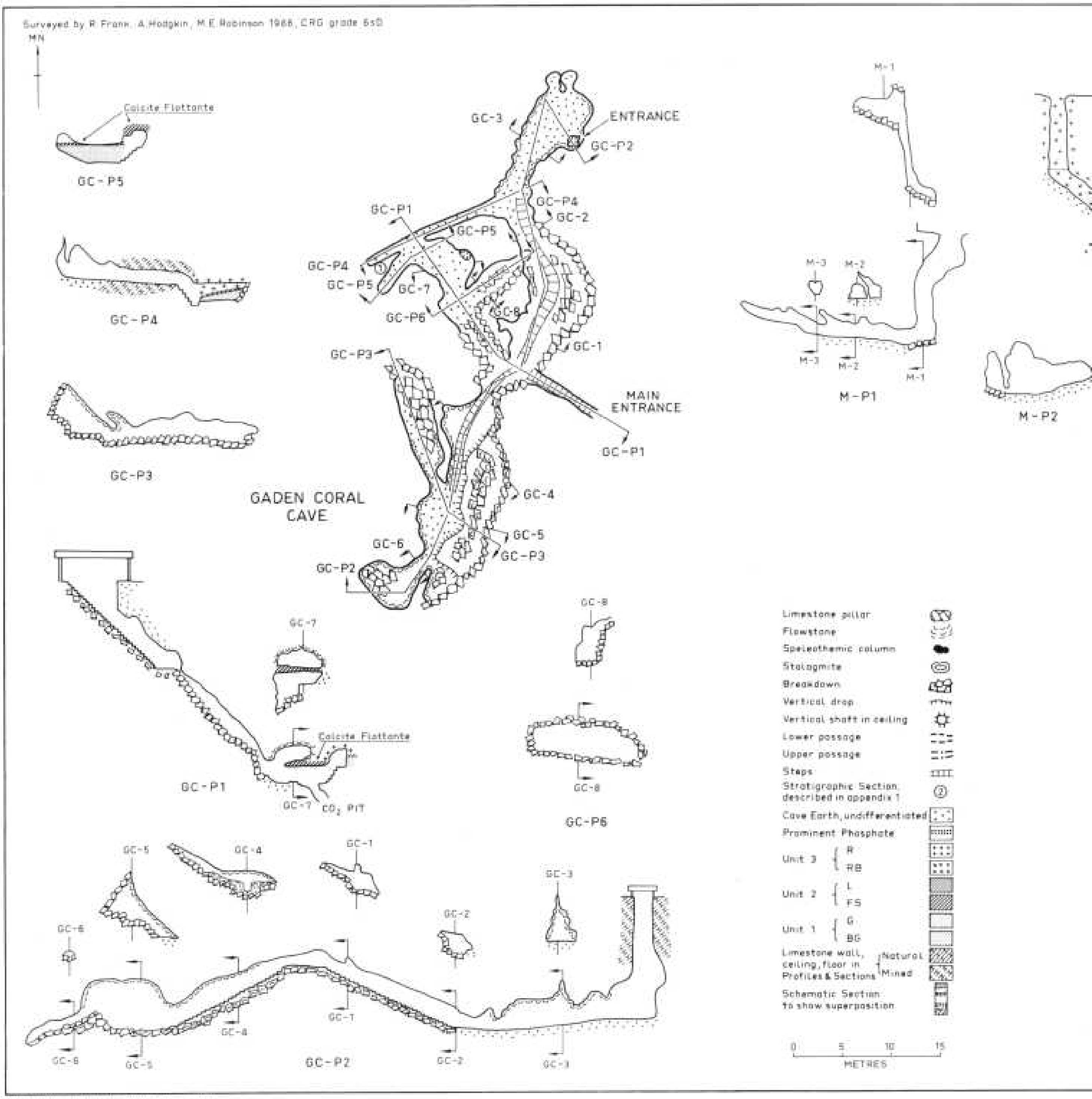
The main entrance is a small collapse doline that has been slightly enlarged. It opens into the cave at the top of a breakdown slope which descends about 12 m. About half-way down the breakdown slope an 18 m long passage leads off to the left. Its floor is relatively flat and consists of wombat-disturbed, red, soil-derived sediment. At the bottom of the breakdown slope the main passage leads off to the left. A small room, more or less in line with the maximum slope of the breakdown, continues for about 10 m and terminates in a sediment-choked bedding plane (?) passage along profile C-P2. To the right from the bottom of the breakdown slope a low speleothem-crowded passage leads to another steep breakdown cone which eventually opens to the surface. This opening has probably been excavated.

The floor of the main passage slopes down gradually for about 5 m until the passage makes a sharp left turn and opens into a big room. This room is about 45 m long, 20 m wide and 14 m high. A large stalagmite reaches to the ceiling at the far end. Behind this stalagmite, fault breccia forms part of the wall and ceiling.

Beyond the large stalagmite the floor of the main passage drops 3 m and the main passage continues for another 30 m where it branches into three passages. Access to the first one on the left is by a steeply inclined flowstone slope which leads up into a partly flowstone decorated room with a small amount of guano on the floor. The second passage to the left is a low crawl for most of its 32 m length. Red, soil-derived mud covers the floor for the first 20 m and from there to the end the floor is mostly flowstone. The third passage is a 12 m long enlarged bedding plane (?) with a 6 m deep pit at the near end. This pit contains water most of the time and only dries up in severe droughts. It is the lowest point in the cave.

Mitchell's Cave

Mitchell's Cave (Figure 2) contains few speleothems. Most of its floor


Surveyed by R. Frank, A. Hodgkin, M.E. Robinson 1988, CRG grade 6sD
MN
Calcite Flottante
GC-P5
GC-P4
GC-P3
GADEN CORAL CAVE
ENTRANCE
MAIN ENTRANCE
GC-P1
GC-P2
GC-P6
CO2 PIT
M-P1
M-P2
Limestone pillar
Flowstone
Speleothemic column
Stalagmite
Breakdown
Vertical drop
Vertical shaft in ceiling
Lower passage
Upper passage
Steps
Stratigraphic Section, described in appendix 1
Cave Earth, undifferentiated
Prominent Phosphate
Unit 3 R RB
Unit 2 L FS
Unit 1 G BG
Limestone wall, ceiling, floor in Profiles & Sections Natural Mined
Schematic Section to show superposition
0 5 10 15
METRES

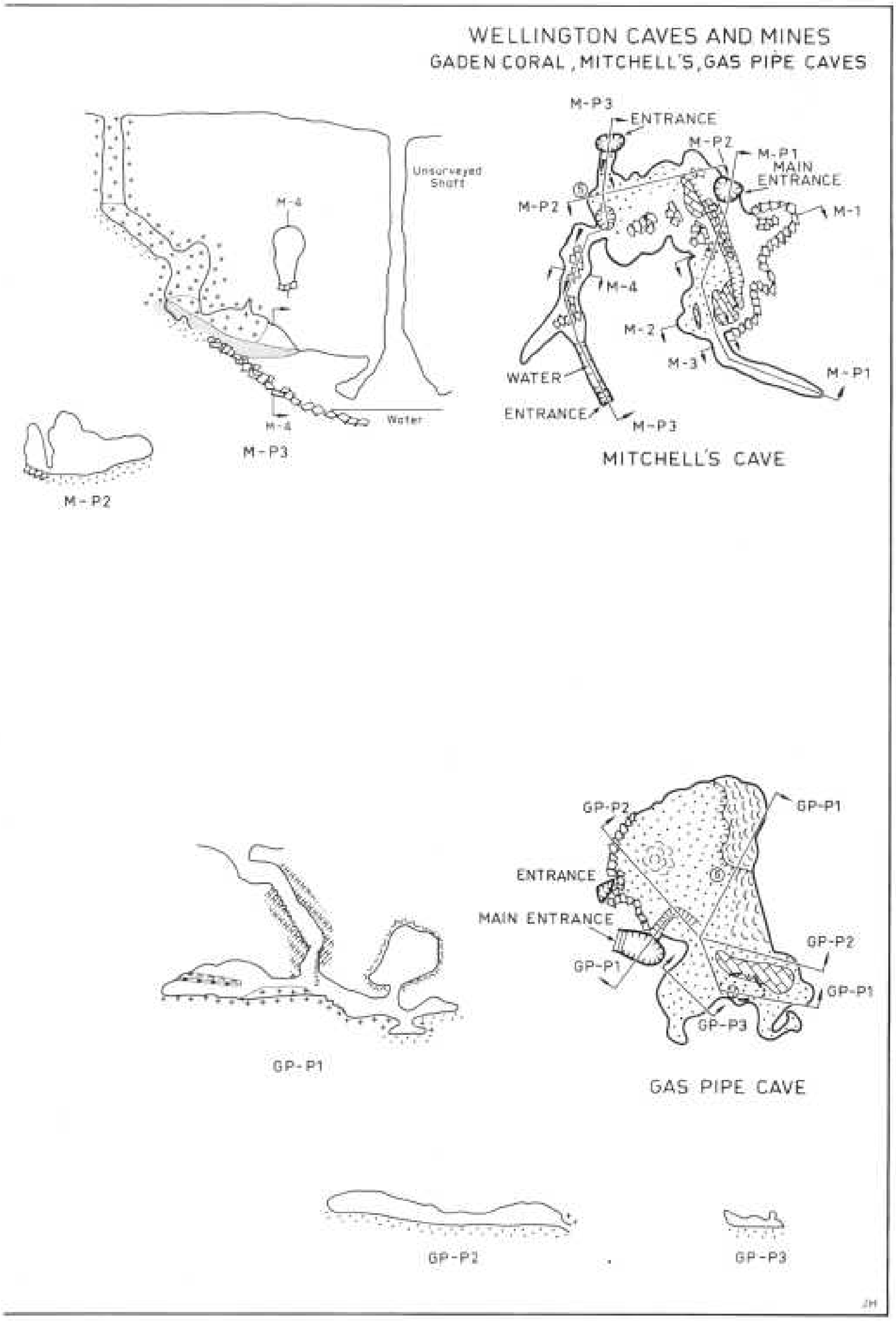
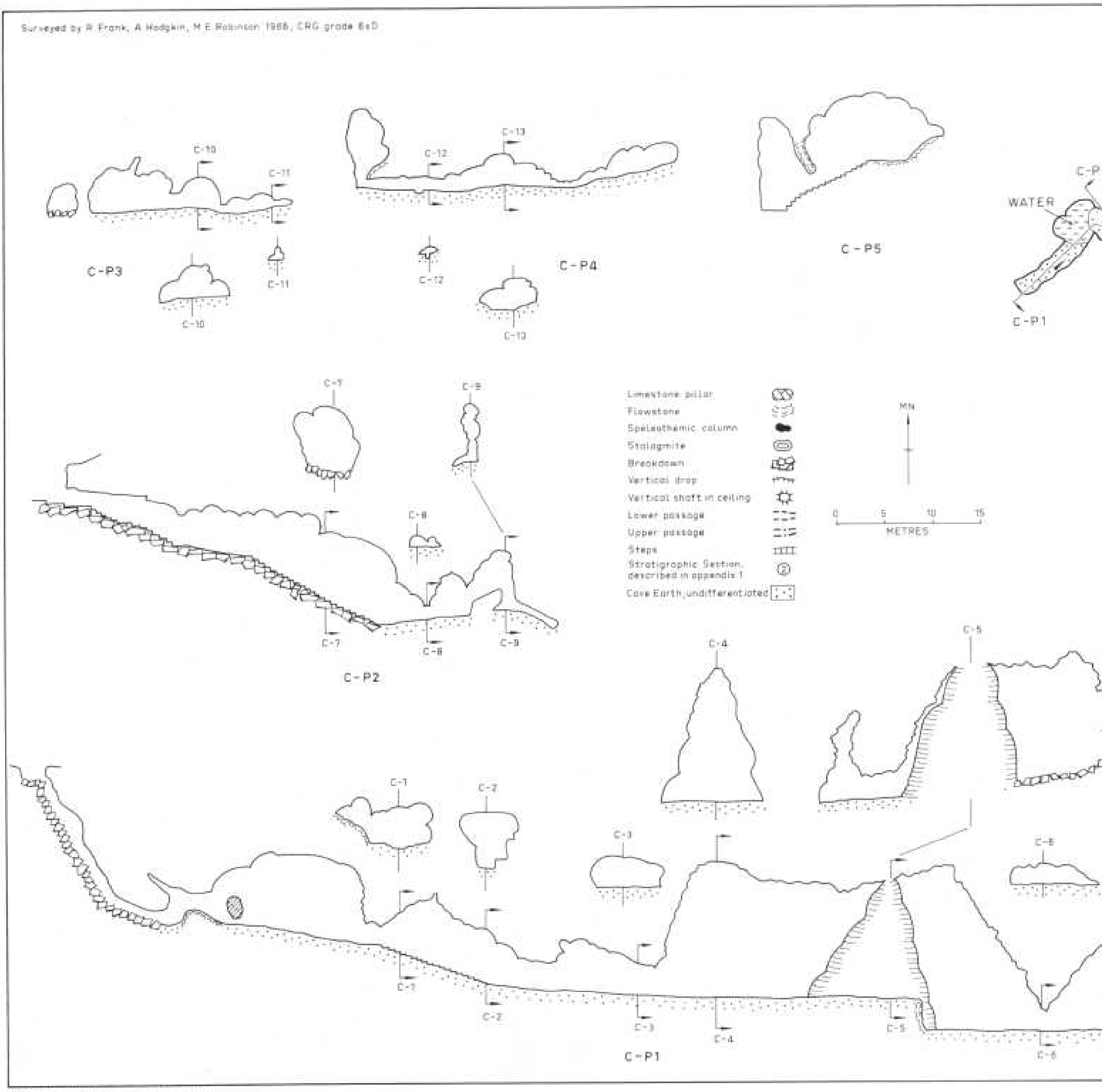

WELLINGTON CAVES AND MINES
GADEN CORAL, MITCHELL'S, GAS PIPE CAVES
M-4
Unsurveyed Shaft
Water
M-4
M-P3
M-P2
M-P3
ENTRANCE
M-P2
M-P1
MAIN ENTRANCE
M-P2
M-1
M-4
M-2
M-3
WATER
ENTRANCE
M-P3
M-P1
MITCHELL'S CAVE
GP-P2
GP-P1
ENTRANCE
MAIN ENTRANCE
GP-P1
GP-P2
GP-P1
GP-P3
GAS PIPE CAVE
GP-P1
GP-P2
GP-P3
JH

Figure 2



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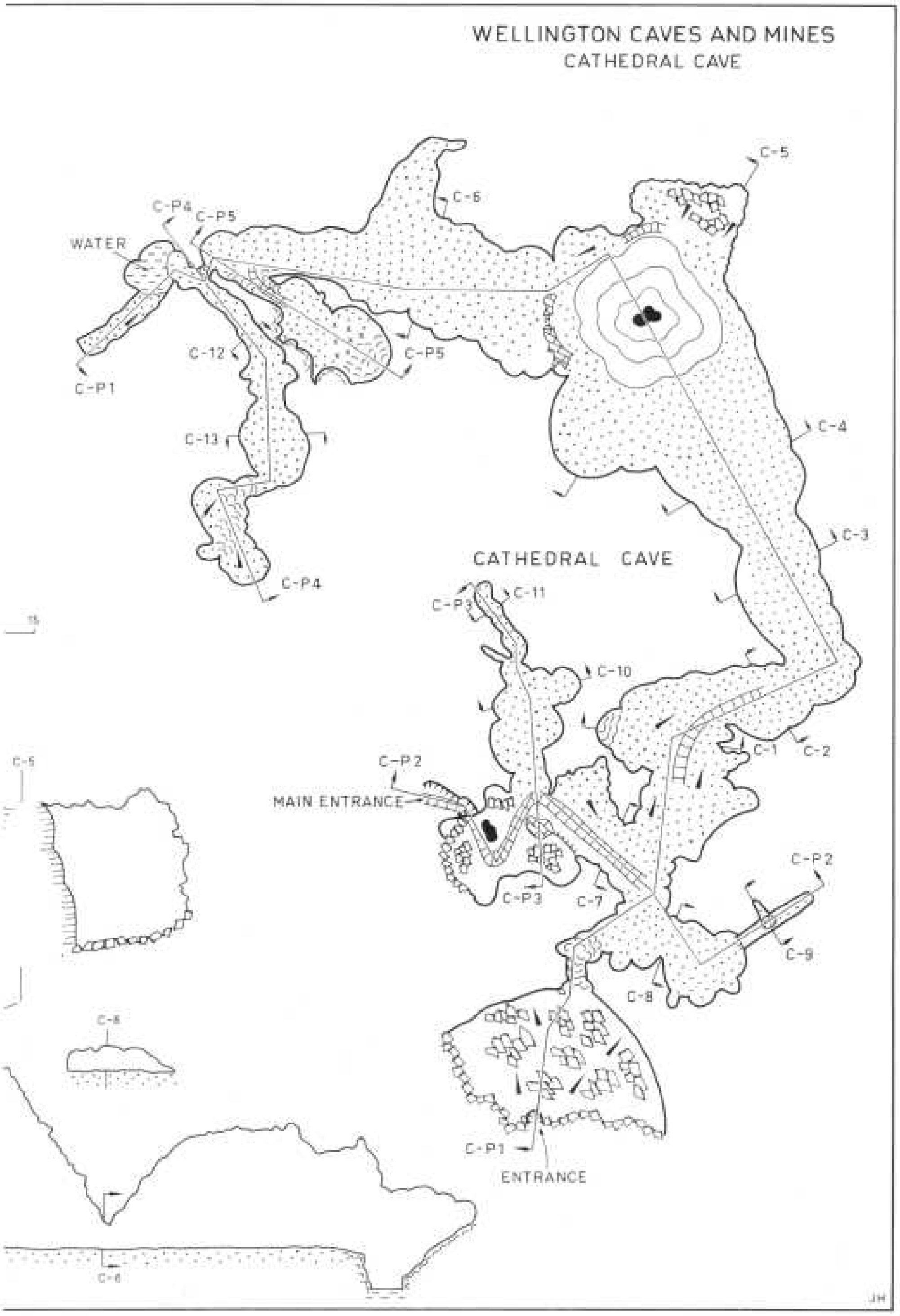
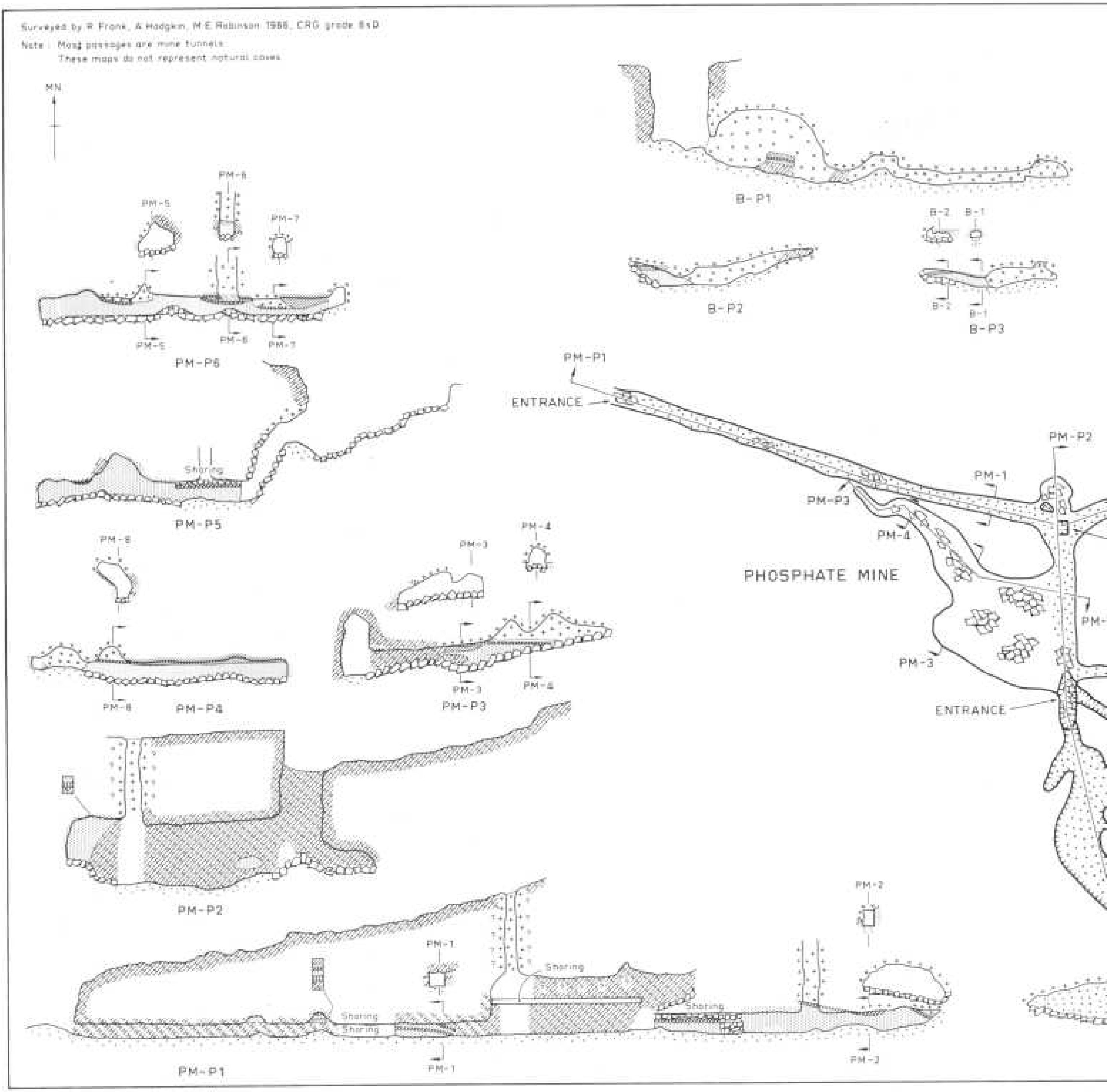

WELLINGTON CAVES AND MINES
CATHEDRAL CAVE
C-5
C-6
C-P4
C-P5
WATER
C-12
C-P5
C-P1
C-13
C-4
C-3
CATHEDRAL CAVE
C-P4
C-P3
C-11
C-10
C-1
C-2
C-5
C-P2
MAIN ENTRANCE
C-P3
C-7
C-P2
C-9
C-8
C-6
C-P1
ENTRANCE
C-6
JH

Figure 3



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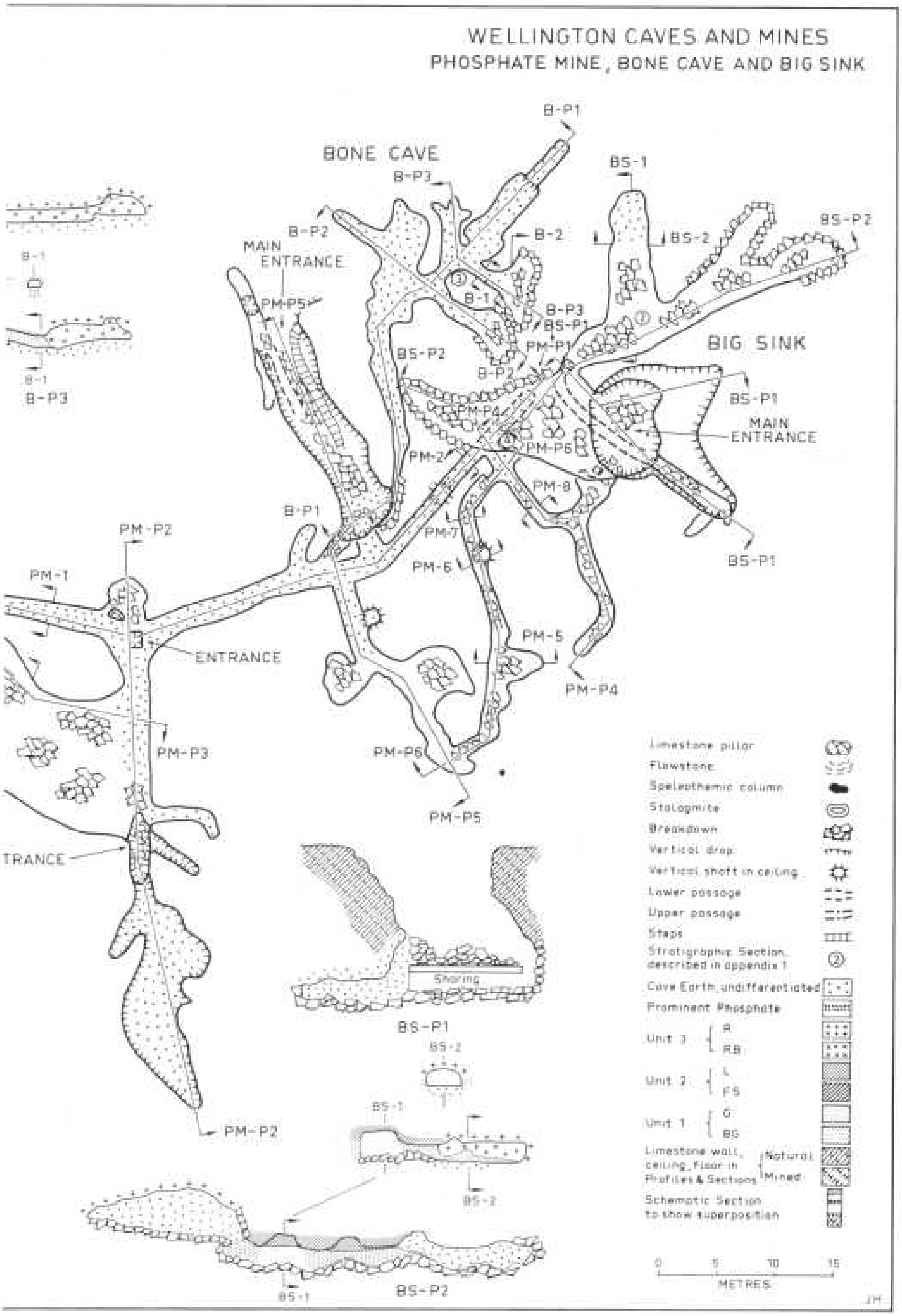
WELLINGTON CAVES AND MINES
PHOSPHATE MINE, BONE CAVE AND BIG SINK
BONE CAVE
BIG SINK
MAIN ENTRANCE
ENTRANCE
TRANCE
B-P1
B-P2
B-P3
B-1
B-2
BS-1
BS-2
BS-P1
BS-P2
PM-P1
PM-P2
PM-P3
PM-P4
PM-P5
PM-P6
PM-1
PM-2
PM-5
PM-6
PM-7
PM-8
Shoring
Limestone pillar
Flowstone
Speleothemic column
Stalagmite
Breakdown
Vertical drop
Vertical shaft in ceiling
Lower passage
Upper passage
Steps
Stratigraphic Section, described in appendix 1
Cave Earth, undifferentiated
Prominent Phosphate
Unit 3 R RB
Unit 2 L FS
Unit 1 G BG
Limestone wall, ceiling, floor in Profiles & Sections Natural Mined
Schematic Section to show superposition
0 5 10 15
METRES
JH

Figure 4

is covered with breakdown and the erosional features on the walls and ceiling are like those in Cathedral Cave and Gaden Coral Cave. The main entrance is a 5 m deep vertical shaft which leads to a narrow elongate vertical fissure that drops another 6.5 m to the main level. Sparsely scattered anastomosis tubes occur on the walls of this fissure. From near the bottom of this fissure a 10 m long tube, formed in bedrock, angles upward at about 20^{o} and ends in bedrock. The main part of the cave extends west into the largest single room which is floored partly with breakdown and partly with red, bone-bearing, soil-derived sediment. Near the rear of this room a steep slope leads upward to the bottom of an excavated shaft which opens to the surface. The walls are composed of the same soil-derived material. A partially excavated 3.5 m deep pit, also near the rear of the room, drops to the top of a steeply inclined breakdown slope which leads down to a passage containing a nearly perennial pond. A few metres farther the water passage ends and a partially excavated shaft in the ceiling leads to the surface.

Gas Pipe Cave

Gas Pipe Cave (Figure 2) is a single small room about 18 m long, 9 m wide and 1 to 3 m high. Erosional features on the walls and ceiling are similar in form to those in the other caves. The floor is mostly red, bone-bearing, soil-derived sediment though two large patches of flowstone occur as a cap. In addition, there is an old flowstone floor attached to the northeast wall and suspended about 1.5 m above the present floor. It has some of the soil-derived sediment adhering to its underside. The two entrances are partially excavated, nearly vertical shafts which drop 12.5 m into the west side of the room. The cave has been reported to have a high CO_2 content (Fraser, 1958).

THE MINES

There are three unconnected mines which are here designated the Bone Cave, the Big Sink and the Phosphate Mine (Figure 4). Most of the tunnels have been excavated through sediment, though in a few places the walls or ceilings are composed of bedrock limestone that either has been blasted or represents a natural cave wall. There are also a few natural cavities that have been broken into by the mining activities. The patches of natural cave and ceiling have an overall appearance similar to those in the other caves but in detail they are angular with sharp relief. They appear to have been partially dissolved after the introduction of the fill.

Bone Cave

The wide fissure entrance does not appear to have had much alteration. The first 15 m of the cave also appears to be natural cavity, with only slight enlargement, and four small patches of natural limestone cave wall are exposed in this section and nearby (profiles B-P1 and B-P2). The remainder of the cave has suffered extensive excavation, however, and probably owes most of its extent to phosphate mining and bone collecting activities.

Big Sink

The Big Sink shows no signs of natural cave with the possible exception of its entrance - a large collapse doline. Mitchell did not mention it, which, considering its size, seems surprising if it were present in his day and there are local reports of the doline entrance being developed after mining activities had ceased.

Phosphate Mine

Most of the tunnels of the Phosphate Mine are the result of phosphate mining. Parts of natural cavities and natural bedrock cave walls are present in the room through which PM-P3 profile runs, in the largest of the two rooms along profile PM-P6, in the room at X-section PM-5 and along profile PM-P2. At the south end of profile PM-P2 a large, natural, solution doline leads down to the main level of the mine.

OTHER CAVES

Lime Kiln Cave is between the Gas Pipe Cave and the Phosphate Mine. It has not been surveyed. It is a 20 m deep, nearly vertical shaft with a small, semi-permanent pool at the bottom. Only a small amount of bedrock is exposed in the cave, near the entrance and at the bottom. Most of the walls, ceilings and floors are composed of large blocks of limestone breakdown and small patches of soil-derived sediment containing some bone.

About 100 m northeast of the Cathedral Cave there is a small, partly de-roofed cave whose bedrock walls drop 3 to 5 m to a soil floor.

At least one other cave, Water Cave, has been sealed. According to Mitchell its entrance was about 100 m west of Gas Pipe Cave.

THE SEDIMENT

The sediments are best exposed in the mines, but all of the caves contain sediment and there are some lithologic similarities in the sediments in different caves. The sediments have been divided into three basic stratigraphic units with further subdivisions.

In addition to underground sediments there is a good deal of cave fill spread over the surface of the ground. Some of this is obviously due to mining activities. However, Mitchell (1839) and other early explorers record bone breccia as occurring on the surface so at least some of it must have resulted from natural processes.

Unit 1

Unit 1 (G, BG) (Plates 2, 3) is the basal unit and is exposed in Gaden Coral Cave, Mitchell's Cave and the mines. It is a red-brown to grey, calcite cemented, gravelly and sandy mudstone to claystone. The textural type varies with the amount, size and degree of preservation of clay aggregates. Bedding is either completely absent (G) or defined by concentrations of cementation into beds ranging from a few centimetres to a few decimetres (BG). Where it is present it is essentially horizontal and may contain interbeds of fairly pure flowstone up to about 40 cm thick. The maximum thickness of the entire unit is about 4.5 m. The bottom of the unit is not usually exposed but it is in contact with limestone cave wall in a few places. The top is usually dipping at angles from about 10^{o} to 30^{o}. It is generally overlain by unit 2, but in some places it is in contact with unit 3.

Median grain size, excluding bone fragments, is generally $< 2\mu$. Extreme range, excluding bone fragments, is from $< 2\mu$ to about 3 cm. Upper range of bone fragments is about 6 cm. Sorting is moderate to very poor and may be unimodal or bimodal depending on the numbers of clay aggregates present in any one place.

Clay aggregates are the dominant detritals making up as much as 90% of the total in places, though they may be less than 5%. They are well-rounded and their composition is similar to that of the matrix. There is generally no internal parallel orientation of the clay but some have a concentric orientation of the clay a few microns thick near the outer edge. The proportions of disseminated clay complement the proportions of clay aggregates.

Within the clay fraction well-ordered kaolinite is dominant but illite and montmorillonite also occur. Quartz and microcrystalline chert are ubiquitous. The quartz is angular to well-rounded and mostly single crystals with undulose extinction. The chert is generally subround to round. Small amounts of felspars in varying degrees of alteration are also present. Bone fragments are rare and invariably of small animals. In situ roots and rootlets are present and, in places where they are abundant, the sediment appears mottled.

Cement varies between 20 and 70% and is mostly calcite but phosphate is also present. The calcite is patchily distributed and contains small amounts of included clay which has been partly displaced in some places. The crystals are subequant to elongate, medium to extremely coarsely crystalline. Lustre mottling occurs in the parts where the crystals are largest. The phosphate has been identified by X-ray diffraction as hydroxylapatite. It occurs as cavity fillings and may be banded and botryoidal.

Unit 2

Unit 2 (Plates 3, 4) is the intermediate unit and it is composed of flowstone (FS) or a laminated sediment (L) with varying texture. The flowstone is usually fairly pure calcite with subparallel banding due to clay inclusions. The crystals are subequant (in less pure material) to elongate (more pure) and range from medium crystalline to extremely coarsely crystalline. Where inclusions occur they are usually of unit 1 material though red clay lumps and bone are also included. In some places the calcite may grade vertically into banded or botryoidal phosphate. The thickness of this subunit varies from a few centimetres to a few decimetres.

The laminated sediment has a texture varying from almost pure clay to granular mudstone. Laminae vary from <1 mm to about 2 cm and are always horizontal. They result from graded bedding. Desiccation cracks are common in the finer material. The total thickness of this subunit ranges from a few centimetres to 1 m.

Median grain size, excluding bone fragments, is generally $<2\mu$. Extreme range, excluding bone fragments, is from $<2\mu$ to about 4 mm. Upper range of bone fragments is about 3 cm. Sorting is poor to moderate and unimodal.

Clay is by far the dominant detrital with well-ordered kaolinite being proportionately more abundant than illite and montmorillonite. Angular to round, single crystal, straight to undulose extinction quartz is present in all samples. Minor amounts of small animal bone fragments, clay aggregates, microcrystalline chert and felspar are also found. In situ rootlets occur rarely. Small, 1 to 2 mm invertebrate burrows may also be present. Pyrolusite staining occurs on crack faces and between laminae.

Cement is usually restricted to desiccation cracks and other diagenetic cavities though it may be more evenly distributed where the grain size is fairly large. It ranges from 0 to 70% and is mostly calcite though collophane may make up as much as 50% of the total. The calcite is usually coarsely to very coarsely crystalline with none to few inclusions of clay. The crystals are subequant to irregular. The collophane may be banded and botryoidal. The calcite has been partly replaced by the collophane in some places.

Unit 3

Unit 3 (R, RB) (Plates 3, 5) is a red, bone bearing unit. Its texture does not vary much and it is generally mud to slightly gravelly mud. Bedding is nearly always horizontal, though it may dip a few degrees, and is almost always discernible. It is mostly due to parallel orientation of the long bones but some alternations in grain size are present, especially in the parts with less bone. Maximum thickness of the unit is about 20 m. It has undergone a fair amount of large scale, post depositional structural alteration in the form of jointing and faulting. Some of the resulting cracks and joints have been filled with overlying unit 3 material or with younger sediments.

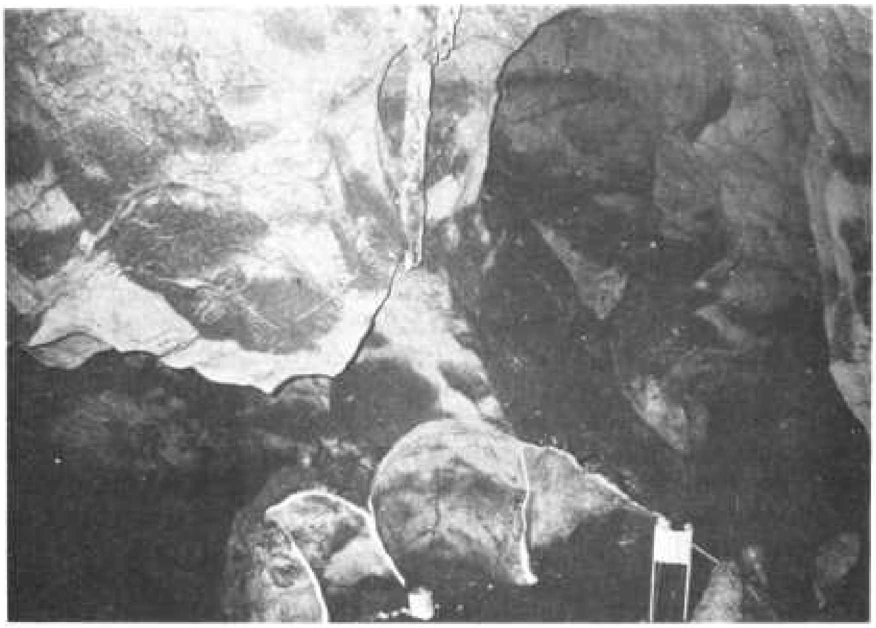

Plate 1 (above)
Bedrock morphology on walls and ceiling in Cathedral Cave, Wellington.

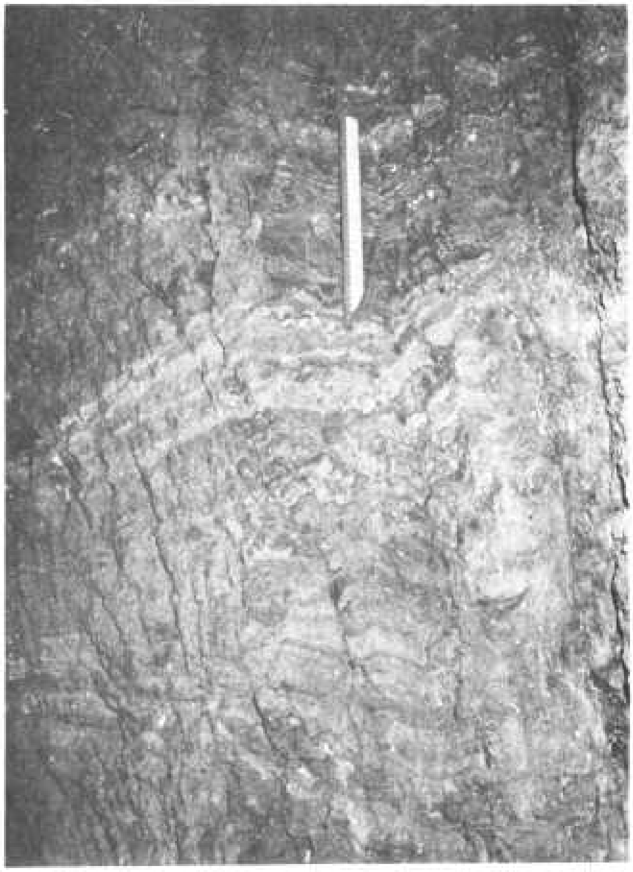

Plate 2 (right)
Unit 1 (BG), Phosphate Mine, Wellington. Flat-lying bedding appears to dip because of curvature of wall. Scale is 30 cm long.

Median grain size, excluding bone fragments, is $< 2\mu$. Extreme range, excluding bone fragments, is from $< 2\mu$ to about 20 cm. Upper range of bone fragments is about 60 cm. Sorting is moderate to poor and generally unimodal.

Clay content is about 60% and does not vary much. Kaolinite is the dominant clay mineral with lesser amounts of illite and montmorillonite. Angular to round, single crystal, undulose extinction quartz makes up most of the remainder of the detritals. Lesser amounts of small and large animal bone fragments, microcrystalline chert, clay aggregates, felspars and pyroxenes are present. Bone content varies from 1% to about 20% and is concentrated in a 1 to 7 m thick bed (RB) near the bottom. Limestone cobbles, some with phosphate coatings, are sparsely distributed through the entire unit. In situ rootlets and roots up to 10 cm in diameter are almost always present and where they are abundant they may impart a mottled appearance to the sediment.

Cement content is low and does not usually exceed about 5%. It is mostly patchily distributed, subequant to elongate, finely to coarsely crystalline calcite with moderate to abundant clay inclusions. It may be concentrated inside bone cavities. Traces of collophane and organic stain are also present.

Younger Sediments

In the Bone Cave near X-section B-2 there is a small patch of red-brown, calcite cemented, clayey pebble conglomerate containing remains of rabbit (Lundelius, personal communication, 1965). The sediment is not solidly cemented but is composed of 6 to 10 cm cemented lumps with small amounts of clay filling the interstices. The median grain size is about 20 mm with an extreme range from $< 2\mu$ to about 8 cm. Sorting is bimodal. The chief detrital constituent is angular limestone rock fragments. The remainder is soil particles of 9/10 unoriented clay (kaolinite, montmorillonite and illite) and 1/10 quartz silt. There is also a trace of small animal bone fragments. The cement is patchily distributed and subequant, coarsely crystalline with none to moderate amounts of clay inclusions.

The sediment designated as unit 3 in the Gas Pipe Cave differs from other unit 3 sediment chiefly in that it contains up to 3% subangular limestone rock fragments and 2% detrital calcite nodules. The proportions of illite and kaolinite are also different, being more equal. This sediment probably accumulated during the later stages of deposition of unit 3 since it is the upper part of a depositional unit and there is no indication of the entrances having been sealed after initial formation.

ORIGIN OF THE CAVES

The cuspate and domed form of the bedrock walls and ceilings and the lack of morphological features usually associated with fast flowing water

Plate 3
Units 1 (BG), 2 (FS) and 3 (RB), Phosphate Mine, Wellington.
Scale is 30 cm long.

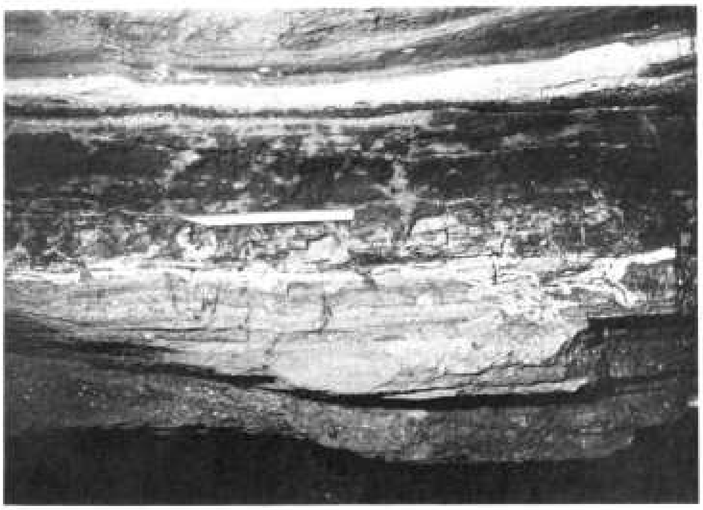

Plate 4
Unit 2 (L), Big Sink, Wellington.
Scale is 30 cm long.

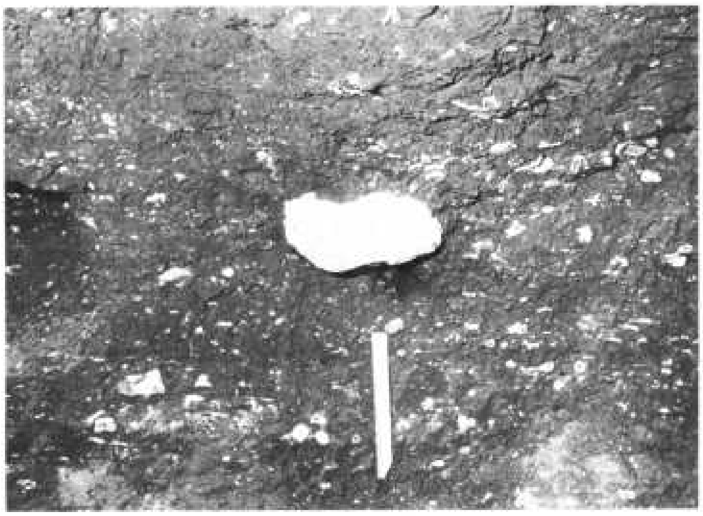

Plate 5
Unit 3 (RB), Bone Cave, Wellington.
Scale is 30 cm long .

indicate that the caves have formed in the saturated zone with no strong directional flow and have not been subjected to vadose development.

This peculiar morphology of the cave walls and ceilings (Plate 1) is similar to that discussed by Cramer (1933) who suggests that these features are formed by solution of eddy currents in the phreatic zone. He also states that eddying may be particularly effective when the cave is composed of a series of large rooms separated by constrictions as in the Cathedral Cave.

The time of origin of the caves cannot be closely defined but there is some indication that they predate the formation of the highest terrace of the Bell River and that they may have formed before the river reached its lowest level in the alluvial corridor to the east of the limestone hill. Small lakes in two of the caves (Cathedral and Mitchell's) and the water-level in a limestone well beneath the highest terrace, indicate that the groundwater level is approximately horizontal and from 1 to 2 m lower than the level of the Bell River. Assuming this situation prevailed in the past, the Bell River would have had to be some 35 m higher than at present in order that the caves be in the phreatic zone. This hypothetical level is about 29 m higher than the highest terrace and 5 m above the highest point of the alluvial corridor.

The apparent absence of stream deposits in the caves precludes entrance development before the Bell River had reached a level some 18 m above its present level (the level of the lowest cave entrance, Gas Pipe Cave). This is still about 12 m above the highest terrace so that the cave entrances could have been open before the formation of the latter terrace.

AGE OF THE DEPOSITS

Samples of bone from unit 3 (RB) in the Bone Cave were collected for ^{14}C dating. There is no organic matter in sufficient quantities for ^{14}C dating in any of the other subunits. Two samples were collected from the wall and ceiling near locality 3, one from near the bottom of the unit and one from near the top. In addition, a supplemental quantity of bone was picked up from the material lying loose on the floor in case there was not enough in either or both of the other samples. The sample from near the bottom of the unit produced a date of 30,610 + or - 2,110 years BP (Tx673). The sample from the loose floor material dated at 22,570 + or - 610 years BP (Tx672). No date was produced from the third sample.

Three samples of a 40 cm thick flowstone within unit 1 from near the north end of profile PM-P2 (Phosphate Mine) were ^{14}C dated by Dr. C.H. Hendy of the Institute of Nuclear Sciences, DSIR, Lower Hutt, New Zealand. The corrected ages (Hendy, 1969) of samples from the top, middle and bottom of the flowstone are 39,100 + or - 4,000 years BP (R2422/1), $>$34,700 years BP (2σ) (R2422/3) and $>$40,200 years BP (1σ) or $>$34,600 years BP (2σ) (R2422/4) respectively. Hendy (personal communication, 1969) states that the actual ages may be much older since as little as 0.2% contamination with "pre-bomb" carbonate in a sample of infinite age could give the calculated ages.

Mr. J. Mahoney, Department of Geology and Geophysics, University of Sydney, supplied fluorine analyses of bone material from various places in Bone Cave, Phosphate Mine, Big Sink, Mitchell's Cave and one surface pit, which had been done prior to this investigation of the caves. These analyses were done by the New South Wales Department of Mines, Geological Survey Branch. Of the 17 analyses, seven are of bone from unit 3, three of bone from unit 1 and seven of bone from sediments which could not definitely be assigned to either of these units. The range of values is high (0.08% to 4.18%), but the analyses from unit 1 generally show a higher value than those from unit 3. One of the analyses showed a value (4.18%) which is above the theoretical maximum for fluorapatite (3.8%) but this does not necessarily shed doubt on the accuracy of the analysis. Oakley (1953) points out that values higher than the theoretical maximum are possible and others (e.g., McConnell, 1938; Town and Sanker, 1968) have shown this to be true.

Unfortunately the large range in obviously contemporary samples (e.g., 0.62, 0.91 and 1.74%) make the analyses of little value except to show age relations which are already apparent from the stratigraphic evidence. Oakley (1963a) has stated that fluorine analyses from bone in limestone cave sediments is of little or no use for relative age determinations. He says that the fluorine content of bones in cave deposits is lower than would be expected and attributes this to prevention of the percolation of fluorides by calcite (1963b). The fluorine content of the samples from Wellington is not low, however, (the mean of the 17 analyses is 1.62%) and the three analyses of samples taken from the same subunit as the ^{14}C dated material and within a few metres and stratigraphically above it show values that are considerably in excess of "average" values given by Oakley (1963a) for Late Pleistocene bone. This fact coupled with the abundance of authigenic collophane in the sediments would seem to indicate that the analyses of the Wellington samples is not just of the fluoride that has replaced the hydroxyl ions in the bone mineral but also includes the fluorine contained in the authigenic secondarily precipitated collophane. It would be virtually impossible to separate the two chemically or physically. This would explain the anomalies and inversions that occur in the fluorine analyses.

HISTORY OF THE SEDIMENTS

Unit 1

The source material for unit 1 was surface soil. This is shown by the detrital assemblage, grain morphology and sorting characteristics. The detrital mineral assemblage contains little other than clays, quartz and chert. The clay minerals are poor provenance indicators because of their relative instability, but the clay types in the presentday surface soils and unit 1 are the same. The chert has the same characteristics as that in the presentday surface soils and the limestone. The quartz grains in all three are similar also except that there is a higher proportion of grains with undulose extinction in unit 1 than in the presentday surface soils or the limestone. This probably represents a downslope contribution of quartz from the Pliocene river sediments that must have been associated with the lag gravels occurring to the south of the caves.

The clay aggregates in unit 1 are most probably preserved soil particles. Their composition and component properties are the same as those of the matrix and they show no textural characteristics that could be attributed to inheritance from a more ordered depositional environment. The samples with the greatest amount of cement also have the largest percentage of clay particles and this, in fact, could be the means of preservation. Poor sorting, large range in roundness and traces of embedded grain argillans are additional evidence for a soil source for the material of unit 1.

The scarcity of primary bedding and the preservation of soil particles suggests that there has been little water involved in the deposition of unit 1. There is also no evidence of significant contributions of wind blown material. Gravity seems to have been the prime depositing agent, and the general texture of the sediment enhances this proposition. Occasionally, small amounts of rainwash may have aided gravity in depositing the material. The concentric orientation noted in the soil particles of one sample could be attributable to reworking by water (Haas, 1927; Nordin and Curtis, 1962). Detached clay balls have been attributed also to strong wind currents (Leitch, 1960). However, some of Brewer's (1964) glaebules exhibit a similar structure and so they could be inherited from the surface soil.

After deposition of unit 1 had ceased there was probably a small amount of erosion resulting from the first influxes of water that deposited the unit 2 material. The evidence is in the detrital and textural similarity between unit 1 material and the lower part of unit 2 (L) at localities 2 and 3. Alternatively, this could represent a continuation of unit 1 material being brought in from the surface and deposited by water rather than gravity.

Unit 2

The source material for the detritals in unit 2 was also surface soil but there was a larger contribution of insoluble residue from the limestone as evidenced by the increased proportion of quartz grains with straight extinction. The agent of deposition was water depositing part of its load as it flowed towards the lowest parts of the cave floors and eroding slightly on the way as evidenced by cut and fill structures in the lower part of unit 2 (L) at locality 2. The finer clays and silt slowly settled out of suspension after the water came to rest in pools as shown by the laminated parts of unit 2. The waters which were bringing in the detritals of unit 2 were also depositing calcite flowstone at the same time (unit 2 (FS)) and the lack of authigenic calcite in the overlying unit 3 indicates that some cementation of unit 1 may also have occurred at this time. The desiccation cracks and invertebrate burrows in unit 2 (L) show that the pools were not continuously replenished but occasionally dried up. In one of the pools, at locality 1, sufficient calcite flottante was produced to give a 30 cm thick deposit of this material. Gèze (1968) states that calcite flottante is produced when the water in a pool becomes supersaturated and Black (1953) suggests the same conditions for a similar aragonitic form in Carlsbad Caverns, New Mexico, U.S.A. Calcite flottante is currently being produced in the pools in Cathedral, Mitchell's and Lime Kiln Caves. Nine of the 13 water samples collected from these pools over a 1.5 year period showed supersaturation with respect to calcium according to Trombe (1952). This indicates that the pool at locality 1 was not continuously replenished with fresh water and that the source of its water may have been through the bedrock rather than through an open entrance. The absence of calcite flottante from other parts of unit 2 (L) suggests that most of the water supplying these pools did not contain high concentrations of $CaCO_3$ and may have entered through open or sediment clogged entrances.

Unit 3

As in unit 1, the detrital assemblage, grain morphology and sorting characteristics show that the material of unit 3 was also derived from surface soil. Similarly, gravity was the prime depositional agent but water may have made a slightly larger contribution than in unit 1 as evidenced by the smaller proportion of soil particles and the intercalations of clay separating beds in unit 3 (R).

After unit 3 was deposited it was cracked and faulted on a rather large scale. This can be seen in numerous places in the Big Sink, the Bone Cave and the Phosphate Mine. Some of these, especially the open ones, could well be the result of the early 20th Century mining activities. The large block with a vertical displacement of about a metre that forms the right wall near the entrance to the Bone Cave is probably an example of this. Most of these cracks and fissures are filled, however, either with unit 3 material or with the younger sediment containing rabbit bones.

There are several factors that may have contributed to the fracturing of unit 3 aside from the mining activities. Since the material of unit 3 consists mostly of clay, expansion and contraction due to alternate wetting and drying may have caused fracturing. This has probably not been a major factor, however, because of the high porosity of the material and the low proportion of expandable clays such as montmorillonite. Suffosion along the contact with the much less permeable unit 2 or along the unit 3-limestone interface may have carried away sufficient material to create undermining and consequent collapse. The deposition of authigenic phosphate along these contacts show that water did flow preferentially along these routes. Root wedging may also have contributed to some small-scale fracturing. Pressure due to the load of the overlying material may have exceeded the shear strength and produced fracturing. The shear strength of the material of unit 3 is probably not greater than about 500 g/cm^2 (Krynine, 1947) and, assuming a bulk density of 1.5 g/cm^3, this pressure would be exceeded with only a little over 3 m of sediment. Unit 3 is up to 20 m thick in places. Resultant fracture due to this loading effect would be assisted by any loss of water after deposition and by the long time available. Compaction due to the weight of the overlying material and expulsion of water could have contributed to fracturing; however, there is no evidence of compaction and it is difficult to estimate the amount of water loss since deposition.

The distribution of bedrock exposed in the mines and natural caves shows that the sediment is contained in a cave system rather than in one or a few large open dolines. The relationships among the natural caves, the sediment and the bedrock indicate that there were considerable underground interconnections of these caves prior to their being filled with sediment. A good deal of filled passage has been re-opened by mining and other excavations, and sediment exposed in these tunnels suggests that there is still a large amount of filled passage. The lack of lateral facies change within units 1 and 3 points to multiple entrances to the system during the deposition of these units. It is suggested that, after initial formation, some of these entrances may have been sealed with sediment and even re-opened again later, while other new entrances may have formed.

PALAEOENVIRONMENT

Reconstruction of the Quaternary surface environment from the vertebrate faunal remains has not been feasible to date. Even though a large variety of species has been recovered, the lack of stratigraphic control on the collections has resulted in a single faunal list which presents ecological anomalies. Stratigraphically controlled collections by E.L. Lundelius and W. Turnbull are now being studied, but the expected palaeoenvironmental interpretations from these investigations may be disappointingly generalised considering the level of knowledge of the ecology of extinct Australian vertebrates (Calaby, in press).

An attempt at palaeoenvironmental reconstruction based on proportions of clay mineral types in the cave sediments did not prove of much value. There were no systematic changes in proportions of clay type through individual stratigraphic sections and variation in clay types within stratigraphic units was greater than between units. A Chi square median test applied to the proportions of kaolinite in the three stratigraphic units gave Chi^2 = 2.21, with two degrees of freedom, indicating no statistically significant difference as far as comparison of proportions of this clay type among the three stratigraphic units is concerned. This general method of using proportions of clay types in cave sediments to interpret the surface palaeoenvironment has been used successfully in three other studies (Frank, 1963, 1965, and in press) where the surrounding geological and soil conditions were more ideal. Its failure to produce meaningful results in the present investigation is attributed mainly to inheritance of clays (principally well-ordered kaolinite) from previously formed soils and to possible diagenetic formation of montmorillonite in the cave sediments.

Alternatively, evidence from the inferred depositional environments of the sediments and from the skeletal grains provide a qualitative estimate of the Quaternary environmental changes.

Pond deposits such as those occurring as unit 2 (L) can be interpreted as meaning either relatively wetter or relatively drier surface environments, depending on conditions prior or subsequent to ponding. If the sequence of events has been stream-pond-stream then this implies a drier environment during ponding. If there is no evidence of a wetter depositional environment before or after the pond then the ponding probably represents a relatively wetter environment.

Since there was obviously much less water involved in the deposition of units 1 and 3 than of unit 2, the surface environment was probably wetter during the accumulation of the middle unit. Whether ponding resulted from a higher subsurface water level or was due to perched water is a moot point. In either case a wetter surface environment is indicated. The even distribution of cement (on a large scale) in unit 1, together with the lustre mottling and lack of void argillans seems to be evidence for the complete post-depositional saturation of unit 1 and hence points to the ponds of unit 2 being the consequence of a higher subsurface water level.

The palaeoenvironmental evidence from the skeletal grains is chiefly that of the relative abundance of preserved soil particles which have been inherited from the surface. Their greater abundance in unit 1 than in unit 3 suggests that there was more water as slopewash involved in the deposition of the younger unit. This is further substantiated by the intercalated clay beds in the lower part of unit 3. In the unit 3 sediment from Gas Pipe Cave, the inherited calcite nodules suggest that the surface environment was drier still during the later phases of deposition of unit 3.

The inferred trend in the surface environment throughout the last 40,000 to 50,000 years, then, is as follows. An environment which was probably wetter than present during the deposition of unit 1 was followed by a further increase in wetness during the deposition of unit 2, and then a decrease in wetness during the deposition of unit 3. During the deposition of the upper part of unit 3 the surface environment was drier still and was probably comparable to that of the present.

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APPENDIX - STRATIGRAPHIC DESCRIPTIONS

REFERENCE: Locality 1; Gaden Coral Cave; units 1 (G), 2 (FS), 3 (R); 1.65 m exposed.

DESCRIPTION:

Unit 1 (G), floor to 60 cm - Red-brown, calcite cemented claystone; no discernible bedding; lustre mottling occurs throughout; contains sparsely distributed, *in situ* roots; top of unit dips about 15° to the east.

Unit 2 (FS), 60 cm to 65 cm - Red-brown to grey flowstone with abundant material of lower unit incorporated in it; some thin, clean levels without unit G material; bedding well defined as lenses with length width ratio of 10 to 20:1; dips in same direction and at same angle as top of underlying unit.

Unit 3 (R), 65 to 165 cm (ceiling) - Red, calcite cemented mud; horizontal bedding poorly defined by sparsely distributed long bones; contains sparsely distributed, *in situ* roots.

A 30 cm thick calcite cemented bed of *calcite flottante* occurs between unit 1 (G) and unit 3 (RB) about 1 to 3 m east of this section.

REFERENCE: Locality 2; Big Sink; units 1 (BG), 2 (L, FS); 2.25 m exposed.

DESCRIPTION:

Unit 1 (BG), floor to 135 cm - Red-brown to grey, calcite cemented, slightly granular claystone; extremely poor horizontal beds 15 to 30 cm thick; occasional patches of lustre mottling; sparsely distributed *in situ* roots.

Unit 2 (L), 135 to 185 cm - Red-brown and white, calcite cemented, slightly granular mudstone; 1 to 4 cm thick laminations due to graded bedding; small amount lustre mottling; calcite filling desiccation cracks in upper part; sparsely distributed small animal bone fragments.

Unit 2 (L), 185 to 195 cm - Red, uncemented clay; 1 to 3 mm laminations due to colour differences (probably graded), fractures conchoidally; grey discolouration along squashed invertebrate burrows probably due to acidification by rootlets; rootlets also occur in desiccation cracks.

Unit 2 (L), 195 to 215 cm - Dark and light red, calcite cemented, mud; poorly defined occasional graded beds 2 to 10 mm thick; sparse lustre mottling in coarser fractions; some manganese stain along desiccation cracks in finer material.

Unit 2 (FS), 215 to 225 cm (ceiling) - Light grey flowstone as one bed; trace 1 to 2 mm globs of red clay randomly distributed throughout; occasional open vugs up to 10 mm.

REFERENCE: Locality 3; Bone Cave; units 1 (G), 2 (L), 3 (RB, R); 2.25 m exposed.

DESCRIPTION:

Unit 1 (G), floor to 60 cm - Red-brown to grey calcite and phosphate cemented pebbly mudstone; lenses of increased calcite cement define bedding which has apparent dip of about 25^o to the northwest; sparse lustre mottling; phosphate concentrated near contact with overlying unit and as vug fillings sometimes surrounding red clay particles; trace of small animal bone fragments.

Unit 2 (L), 60 cm to 80 cm - Red-brown, black and white, calcite and phosphate cemented sandy mudstone; 1 to 10 mm laminations in upper part which is more clayey; lustre mottling in lower part; occasional cut and fill structure; manganese staining along desiccation cracks.

Unit 2 (L), 80 cm to 90 cm - Red, uncemented clay; desiccation cracks, sometimes filled with calcite, have separated 6 to 10 cm platy lumps; horizontal fine laminae due to colour differences (probably graded); fractures conchoidally; contains rare small animal bone fragments, invertebrate burrows and manganese stain.

Unit 3 (RB), 90 cm to 210 cm - Red mud with sparsely and patchily distributed calcite cement; bedding is defined by parallel orientation of long bones and is horizontal to slightly dipping towards north; 10 to 20% small and large animal bone fragments are evenly distributed; roots up to 10 cm in diameter sparsely distributed and in situ; trace of rounded limestone cobbles with phosphate coatings randomly distributed.

Unit 3 (R), 210 cm to 225 cm (ceiling) - Red, uncemented mud; extremely poor graded beds 5 to 10 cm thick; 10% small animal bone fragments; trace large animal bone fragments; sparsely distributed in situ rootlets.

REFERENCE: Locality 4; Phosphate Mine; units 1 (BG), 2 (FS), 3 (RB); 2.70 m exposed.

DESCRIPTION:

Unit 1 (BG), floor to 60 cm - Red-brown, calcite cemented slightly pebbly clayey mudstone; extremely poor graded bedding dips about 30^o towards southeast; abundant clay, sand, granules and pebbles; trace small animal bone fragments.

Unit 2 (FS), 60 cm to 90 cm - Grey, red and white flowstone; 1 to 30 mm subparallel bands defined by red clay inclusions and crystal size differences; dip same as underlying unit; coarsely to extremely coarsely crystalline subequant calcite is oriented normal to bedding; rare red clay filled vugs and small animal bone fragments.

Unit 3 (RB), 90 cm to 180 cm (ceiling) - Red, uncemented mud; horizontal bedding defined by parallel oriented long bones; 10 to 20% bone fragments are mostly of small animals; rare, in situ rootlets and invertebrate burrows.

REFERENCE: Locality 5; Mitchell's Cave; units 1 (G), 3 (R, RB); 21 m exposed.

DESCRIPTION:

Unit 1 (G), 0 m to 1.5 m - Red-brown to grey calcite cemented coarse sandy mudstone; no discernible bedding; top dips about 25° towards southwest; sparse lustre mottling.

Unit 3 (R), 1.5 m to 4.5 m - Red, uncemented mud; horizontal bedding defined by parallel orientation of long bones and extremely poor grading; 5% bone fragments are mostly of small animals.

Unit 3 (RB), 4.5 m to 12.0 m - Red, uncemented mud; properties similar to underlying unit except 10% large and small animal bone fragments.

Unit 3 (R), 12.0 m to 21.0 m - Properties similar to those between 1.5 and 4.5 m.

REFERENCE: Locality 6; Gas Pipe Cave; unit 3 (R); 1 m exposed.

DESCRIPTION:

Unit 3 (R), floor to 1 m - Red, pebbly to cobbly mud with slight patchy calcite cementation; very poor horizontal bedding defined by subparallel orientation of limestone rock fragments and long bones which become more sparse towards top; contains calcite nodules and small amounts of in situ roots.

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