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The Verandah Cave, Borenore, N.S.W.,
showing the top-storey meander niche
incised into the limestone by Boree Creek.

Photo by A. J. Pavey

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ADDENDUM TO "SEDIMENTARY AND MORPHOLOGICAL DEVELOPMENT OF THE BORENORE CAVES, NEW SOUTH WALES"

The following note from R.M. Frank has just been received and refers to Helictite, 10 (4) : 84-86, and to page 41 in this issue.

"Further work in the Australian National University Radiocarbon Laboratory, under Mr. H. Polach, on the organic matter in flowstone of Pit 2 in the Arch Cave (Helictite, 10 (4) : 84-86) has yielded a ^{14}C date of 27,760 $^{+1860}_{-1510}$ BP (ANU-294).

"This corroborates the inorganic ^{14}C date from the same flowstone and adds support to the time of occurrence of the dry period.

"The author is grateful for the fresh and successful attack on a difficult sample by the Australian National University Radiocarbon Laboratory."

SEDIMENTARY AND MORPHOLOGICAL DEVELOPMENT OF THE BORENORE CAVES, NEW SOUTH WALES, II

R.M. FRANK

Geography Department, University of the West Indies,
Kingston, Jamaica

THE TUNNEL CAVE AND ASSOCIATED FEATURES

The Tunnel Cave (Fig. 1, 2) is near the downstream end of the limestone outcrop. It is a through-cave with a blind-valley upstream entrance and a downstream exit that opens out from the base of a cliff face at a bend of Boree Creek. There are two collapse doline entrances, one near the upstream entrance and another about half way along the cave. The ephemeral stream, Tunnel Cave Creek, heads about 1 km south of the cave, runs through the cave, and joins Boree Creek (see Part I, Fig.1). The main part of the cave is about 250 m long and averages about 3.5 m wide and 3 m high, but the passage becomes higher and narrower downstream.

The cave stream enters through a small opening at the lower east side of the upstream entrance and runs between a bedrock wall and the foot of a breakdown mass for 45 m before entering the main passage. It is concealed for part of this distance by large blocks of breakdown which rest against the eastern bedrock wall. The entrance room is almost entirely floored with breakdown and contains a few old speleothems lying loose on the floor. To the north of the entrance room and above the level of the main passage is an irregularly shaped room which leads to a small entrance opening into the bottom of a large triangular-shaped, collapse doline. This room is also floored with breakdown and has a light-hole at its eastern end which leads to the surface.

The main passage continues for about 25 m beyond the entrance room at which point there is a short breakdown-filled side passage to the left of the stream. Another 25 m farther along the main stream passage, side passages lead off both to the right and the left. The one to the right is choked with breakdown. The one to the left leads to a short maze of tight crawlways with floors of soil-derived sediment and with walls and ceilings of bedrock. Spongework is well-developed in this area.

About 35 m farther along the main passage the ceiling lowers abruptly. It is covered with small, close-set *Deckenkarren*, 30 to 60 cm long, whose forms approach those of more symmetrical pendants. The bottom parts of some of the longer *Deckenkarren* are buried in recent alluvium. To the

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Note: Part I appeared in *Helictite*, 10(4), October 1972, pp. 75-91.

right of this low ceiling is the collapse-doline entrance which is about midway along the length of the cave. The entrance shaft is lined with slightly cemented breakdown and loose, red, soil-derived sediment containing some bone fragments. The low ceiling above the main stream passage rises again after about 7 to 8 m. A few metres farther along there is a tight crawlway to the left which leads to a series of small passages which are only slightly higher than the main passage.

A few metres farther along the main stream passage there is a sharp double bend in the main passage. There is an apparently permanent pool of water here which is fed by a spring at least part of the time. Bedrock benches occur on both sides of the pool (050016 and 053013, Fig.1). The one on the left bank is partly covered with flowstone. The one on the right bank is exposed and has a scalloped surface. Both of these benches are from 60 to 90 cm above the stream bed. There are additional, less well-developed, bedrock benches within the main stream passage upstream of these between cross-section T-2 and T-13; all of these are partly or completely covered with recent river sediments, ancient river sediments, or breakdown. Their height above the stream bed is approximately the same as that of the two just described.

The water which rises in the pool between the two bedrock benches descends a waterfall, 1.5 m high, just downstream from the exposed bench. From this point it may flow all the way to Boree Creek or it may sink again in the alluvium before reaching Boree Creek.

From the waterfall, the main passage is high, narrow, and straight for about 20 m before it enters the terminal room of the cave. This room is about 7.5 m wide, 60 m long, and has a maximum height of about 20 m. The stream channel runs along the left wall and is partly separated by bedrock from the main room near the downstream end. The stream flows beneath three bridges before entering the final, separate passage. The first and the last of these bridges are composed of flowstone and are extensions of large flowstone masses which slope upward toward the south side of the room. The middle bridge is a bedrock projection of the north wall. The upper surfaces of all three bridges are at approximately the same level as the bedrock benches described earlier.

The floor of the terminal room, other than the stream bed, is covered with breakdown, flowstone, and loose sediment which is mostly soil-derived material. There are two flowstone sheets near the west end (063011 and 065014, Fig.1) which are suspended above the level of the present floor.

There are three levels of exits from the cave. The stream flows from the cave at the level of Boree Creek. About 2 m higher and south of the stream channel the exit is interrupted by limestone pillars. The floor is covered here with a veneer of sediment, a mixture of flood-deposited alluvium and soil-derived material, but just outside of the drip line,

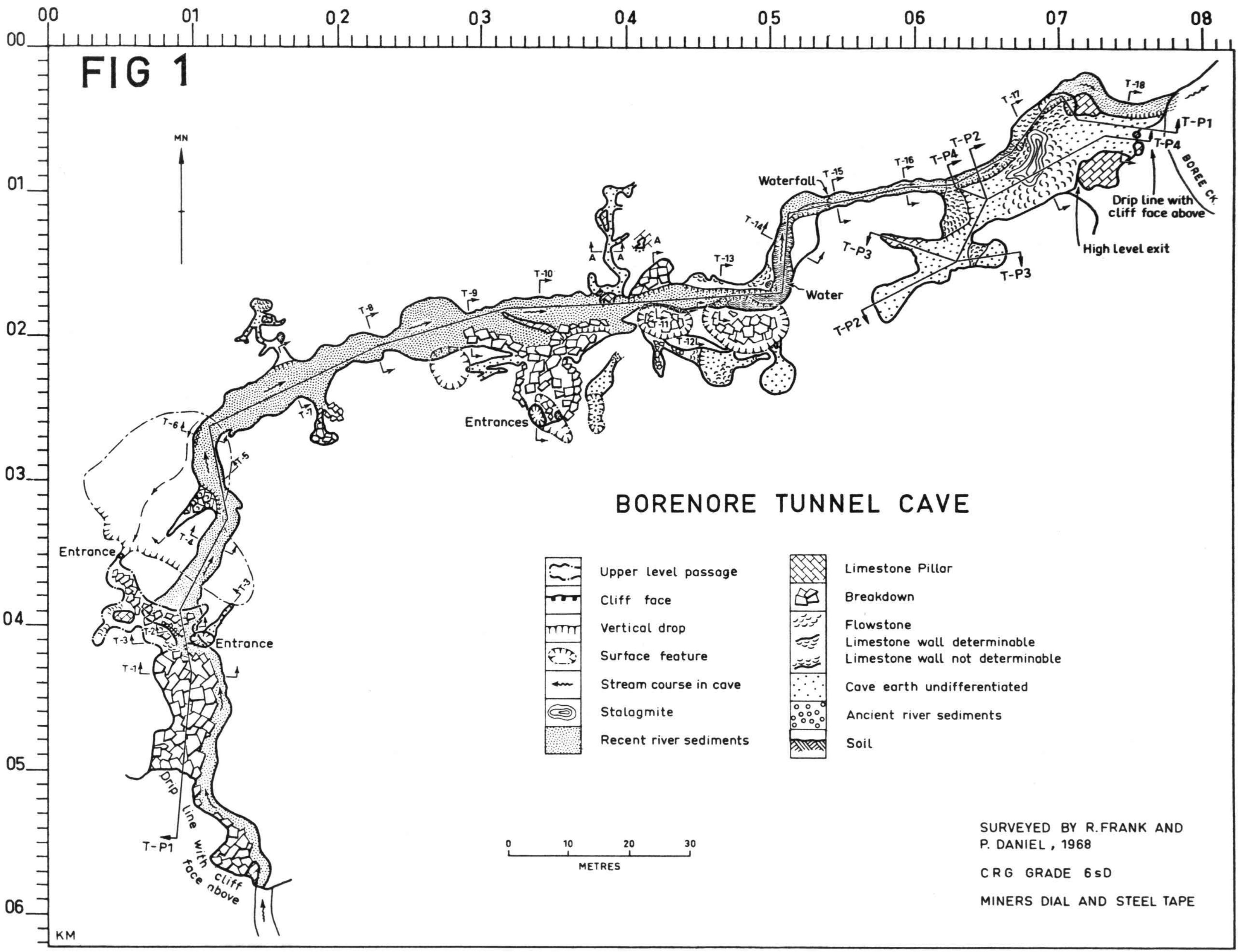
FIG 1
MN
BORENORE TUNNEL CAVE
Upper level passage
Cliff face
Vertical drop
Surface feature
Stream course in cave
Stalagmite
Recent river sediments
Limestone Pillar
Breakdown
Flowstone
Limestone wall determinable
Limestone wall not determinable
Cave earth undifferentiated
Ancient river sediments
Soil
0 10 20 30
METRES
SURVEYED BY R.FRANK AND
P. DANIEL, 1968
CRG GRADE 6sD
MINERS DIAL AND STEEL TAPE
Entrance
Entrance
Entrances
Waterfall
Water
High level exit
Drip line with cliff face above
Drip line with cliff face above
BOREE CK
KM

bedrock is exposed at the same level. The third exit is about 15 m above the level of the stream bed and southwest of the other exits.

Numerous dolines and small caves occur in the vicinity of the Tunnel Cave. Besides the two dolines already mentioned which lead into the Tunnel Cave, there are three others which lie above the cave. The most westerly of these (028022, Fig.1) is about 6 m in diameter and 3 m deep. It is bowl-shaped and filled with soil. The other two are partly roofed collapse dolines. The smaller lies a few metres east of the central entrance to Tunnel Cave (038024, Fig.1). It is about 3 m wide and 12 m long with a bedrock roof extending for about 5.5 m. It is floored with soil-derived material and breakdown. The larger one (045020, Fig.1) is about 25 m long, 9 m at its widest, and has a maximum depth at the east end of 12 m. There are two small caves leading from its south wall.

About 110 m west of the upstream entrance to Tunnel Cave there are two small bowl-shaped and soil-floored dolines with a maximum depth of 2 m. A vertical shaft with three entrances occurs some 150 m north of the same entrance to Tunnel Cave. It is 7.5 m long, 1 to 3 m wide, and 12 to 15 m deep with a floor composed of breakdown.

The Verandah Cave, a superb example of a meander-niche cave, occurs some 300 m downstream from the Tunnel Cave exit. Boree Creek has incised into the limestone cliff to produce an ingrown meander niche 30 m wide and 85 m long. The cave is in two storeys. The upper one is 13 m above the level of Boree Creek and represents a single meander cut of the creek. It is about 2.5 m wide. The ceiling and walls of the lower storey contain evidence of six successive meander cuts by the creek. Large scallops occur on these walls and ceiling, and breakdown and alluvium cover the exposed floor. The cave has been described more fully by Jennings (1970).

Cave Sediments

Sediments in the Tunnel Cave and vicinity are patchily distributed and there is only one good contiguous sequence. However, sedimentological variety partly compensates for the lack of stratigraphic contiguity. In fact, the variety is so great that at least five depositional environments are represented and even within these there are significant lithologic differences. The five depositional environments of the sediments are entrance facies, alluvial deposits, pond deposits, flowstone, and stagnant-water phreatic deposits. One deposit is difficult to classify, but is probably alluvial.

Entrance-facies deposits occur near all the presentday openings leading into the caves and also in high-level side passages especially at 015018, Fig.1. The major part of that near the presentday openings is quite recent, but there are also remnants of more ancient material. Samples of the ancient material were taken from the irregularly shaped upper room near the upstream entrance (005039, Fig.1); from the high-level side passage at 015018, Fig.1, and from the terminal room at 063011, Fig.1. All these samples contain soil particles and the clastic material from the irregularly-shaped upper-room sample is composed almost entirely of soil particles. This sample and that from the terminal room also contain high proportions of calcite cement (65 and 70 per cent, respectively), and in the latter the entrance-facies material is incorporated in flowstone. In this deposit many of the soil particles have been disrupted and split apart by the displacive authigenic calcite. This deposit has about a 15^{o} depositional dip to the north, towards the stream. Thin sheets of flowstone are also present within the sequence of entrance-facies at 015018, Fig.1, in the high-level side passage.

Presentday alluvium occurs throughout the main stream passage as bedload gravel and flood deposits of finer material in side alcoves. In addition, there are remnants of older, cemented stream gravel adhering to the walls of the main stream passage a few tens of centimetres above the stream bed (cross-sections T-2, T-6, T-7, T-8, T-15, Fig.2). These older deposits do not differ markedly from the presentday alluvium, except for the calcite cementation, and both contain detrital material from the nonlimestone rocks upstream of the cave. This includes ironstone and other sedimentary rock fragments. Two other old alluvial deposits and one of probable alluvial origin are present in a high-level alcove at 053014, Fig.1, in crawlways to the left of the main passage at 039013, Fig.1, and in the terminal room at 063015, Fig.1. These three deposits differ considerably in overall texture and composition but they do have one type of detrital constituent in common, namely, fragments of Liesegang-banded sediment. An in-place outcrop of Liesegang-banded sediment occurs at 051023, Fig.1, and is described below. The alluvial deposit in crawlways at 039013, Fig.1, is composed almost entirely of this Liesegang-banded material. The alluvium in the high-level alcove at 053014, Fig.1, contains additional material and has a calcite cement which shows recrystallization according to the criteria of Folk (1965). The probable alluvial material in the terminal room is a conglomerate with a dense iron cement. It contains ironstone pebbles in addition to the Liesegang-banded fragments and has a sodium sulphate precipitate occurring as a partial void filling.

Two pond deposits occur in the Tunnel Cave. One comprises the upper 150 cm of the sediment sequence in the high-level side passage at 015018, Fig.1, and overlies the previously described entrance-facies deposit. It is interbedded with flowstone layers, the uppermost of which caps the entire sequence. The other pond deposit occurs at the high-level exit from the Tunnel Cave (072010, Fig.1). Its detrital assemblage is composed mostly of fine sand-sized mud balls which are arranged in graded beds 2 to 15 mm thick. The deposit is well-cemented with calcite and collophane. Some of the calcite is pseudomorphic after acicular aragonite. The collophane was probably derived from the incorporated bone fragments since analyses of the limestone by Carne and Jones (1919) show no phosphate.

Flowstone is present in several places in the caves but is concentrated in the terminal room where some of it occurs as sheets suspended up to 1 m above the present floor. One of these sheets (at 063011, Fig.1) has already been mentioned in the description of the entrance-facies deposits. This was dated by Dr C.H. Hendy at 27,900 plus or minus 1,500 years BP. The flowstone layers interbedded with the clastic entrance-facies and pond deposits in the high-level side passage at 015018 (Fig.1) increase in thickness and frequency towards the top of the sequence. Hendy has provided radiocarbon dates from the topmost, capping flowstone layer of >41,300 years BP with one standard deviation and >34,600 years BP with two standard deviations, and from another flowstone layer 75 cm below the top of 39,100 plus or minus 3,500 years BP. These two samples may in fact be much older than indicated since as little as 0.2 per cent contamination with "pre-bomb" carbonate in a sample of infinite age could give these ^{14}C dates (Hendy, pers.comm., 1969).

There are three deposits which are considered to have been deposited under stagnant-water phreatic conditions. One of these occurs in the crawlways to the left of the main passage at 039013, Fig.1, another is adhering to the walls of the large collapse doline at 046018, Fig.1; and the third comprises the south wall of the small room south of the large collapse doline (051023, Fig.1). The first two are nearly identical and are probably contemporaneous deposits. The clastic material in them is a structureless clay, for the most part, with small amounts of quartz silt. The clay has been cracked during desiccation into polyhedral cells, 1 to 2 cm in diameter. These cells have been filled later with calcite. Traces of guano have been added during or after desiccation. The remaining deposit is composed of insoluble residue from the limestone to which has been added calcite cement, and limonite in the form of Liesegang bands. That the banding in the deposit is Liesegang banding is evidenced by its convoluted nature in outcrop (Plate 1) and its diffuseness in thin section (Plate 2). Also, there are no clastic textural changes associated with the banding that would indicate it to be a primary structure. Identification of the banding as Liesegang banding was first made by Dr K.A.W. Crook, Department of Geology, Australian National University, Canberra.

Additional sedimentary detail of samples of the sediments just described are tabulated in Frank (1972). *

Development of the Cave

The Tunnel Cave and its adjacent features provide good examples of the two classical types of cave development - vadose and phreatic. The main

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* Copies of the tables may be obtained from the Department of Biogeography and Geomorphology, Australian National University.

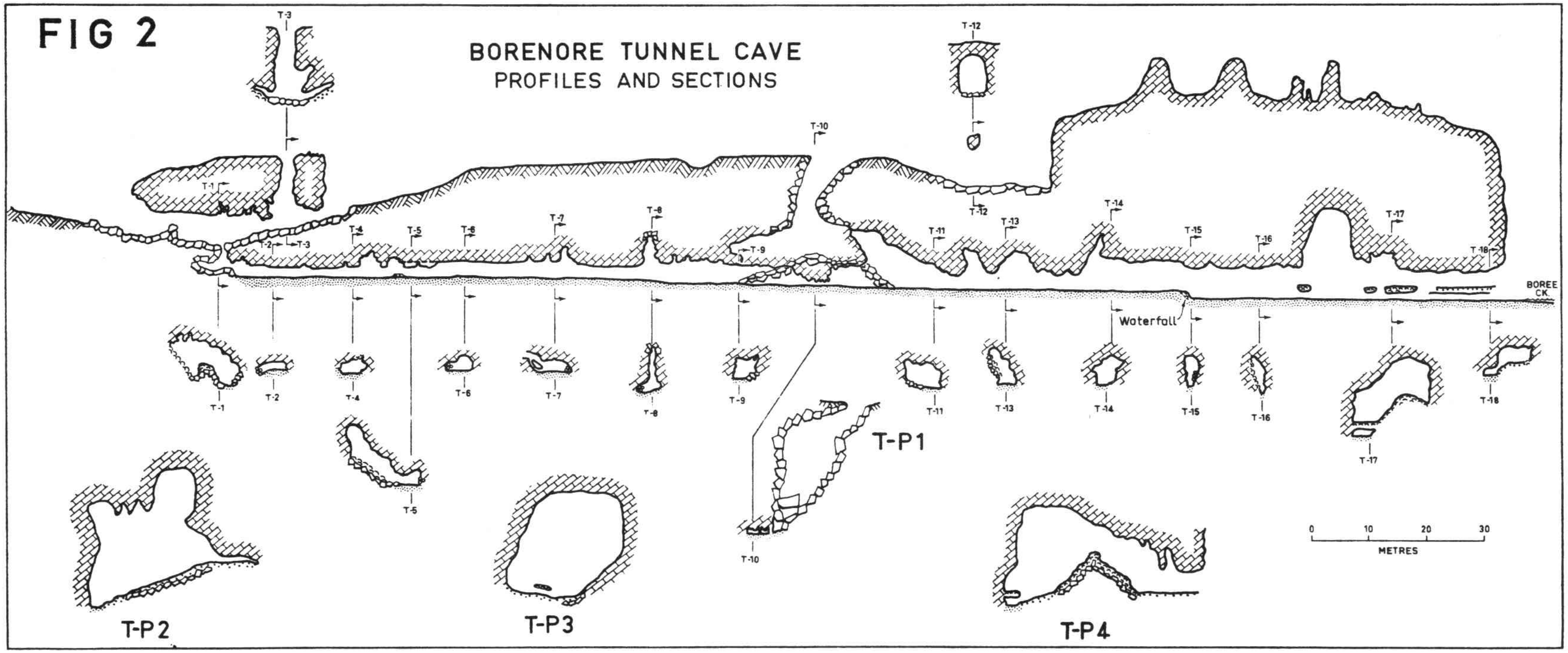


FIG 2
BORENORE TUNNEL CAVE
PROFILES AND SECTIONS
T-1
T-2
T-3
T-4
T-5
T-6
T-7
T-8
T-9
T-10
T-11
T-12
T-13
T-14
T-15
T-16
T-17
T-18
T-P1
T-P2
T-P3
T-P4
Waterfall
BOREE CK.
0 10 20 30
METRES

stream passage displays a simple but pronounced vadose morphology with scalloped walls, bedrock benches, and alluvial deposits. Above and lateral to the main stream passage are the truncated remnants of the original system formed under saturated conditions. In addition, there is some evidence for fossil karst that has been exhumed during the development of the Tunnel Cave.

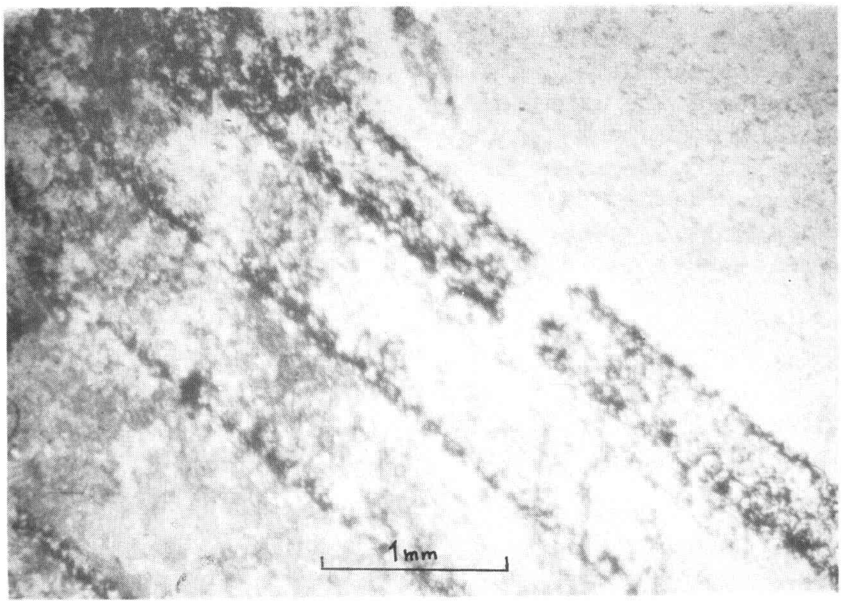
The fossil karst cavities are not distinguishable by bedrock morphology for they have become an integral part of the younger Tunnel Cave and, in fact, some parts have been used by the stream which has formed the vadose system of the present cave. Two deposits are suggestive of fossil karst sediment. The first is the Liesegang-banded sediment in the small cave south of the large collapse doline (051023, Fig.1). Remnants of this material also occur in the walls of the large doline. Texturally and mineralogically this sediment gives every indication of being a deposit of insoluble residue of the limestone. It has no discernible bedding and the pronounced bimodal size distribution, with a dominance of clay and a lesser amount of quartz granules and coarse sand, imply that there was no size selection by a depositing agent. The peculiar morphology of the quartz grains is common only to it (Plate 3) and the limestone (Plate 4). The most probable source for the iron of the Liesegang-bands is the biotite in the limestone since there is up to 15 per cent biotite in the limestone and no biotite in the Liesegang-banded sediment. However, some of the iron may have been derived from the Tertiary volcanics which, according to Süssmilch and Jensen (1909), contain significant amounts of hornblende.

The other sediment which is suggestive of a fossil karst deposit is the limonite-cemented pebble conglomerate in the terminal room of the Tunnel Cave (063015, Fig.1). This material bears a strong resemblance to the lateritic ironstones which are so common throughout Australia. The fact that there are no exposed outcrops of ironstone in the cave, only boulders and smaller sized gravel, makes it difficult to decide whether the material was (a) deposited in the cave as alluvial gravel and later cemented, or (b) deposited in the cave as fragments of lateritic ironstone, or (c) simply lateritic ironstone that has been let down into the cave during solution of the limestone. The large size of some of the boulders (up to 1.5 m) and the bedrock limestone ceiling above seem to disfavour the last two possibilities, though large fragments could have entered as in case (b) through a sediment-concealed cavity or even through the present high-level exit. For this to occur the floor topography would have had to be different from its present conformation for the boulders to have reached their present position at the top of a slope. The presence of fragments of the Liesegang-banded sediment in the deposit also favour an alluvial origin. A source for the iron cement would have been readily available from the biotite in the limestone and from the ironstone pebbles of the deposit.

Cave sediments in which there are considerable amounts of ferric iron precipitates are rare in Late Quaternary deposits whereas they are more common in older, fossil karst deposits (for example, Bretz, 1950; Llopis

Plate 1. Liesegang-banded sediment in small room south of large collapse doline, Borenore Tunnel Cave area. Sediment rests against limestone wall exposed at lower right. Photo covering about 10 m^2 taken looking south from 051203, Fig. 1.

Plate 2. Photomicrograph of Liesegang-banded sediment. Liesegang bands are darker. Plane light.



Lladó, 1955; Callahan, 1964). It is principally for this reason that the two deposits at the Tunnel Cave are considered to be fossil karst deposits. In addition, there is the fact that none of the other cave sediments in the area contain appreciable amounts of ferric iron precipitates even though ferrous iron is available in quantities larger than normal because of the unusually high proportion of biotite in the limestone. The reason that cave sediments with large amounts of ferric iron precipitates are usually confined to palaeokarst is partly as follows. Although iron minerals are virtually ubiquitous in limestones and limestone-derived soils, they are almost always in the ferric state. Consequently, the iron is not available in significant quantities for solution and transportation within the pH range normally associated with a karst environment. Because of this, the iron for ferric precipitates must come from ferrous minerals (which are scarce) or from very low concentrations of ferric ions in solution at this relatively high pH. Both these processes take a considerable length of time and probably longer, in fact, than the normal life-span of a cave system.

Development of the present cave system began with the formation of solution cavities within the saturated zone. The time relations of the palaeokarst, the phreatic development, and the extrusion of the Late Miocene basalt are not determinable, though the absence of basalt or other primary volcanic rocks in the caves suggests that all cave development observable today was formed after the volcanic event.

The vadose history of the cave records a succession of three auto-piracies before the stream finally reached its present course. That is, the ancestral Tunnel Cave Creek has sunk at three points along its own valley each successive one being farther upstream. The main evidence for this is the three ceiling levels in the main stream passage at 5, 2.5, and 1.5 m above the present stream level upstream from the waterfall. These ceiling levels are not well-developed for they are punctured by domes and other irregularities which are remnants of the old phreatic system. However, their upstream terminations correspond with surface dolines that acted as swallow holes and the general decrease in passage irregularity upstream also indicates a corresponding decrease in age of the passage. It is well established that cave ceilings of this type represent solutional planes (Jennings, 1964, 1968; Jennings and Sweeting, 1963) even though there is disagreement as to the details of formation (see Frank, 1972).

The earliest sinking point of the ancestral Tunnel Cave was the large collapse doline at 045020, Fig.1. The stream may have had an earlier, surface course to the north of this sinking point as suggested by occasional, rounded pebbles and cobbles on the surface. However, these pebbles and cobbles could be remnants of ancient Boree Creek alluvium.

The clayey fine sandstone from the high-level alcove at 053014, Fig.1, and the pebble gravel in the small crawlways to the left of the main

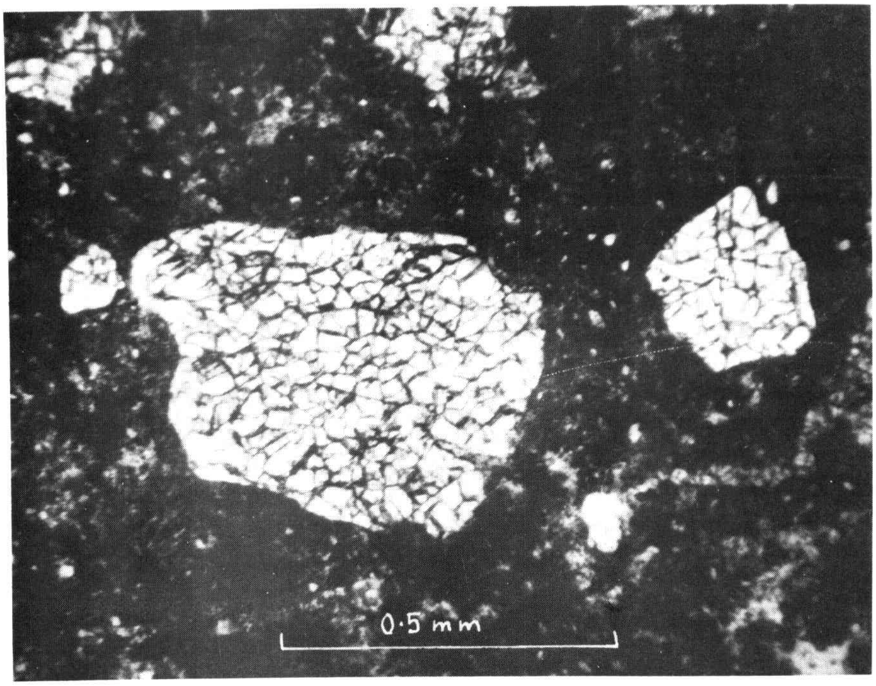
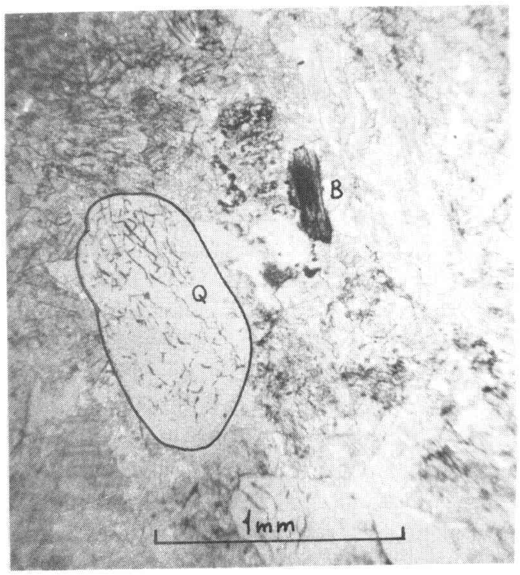


Plate 3. Photomicrograph of quartz grains in Liesegang-banded sediment from small room south of large collapse doline, Borenore Tunnel Cave area. Plane light.

Plate 4. Photomicrograph of Borenore Limestone showing quartz (Q) and biotite (B). Plane light.



passage at 039013, Fig.1, are stream deposits produced by the ancestral Tunnel Cave Creek when it entered the cave through the large collapse doline. The subrounded lumps of Liesegang-banded gravel making up almost all of the pebble gravel show that it was transported by a stream which passed through the large collapse doline where the original deposit of the Liesegang-banded material occurs. The moderate sorting and unimodal size distribution of the clayey fine sandstone indicates that it too was deposited by a stream, and the Liesegang-banded fragments in it also suggest that it was brought in by the same stream that carried the pebble gravel. The patch of clayey fine sandstone is at a level of about 2 m above the level of the pebble gravel. This does not necessarily imply that the sandstone was deposited earlier than the gravel. The gravel is in a phreatic passage which shows no significant alteration by a later vadose stream, and so it could have simply sunk to the lowest accessible cavity which was at a moderate depth below the main stream passage. The pond deposit at the high-level exit from the terminal room is difficult to place chronologically. Its graded bedding suggests deposition in a pond or pool with low current velocity. It could have been deposited in a pool adjacent to Boree Creek or the ancestral Tunnel Cave Creek when one or both of these streams was at approximately this level. Its position is 6 to 10 m above the 5 m ceiling in the main passage and so it is certainly one of the earliest deposits. Its chronologic position, though imprecise, is probably sometime during this earliest vadose stage.

Two additional deposits which fit into this earliest vadose stage are the calcite-cemented clays occurring in the small crawlways to the left of the main passage (039013, Fig.1), and in the walls of the large doline, at 046018, Fig.1. These two sediments are typical still-water cave deposits. Their place in time is even less definite than the previously discussed pond deposit, and they could have been laid down during the phreatic stage or any time during the first vadose stage. Their peculiar structure, with the small lumps of clay surrounded by cells of calcite cement, is interpreted as being due to calcite precipitation occurring along desiccation cracks as the clay shrunk upon drying.

The second sinking of the ancestral Tunnel Cave Creek took place through a swallow hole in the vicinity of the large triangular doline at 0103, Fig. 1. This swallow hole has since been plugged by breakdown and soil, and the present configuration of the triangular doline is not the same as the old swallow hole. At this time the 2.5 m ceiling was formed and the stream cut its bedrock channel down to a level corresponding to the tops of the bedrock benches at 051015, Fig.1. In the terminal room this level is represented by the tops of the bedrock bridges. The stream probably entered through the side passage on the left bank at 010032, Fig.1. Entry at this point accounts for the asymmetry of the passage cross-section at cross-section T-6 where the highest part of the ceiling is on the inside of the meander. During this stage the stream followed approximately the same route downstream from its entry point as it does at present. The two exceptions were at 033018, Fig.1, and along the final 20 m. At 033018, most of the flow was to the right of the bedrock partition through the area now nearly covered by breakdown, since the ceiling of the passage to the left of this partition is below the level of the bedrock benches, that is, lower than the stream bed of the second stage. The last 20 m of the present stream passage is also below this level and the stream probably followed a course through the terminal room close to the T-P1 profile line at a level just below the present sediment-covered floor. During this stage, the gravel which now occurs as calcite-cemented remnants in several places along the main stream passage was deposited.

The sequence of pond and entrance-facies deposits in the high-level side passage at 015018, Fig.1, accumulated during the second stage also. However, the absence of alluvium shows that the area of deposition of this material was not in the direct path of the stream. The lower 90 cm was deposited as entrance-facies material with occasional short periods of clastic non-deposition during which the thin interbedded flowstone layers accumulated. During the deposition of the upper 150 cm of pond deposit, flood water from the stream periodically reached the area. Flowstone accumulated during low flow after each previous pond had dried up. The increase in frequency and thickness of the flowstone layers toward the top records decreasing frequency of flooding during which time the stream was in the process of shifting to the next swallow hole upstream. Flood water finally abandoned the area and a thick cap of flowstone was deposited over the whole sequence. Hendy's (pers. comm., 1969) analyses of the carbon isotopes of the two flowstone layers at the top and at 75 cm below the top of the sequence indicate that the lower one was deposited under conditions of strong evaporation and therefore was probably formed while there was still a direct opening to the surface. However, isotopic analysis of the carbon in the top flowstone shows that there was no strong evaporation during its deposition and hence that the opening was sealed at this time. The chemical basis of the relationship between evaporation and carbon isotopes in speleothems is discussed in Hendy (1969).

Between the second and final vadose stages, there was a period of time when the stream was absent. During this time flowstone formation took place in the terminal room cementing the previously deposited alluvial and entrance-facies material. Remnants of this flowstone, with its incorporated clastics, are present today as sheets suspended above the floor (063011 and 065019, Fig.1) and at 063010 a part of one of these sheets bridges the presentday stream bed. Since this flowstone was formed in the stream bed of the second vadose stage without assuming the form of rimstone dams, it shows that there was no flow in the stream at the time of flowstone formation. A temporary alternative route for the stream during this time is ruled out since the flowstone was formed at the upstream end of the terminal room where the stream channel is contained between bedrock walls (see Fig. 1, 2). The climatic implications of this are discussed in a later section. The entrance-facies material making up part of the clastics in the flowstone sheet most likely came into the cave through what is now the high-level exit. This is indicated by the detrital collophane which was probably derived from the erosion of the pond deposit at the high-level exit.

The ^{14}C date on the flowstone sheet in the terminal room gives a rough chronological location for the dry phase of about 28,000 years BP. Since this is a date from the top of the flowstone sheet, the dry phase must have begun long enough before this so that some 1 m of flowstone could form.

The last vadose stage in the development of Tunnel Cave began sometime after about 28,000 BP. The stream entered the cave through the southern end of the entrance room probably close to where it enters at present but slightly higher and to the west. During this last stage, the stream formed the 1.5 m ceiling at the upstream end of the cave. It also incised itself into the former stream bed about 0.5 to 1 m to produce the bedrock benches and erode much of the gravel that had been previously deposited during the second stage. Calcite-cemented remnants of this gravel still occur in several places along the main passage. At 035020, Fig.1, the stream's route was slightly different than during the former stage, namely, to the left of the bedrock partition. This change was forced by breakdown resulting from the collapse of the doline above. The route of the stream through the terminal room must have been initially both over the top of the flowstone and through the sediment below as shown by the erosion on the top and upstream edge of the flowstone sheet at 063010, Fig.1. Gradually, the less resistant, uncemented material below was removed and a bridge of flowstone spanned the stream. Where the bridge was thinner or weaker, it collapsed to leave the smaller, isolated bridges that are now present. Concomitant with stream degradation, slope denudation of the flowstone and clastic material on the floor of the terminal room was taking place. This resulted in a lowering of the floor of up to 1 m and left remnants of flowstone sheets suspended above the presentday floor level.

Sometime during this last vadose stage the stream began to flow along the route that it now occupies for the last 20 m in the cave. A slight downslope shift was all that was required to gain this route for the final 10 to 12 m, but the first 8 to 10 m is separated from the older channel by bedrock. This suggests that there was already an incipient passage through the bedrock which was taken over by the stream and gradually enlarged until it was able to take the entire discharge - a small-scale capture similar to that which occurred farther upstream at 035020, Fig.1. This final level of the stream channel over the last 20 m was not reached until Boree Creek had cut down to its present level. The waterfall (054011, Fig.1) is the present position of a nick point which resulted from the adjustment of the Tunnel Cave Creek to the downcutting of Boree Creek, the cave stream's base level. The spring just upstream from the waterfall is an indication that the cave is continuing to develop in a manner similar to its past history.

A summary of the sequence of the major events at the Tunnel cave is given in Table 1.

TABLE 1. Sequence of major sedimentary and morphological events in the Borenore Tunnel Cave

1. Development of palaeokarst. Deposition of: insoluble residue (now Liesegang-banded sediment), iron-cemented sediment in terminal room.

2. Stream into Tunnel Cave through large collapse doline at 045020, Fig.1. Development of 5 m ceiling. Deposition of: sandstone in high-level alcove at 053014, Fig.1; pebble gravel in crawlways at 039013, Fig.1; pond deposit at high-level exit; stagnant-water phreatic clay at 039013, and 046018, Fig.1.

3. Stream into Tunnel Cave through large triangular doline. Development of 2.5 m ceiling. Deposition of: sediment sequence in high-level passage at 015018, Fig. 1, around 40,000 years BP; entrance-facies in terminal room; alluvium in main passage.

4. Temporary drying up of stream due to dry climatic phase. Deposition of flowstone in terminal room around 28,000 BP.

5. Stream again active and into Tunnel Cave through southern end of entrance room. Development of 1.5 m ceiling. Partial degradation of alluvium in main passage and incision into bedrock floor to produce benches.

6. Further stream incision downstream from waterfall.

CONCLUSION

In two directions, the foregoing accounts of the Borenore caves converge in their significance, namely in climatic change and the role of stream capture.

Palaeoclimate

There is evidence for a dry climatic phase in the Borenore area around 28,000 BP in the two ^{14}C flowstone deposits in the Arch Cave pit 2 and the terminal room of the Tunnel Cave.

Both of these flowstone deposits, sandwiched between alluvium, record a period of absence of the streams from their channels and then a return of the streams to the same channel. These events could mean either temporary lateral diversion of the streams or temporary cessation of flow. For the Tunnel Cave, the first alternative is ruled out since the flowstone was formed at the upstream end of the terminal room where the stream channel was contained between bedrock walls. The second alternative, temporary cessation of flow, strongly indicates less available water and hence a drier climate than before or after the deposition of the flowstone. In the Arch Cave, even though there is no evidence to show that the temporary absence of the stream was not due to lateral shifting, the near contemporaneity of the event with the one in the Tunnel suggests a common cause.

Stream Capture in the Caves

Despite the lack of similarity in form of the Arch and the Tunnel Caves, there has been some similarity in their developmental processes. Multiple stream captures have occurred in both. There are four captures recorded in the Arch Cave and six in the Tunnel Cave. Of these ten, six have been surface to underground captures and the remainder have been underground to underground captures.

For stream captures to occur, the minimum wetted perimeter of the capturing route must be large enough to take all the stream discharge before the original route has cut down below the level of the capturing route. In surface to underground captures there is evidence that this phenomenon occurs frequently, especially in impounded karst. In fact, once a stream diversion has begun, most factors work in favour of the capturing route (see Frank, 1972).

The four underground to underground captures in the Borenore Caves have been assisted in their development by aggradation of the original route, though there have been two separate causes of this aggradation.

In the Arch Cave, diversion of the stream from the irregularly shaped cave into the arch south of the limestone pillar was effected by alluvial aggradation of the channel in the irregularly shaped cave. Ultimate capture was assisted by the dry climatic phase which occurred during that time. During the waning and waxing of this dry phase the lower, potential route through the arch received the available water more constantly than the higher, original route thus enlarging the potential route sufficiently so that it could take all the discharge even after the return of a wetter climate. This same mechanism of diversion was responsible for the small capture at the downstream end of the Tunnel Cave.

The final, small capture in the Arch Cave, which resulted in Boree Creek being diverted from the south to the north of the limestone pillar, was brought about by breakdown aggradation of the original channel. That is, collapse of the roof into the original channel blocked it resulting in more water being forced through the potential route north of the limestone pillar. Palmer (1969) has also found that this mechanism operates in Indiana caves to produce diversion, though not necessarily capture, of streams. The small capture in the Tunnel Cave near the middle entrance was due to similar causes.

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