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Halls and Narrows: Network caves in dipping limestone, examples from eastern Australia

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Abstract

Structurally guided network caves formed in limestones dipping at greater than approximately thirty degrees differ in plan and section from maze caves developed in horizontal to gently dipping limestone. These caves are characterised by the development of large elongate cavities oriented along strike called *halls* and smaller, short cavities oriented perpendicular to strike called *narrows*. Halls typically terminate blindly along strike. A range of hall and narrows development is recognised, resulting from increases in dip and differing disposition of joints. Entrances to hall and narrows caves appear to have little genetic relationship to the caves. Hall and narrows caves are common in the steeply dipping Palaeozoic limestones of eastern Australia. While the origin of these caves has yet to be completely explained, many of their features suggest that hydrothermal or artesian water had a role in their development.

Keywords: speleogenesis, cave morphology

Introduction

In a previous paper (Osborne, 1999a) I described how the cross-sectional shape of cave passages developed in Palaeozoic limestones of the Tasman Fold Belt in eastern Australia (Fig. 1) differs from those illustrated in conventional texts. While the texts described cave development in horizontal to gently dipping limestone, much of the limestone in eastern Australia is steeply dipping. As a consequence the cross-sectional shape of cave passages were found to be different and genetic interpretations based on conventional textbook descriptions of passage morphology were found to be misleading. This paper extends the previous work by examining the gross morphology of structurally guided network caves developed in dense, steeply dipping limestones as reflected in maps and cross-sections.

Maze caves, consisting of structurally guided passages developed in horizontal to gently dipping limestone, have long been recognised and described (Palmer, 1975, Ryder, 1975). Bakalowicz *et al.* (1987) considered that some types of maze caves were formed by descending (*per descensum*) meteoric waters, while others formed by ascending (*per ascensum*) hydrothermal or artesian waters. Klimchouk (1996) described the development of large complex maze caves by artesian processes in the gypsum karst of the Ukraine.

This paper considers the range of structurally guided network caves that can develop in limestones under different structural settings. Maze caves are but one example of this type of cave structure. The emphasis is on a particular style of cave development, *hall and narrows*, which is characteristic of structurally guided caves developed in limestones dipping at more than 30 degrees.

The examples on which this paper is based, and the author's field areas, are located in the Tasman Fold Belt, which underlies the highlands of eastern Australian. The Early Palaeozoic limestones of the Tasman Fold Belt were deposited as carbonate ramp and platform deposits in the shallow seas of an active volcanic island arc. As a consequence lateral facies changes are frequent. Some of the limestone bodies are allochthonous blocks that slid into deep water soon after deposition. Major regional orogenic phases, from the Late Ordovician to the Early Carboniferous have folded the limestones, with many undergoing multiple phases of deformation.

This is a quite different geological environment from that in which the Inception Horizon Hypothesis was developed, and some of the observations reported in this paper are likely to be specific to cave development in multiply folded Palaeozoic terrains.

Fig. 1. Eastern Australia showing major karsts developed in Palaeozoic limestones of the Tasman Fold Belt.

Hall and Narrows morphology

Hall and narrows caves consist principally of two types of cavity; halls and narrows joined in a geometric pattern. *Halls* are elongate structurally guided cavities. They are generally higher than they are wide and usually end blindly along strike. Shannon (1970) perceptively described cavities of this type as having "cross-sections of door-way proportions". Typically halls are guided by bedding, rather than by joints or fractures.

Narrows are cavities of small cross-section and relatively short length that join halls together. Typically, narrows are guided by structures oriented perpendicular to strike, such as cross-joints. Frequently, parallel halls are joined by a single narrow. Some halls are not blind, but joined to similar cavities developed along strike by narrows. This is the case with Caesars Hall in Wyanbene Cave (Figs 1 and 16) from which halls are named.

Development of network caves in different structural settings

Just as the cross-sectional shape of cave passages can differ with the dip of the limestone (Osborne, 1999a), the gross geometry of network caves, reflected in their plans and cross-sections, is influenced by the angle of dip of the limestone. In the discussion that follows it is assumed that caves begin to form along, and are guided in their latter development by:

- particular lithostratigraphic horizons, described as inception horizons by Lowe and Gunn (1997)

and

- joints and fractures acting as inception links (Lowe, 2000).

It is also assumed that the bedrock is massive and recrystallised, with no remaining primary porosity and that inception horizons are widely spaced.

The examples that follow form a sequence between two extreme end members:

- a rectilinear maze in horizontally-bedded limestone guided in plan by two sets of vertical joints

and

- a rectilinear maze in vertically bedded limestone guided in plan by bedding and one set of vertical joints and in section by a prominent set of horizontal joints.

Hall and narrows development occurs between these two extremes. It is a common form of cave morphology in the Tasman Fold Belt of eastern Australia (Fig. 1) where impounded karsts are developed in elongate narrow outcrops of steeply dipping limestone. As well as occurring as separate entities, hall and narrows morphology is found in sections of many of the more complex caves and cave systems in eastern Australia, such as those at Bungonia and Jenolan in New South Wales (Fig. 1).

For each case discussed, figures are provided which give a simplified diagrammatic example, followed by the map and section of a real cave illustrating each particular permutation.

Gentle dip and vertical joints

Where the limestone is horizontal or gently dipping (up to 30°), joints guide the development of caves in plan (Fig. 2). The result is the classic maze cave pattern described by Palmer (1975). True maze caves are not common in eastern Australia, as lower Palaeozoic limestones usually dip at 40 degrees or more. Good examples of maze caves do occur in less-deformed Ordovician limestones at Ida Bay in Tasmania and Cliefden in New South Wales (Fig 1).

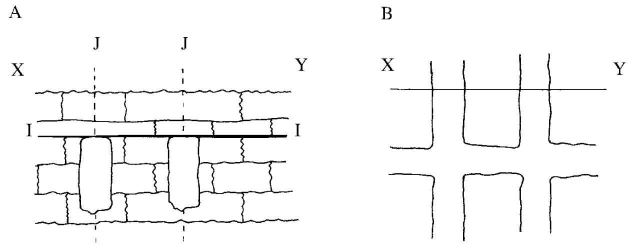

Fig. 2 Cross-section (A) and plan (B) of a horizontally bedded limestone body, in which two sets of vertical joints are developed. I = inception horizon, J = joints. A maze cave is developed, with passages forming at the intersection of joints with inception horizons.

Exit Cave (Fig. 3) at Ida Bay in southern Tasmania is considered to be the largest maze cave in eastern Australia, with plan length exceeding 40 km. The cave is developed in horizontally bedded limestones of Ordovician Gordon Group. The limestone mass containing the cave is capped by clastics of the Late Carboniferous Parmeener Supergroup. The clastics rest on, and infill, an irregular, karstic, unconformity surface on the limestone. Palaeokarst deposits of two distinct ages are exposed both in the Lune River Quarry, which drains into the cave (Osborne, 1995, Osborne and Cooper, 2001), and in the cave.

While surveys of the cave remain incomplete, available maps suggest that vertical joint sets striking NNW-SSE and NE-SW (Fig. 3) guided cave development. Major passages in Exit Cave are rectangular in cross-section, often 10 m wide by 30 m high. Trunk passages do not increase in size downstream of junctions and in places they actually decrease in size downstream. Osborne and Cooper (2001), following Bakalowicz *et al*. (1987), took the lack of systematic downstream increase in passage size as one of the characteristics suggesting that the cave had a hydrothermal origin.

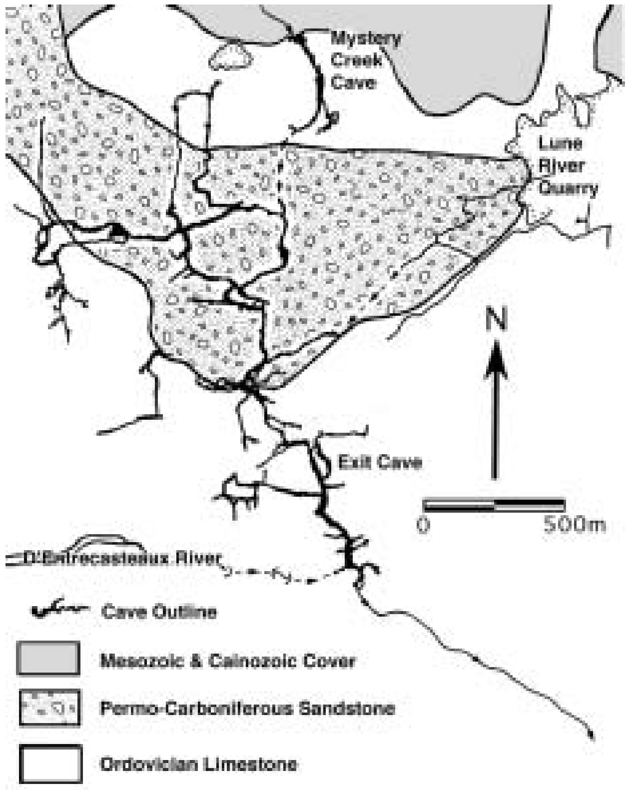

Fig. 3 Exit Cave, Ida Bay, Tasmania. Streams in the cave flow to the south. Note how passage size does not increase systematically to the south.

Moderate dip and vertical joints

As bedrock dip increases above 30 degrees, a hall and narrows pattern, rather than a maze pattern develops. Joints parallel to bedding guide the halls, while joints perpendicular to bedding guide the narrows.

Fig. 4 illustrates this style of cave. The limestone has a moderate dip (40°) and there are two sets of vertical joints, one parallel to strike and the other normal to strike. Halls follow strike-joints. They originate at the intersection of strike joints with inception horizons. Narrows develop down the bedding planes, following joints normal to bedding. In many instances the narrows are low, wide, bedding plane “flatteners”.

Caves with this structure are common in the Permian limestones of the New England Fold Belt of New South Wales (a sub-division of the Tasman Fold Belt). Yessabah Bat Cave (Figs 1 and 5) shows many of the characteristics of this type of cave. It consists essentially of two NE-SW trending halls, joined by a low sloping narrow. Both halls have blind terminations (apart from the entrance). A cupola is developed at section B-B’ in the western hall.

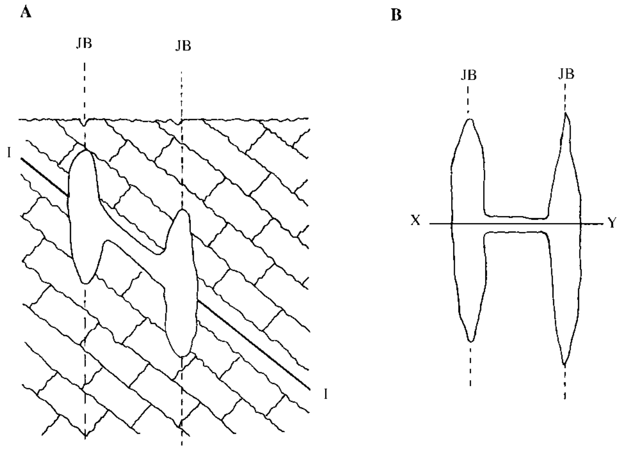

Fig. 4. Cross section (A) and plan (B) of a moderately dipping limestone body in which one set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpendicular to the strike direction. I = inception horizon, J = joints. Halls (H) are guided by joints parallel to bedding. They are joined by Narrows (N) which are guided by the intersection of the inception horizon with joints perpendicular to bedding.

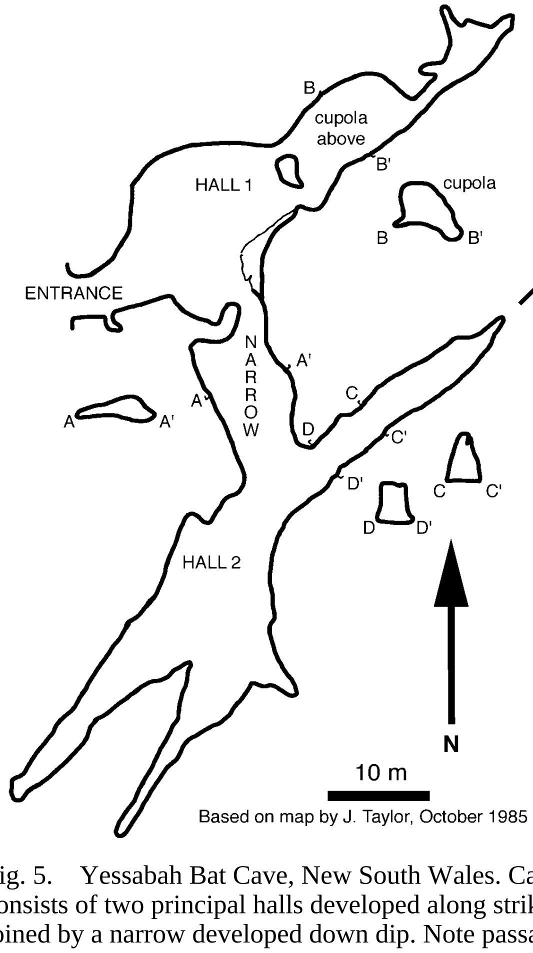

Fig. 5. Yessabah Bat Cave, New South Wales. Cave consists of two principal halls developed along strike, joined by a narrow developed down dip. Note passage cross-sections at "C" and "D". S = strike of limestone, d = dip direction.

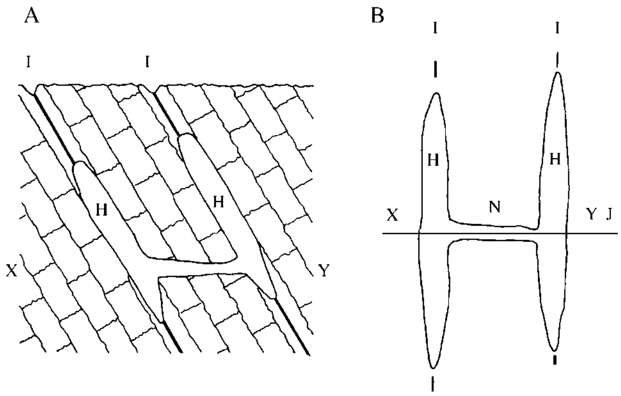

Fig. 6. Cross section (A) and plan (B) of a steeper-dipping limestone body in which one set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpendicular to the strike direction. I = inception horizon, J = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N) which are guided by joints perpendicular to bedding.

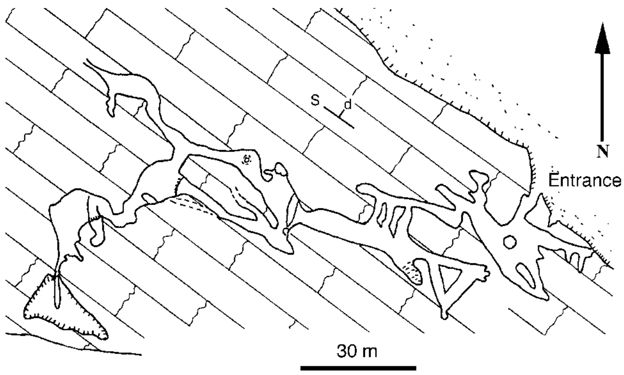

Fig. 7. Transmission Cave, Cliefden Caves, New South Wales. Map after Osborne (1978). Eastern part of cave consists of halls developed along strike, joined by narrows following joints. S = strike of limestone, d = dip direction.

Steeper dip and vertical joints

When dips become steeper (approximately 60^{o}), halls are guided principally by the bedding, while narrows follow vertical joints, oriented perpendicular to bedding (Fig. 6).

Transmission Cave at Cliefden Caves (Fig. 7) consists of a series of halls guided by both bedding and steeply dipping joints with strikes close to that of the bedding. The halls are joined together by short narrows guided by two sets of vertical joints, striking roughly perpendicular to bedding. The larger halls generally have a triangular cross-section, but show no sign of being produced by structurally-guided breakdown, rather the cross-sectional shape appears to result from the interplay of variable rock solubility and the intersection of structural planes. Some of the smaller halls are narrow sloping-sided rifts developed along bedding. Speleogens in the cave include bell holes, blades, roof pendants, rock bridges and complex spongework. The entrance has formed where cliff retreat has exposed a narrow.

This type of cave is common in eastern Australia. Examples are found at Mt Etna, Queensland (the "rainwater inflow" and "ramifying caves" of Shannon, 1970), Stockyard Creek, New South Wales (Holberton, 1984) and Timor, New South Wales (James *et al.*, 1976; Osborne 1986) (Fig. 1).

Very steep to vertical dip and vertical joints

Where bedding is very steep to vertical, cave development is guided along strike by inception horizons and normal to strike by vertical joints (Fig. 8). This produces halls with almost vertical walls in easily dissolved beds, joined by constricted narrows guided by joints through resistant beds. Horizontal joints, if present, can determine the disposition of narrows in the vertical plane.

Dip Cave at Wee Jasper, New South Wales (Figs 1 and 9) is an outstanding example of this type of cave. It consists of five major parallel halls developed along strike, joined together by a few, often only one, tiny narrows running perpendicular to strike. The halls are rectangular in cross-section. Parting along vertical beds has resulted in breakdown, modifying the sides of the halls.

The walls and ceilings of Dip Cave have pitted etched surfaces. Remnant deposits of sediment, situated at various levels in the cave remain from large quantities of poorly sorted sediment and flowstone that once partly filled the cave and have since been removed. Phreatic speleogens have formed on both bedrock and flowstone. Remnants of stalagmite occur on the ground surface adjacent to two of the cave's vertical entrances.

Examples from Chillagoe Caves in Queensland (Fig. 1) described by Ford (1978) illustrate a situation somewhat the reverse to that of Dip Cave. In the Queenslander-Cathedral Cave System (Fig. 10) major halls are guided by joints perpendicular to the strike of bedding and joined by narrows (on occasions widened into chambers) trending parallel to bedding.

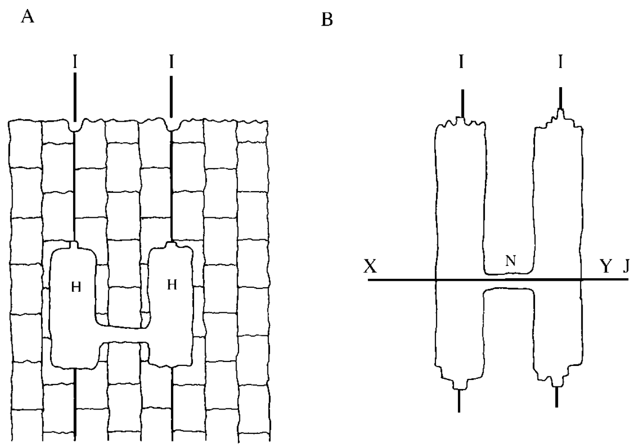

Fig. 8. Cross section (A) and plan (B) of very steeply dipping to vertically bedded limestone body. One set of vertical joints is developed parallel to strike and another set of vertical joints is developed perpendicular to the strike direction. "I" = inception horizon "J" = joint Halls (H) are guided by the inception horizons. These are joined by Narrows (N) which are guided by joints perpendicular to bedding.

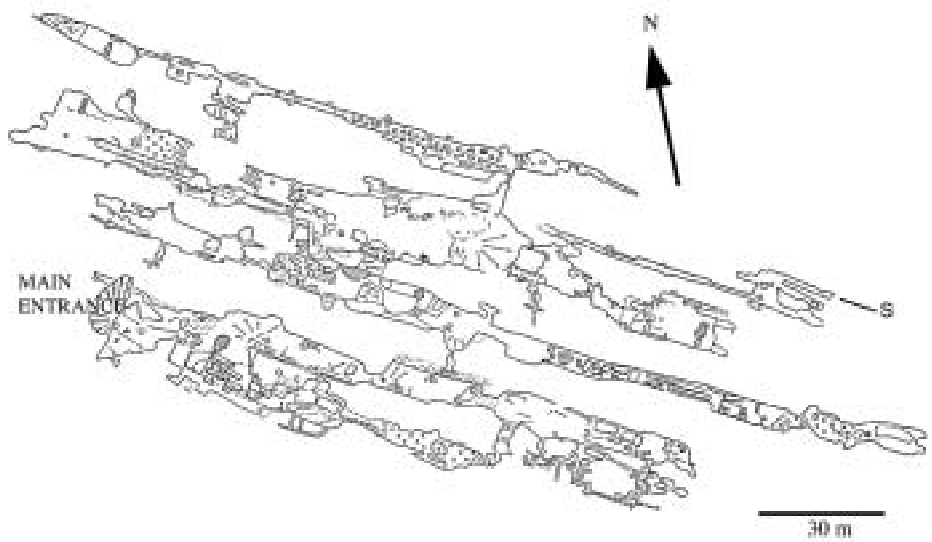

Fig. 9. Dip Cave, Wee Jasper New South Wales after Jennings (1963). Cave consists principally of a series of halls guided by bedding, which strikes NW-SE and dips vertically. The narrows in this cave are small passages that join the halls at ceiling level. S = strike of vertical bedding.

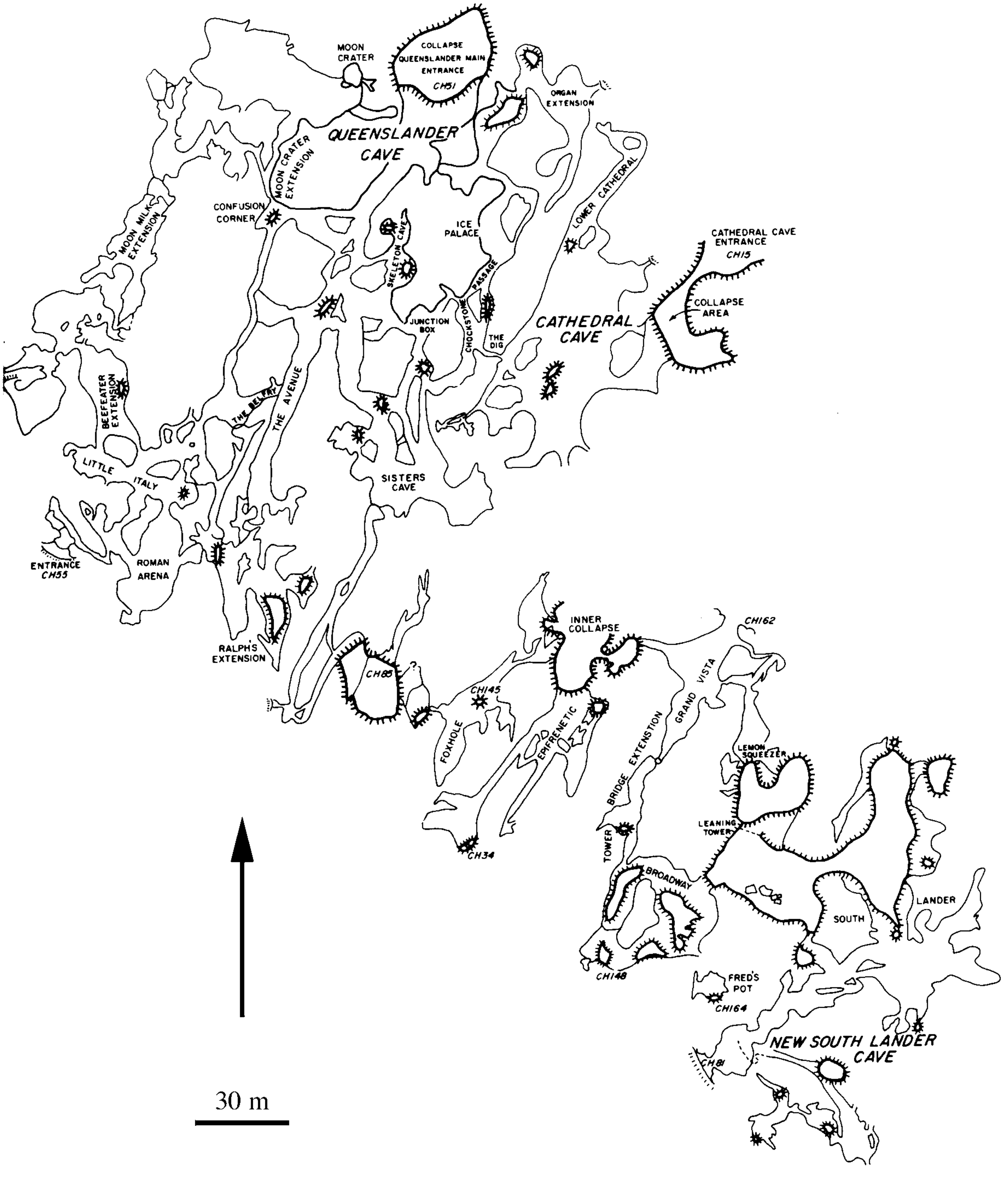

Fig. 10. The Queenslander-Cathedral Cave System, Chillagoe, Queensland after Ford (1978). Halls, trending NE-SW, follow vertical joints that strike perpendicular to bedding (J). Narrows, and a few chambers, are oriented parallel to bedding (B) which is almost vertical.

Steep dip and horizontal joints

The combination of steeply dipping beds, prominent sub-horizontal joints and vertical joints perpendicular to bedding can produce a cave that mimics in plan true mazes developed in horizontal limestone (Figure 11). In this case the sub-horizontal joints, rather than the bedding, guide cave development in the vertical plane, while inception horizons and joints perpendicular to bedding guide the horizontal (plan) development of the cave.

Ashford Cave in northern New South Wales (Figs 1 and 12) is a network cave developed in steeply dipping limestone in which sub-horizontal joints are developed. Prominent halls have developed along strike, joined by short, low narrows with relatively flat ceilings. In some parts of the cave, the halls also have flat ceilings.

Gillieson (1981) interpreted the flat ceilings as products of epiphreatic solution. Many, however, appear to follow the irregular sub horizontal joints, rather than truncating them. This suggests that the ceilings may have formed by structurally guided solution, rather than by epiphreatic or paragenetic planation. Small bell holes and large cupolas have formed in some parts of the hall ceilings. Other speleogens developed in the cave include roof pendants and small symmetrical pits (approximately 5mm in diameter) that occur on both the walls and ceilings.

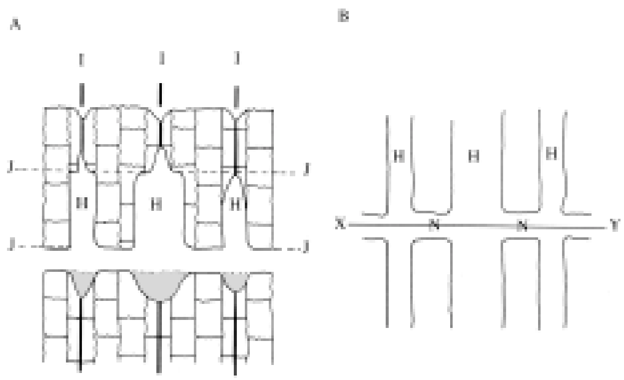

Fig. 11. Cross section (A) and plan (B) of a very steeply to vertically dipping limestone body. A set of vertical joints is developed perpendicular to the strike direction.
A prominent set of horizontal joints is also developed.
"I" = inception horizon, "J" = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N) (Flats) which are guided by joints perpendicular to bedding and guided (constricted) in a vertical plane by horizontal joints.

Fig. 12. Ashford Cave, New South Wales. Halls are guided by vertical bedding, which strikes east-west. These are joined by broad "narrows", which are laterally guided by vertical cross-joints and vertically guided by horizontal joints. S= strike of vertical bedding.

Steep dip and dipping Joints

When a limestone body has steeply-dipping beds and more gently-dipping joints parallel to strike a system of stepped halls can develop, joined by short, steep narrows that have been guided by vertical joints perpendicular to strike (Fig. 13).

This type of development occurs in Flying Fortress Cave at Bungonia (Fig. 14). The cave consists of two, north-south trending, principal halls; an upper, western, hall that includes the entrance and a lower, eastern, hall, Magnathera Chamber. These are joined by a westward-sloping passage, which is essentially a set of at least four close-spaced halls joined by a slightly enlarged northwest to southeast trending narrow. Magnathera Chamber consists of two halls that have coalesced at the southern end where they terminate at a dyke. A hole in the floor on the eastern side of the chamber drops 12 m to a hall below.

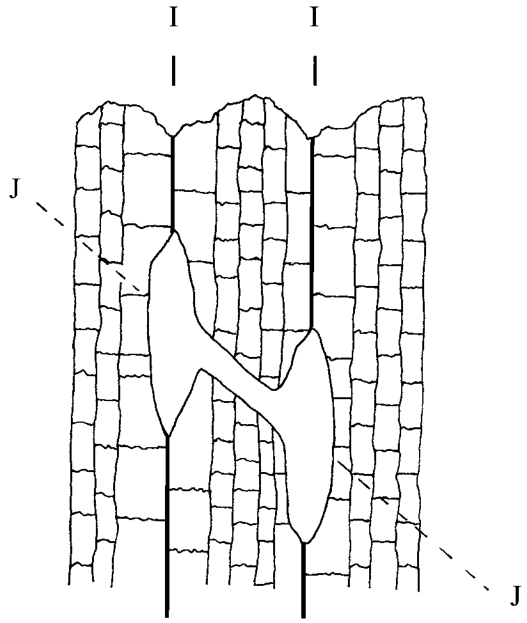

Fig. 13 (above). Cross section of a very steep dipping to vertically bedded limestone body. A set of vertical joints is developed perpendicular to the strike direction.
A prominent set of dipping joints is also developed.
“I” = inception horizon, “J” = joints. Halls (H) are guided by the inception horizons. These are joined by Narrows (N), which are guided by joints perpendicular to bedding and guided (constricted) by the dipping joints. This has resulted in a system of stacked halls joined by short, steep narrows.

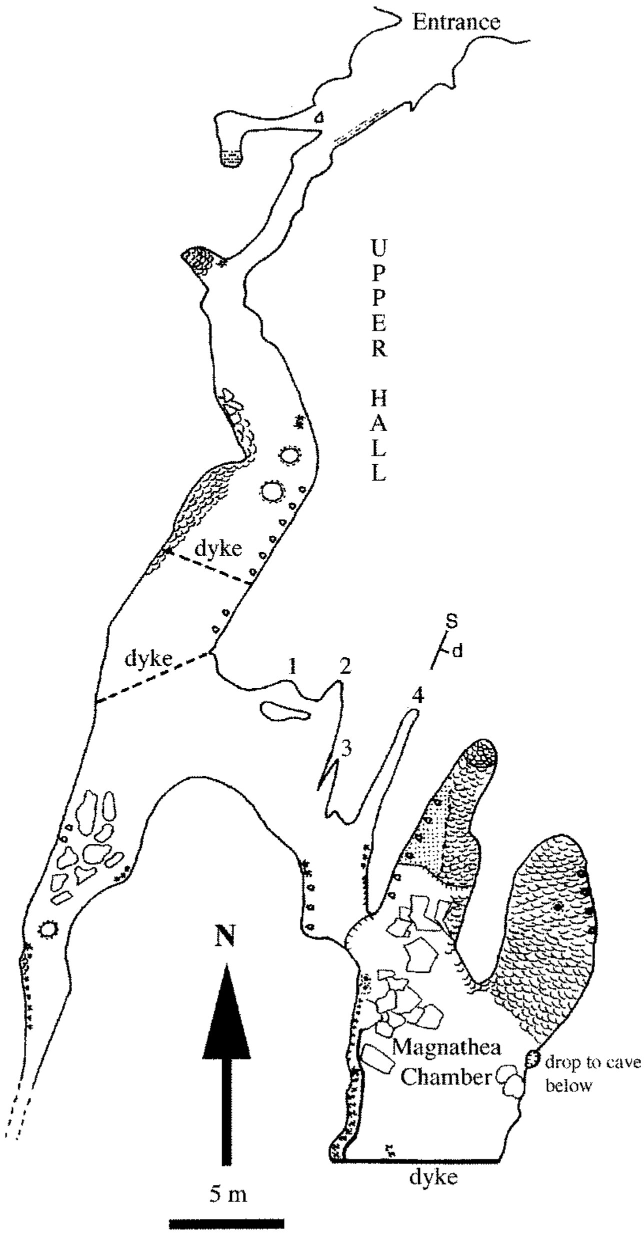

Fig. 14 (right). Flying Fortress Cave, Bungonia Caves. New South Wales. Cave consists of two principal halls, following strike, joined by an eastwardly–sloping narrow. The narrow penetrates a series of steeply dipping beds with variable solubility, resulting in the development of a series of minor halls (1, 2, 3 and 4) along the more soluble beds. Map after Bauer and Bauer (1998). S = strike of limestone, d = dip direction. The joint which guides the narrow has the same strike and dip direction as the bedding, but much gentler angle of dip.

Development along a principal vertical structure

The halls first described by Osborne (1996) were not blind cavities joined at right angles by narrows, as in the examples above, but rather elongate semi-blind cavities in a series, developed along strike in the same structure. These halls are separated by constrictions (narrows) as shown in Fig. 15. Narrows occur where materials of low solubility, such as dykes, ore bodies and palaeokarst deposits filling cross-joints, intersect the limestone perpendicular to strike.

Wyanbene Cave (Fig. 16) is a system of halls and narrows through which a stream flows. A few closely spaced vertical joints running parallel to strike have guided the Halls. These joints are filled with sulfide-bearing palaeokarst deposits that are weathering under vadose conditions (Osborne, 1996). The weathered palaeokarst deposits have fallen away from the bedrock and then been removed by the stream, exhuming the halls in the process. This process continues today. Similar systems of halls and narrows through which streams now flow are also found at Jenolan Caves (Osborne, 1999b).

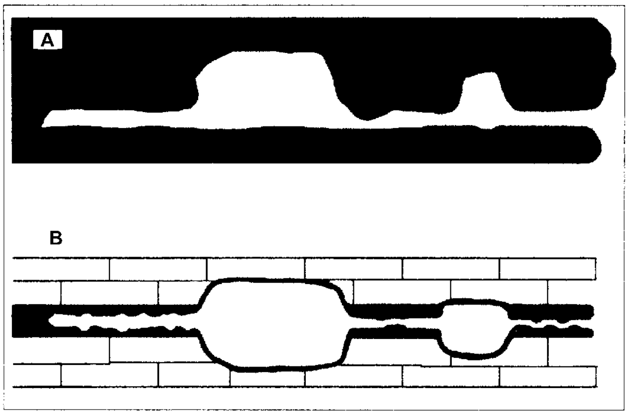

Fig. 15. Cross-section (A) and plan (B) of a hall and narrows cave developed along an ore vein or dyke that follows strike in vertically bedded limestone. Halls result from expansion of the initial cavity into the limestone host rock.

General characteristics of hall and narrows caves in Eastern Australia

Hydrological isolation

Most hall and narrows caves seem to have little, if any, relationship with the hydrology of the landscapes in which they are situated. It is rare for permanent springs to rise from these caves, and ever rarer for permanent streams to sink into them. Most do not contain permanent bodies of water.

Some hall and narrows caves occur high in hills and ridges, hundreds of metres above the floors of adjacent valleys. Others occur directly adjacent to, and within ten metres vertically of, the beds of major streams, but do not appear to be genetically related to them.

Blind termination along strike

One of the most significant features of hall and narrows caves is the blind termination of halls along strike. While this is a feature of many, perhaps hundreds, of small caves and sections of large caves in eastern Australia, the significance of these cavities and the implications of their blind terminations seems to have escaped comment in the literature.

Many, including myself (Osborne, 1993), discussed elongate cavities, now recognised as halls, as though they were abandoned stream passages or phreatic conduits along which water formerly flowed. In the case of Bungonia Caves there was frequent discussion about the location and elevation of palaeosprings from which water "flowing" in these "passages" might have risen in the past (see James *et al.*, 1978).

Blind terminations along strike can take a number of forms. Some halls become narrow along strike, forming a conical or v-shaped termination in the guiding bed or joint. In others the termination is more rounded. Flat terminations occur where the hall ends at a structural plane. Some halls, for example Magnathera Chamber, and other smaller halls in Flying Fortress Cave at Bungonia (Fig. 12), terminate abruptly at dykes.

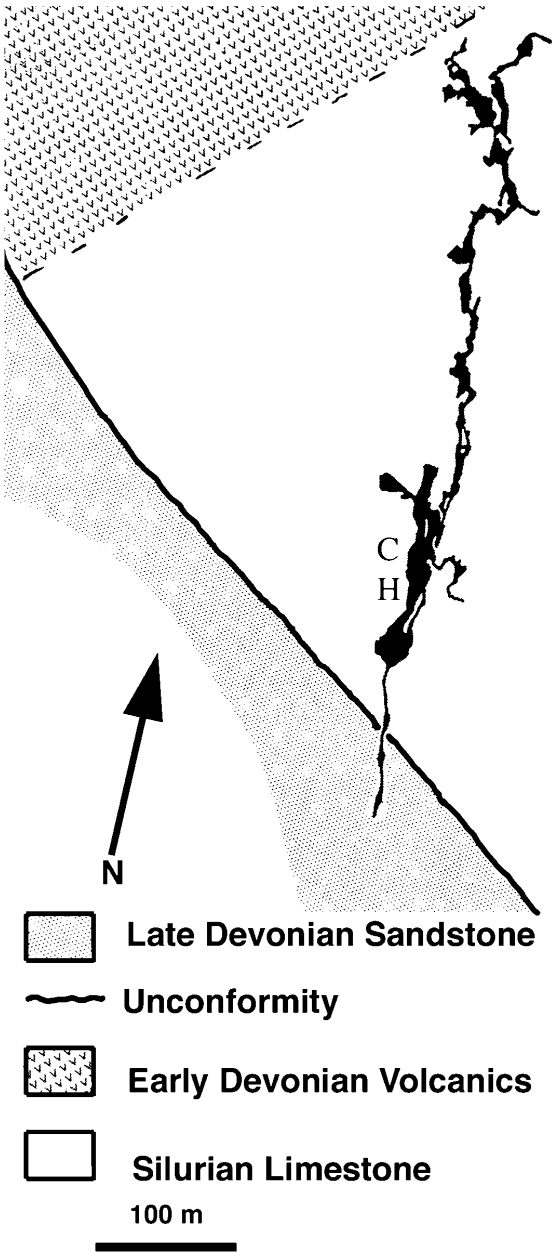

Fig. 16. Wyanbene Cave, New South Wales. The cave consists of a series of halls and narrows of which Caesars Hall (CH on map) is the largest. Map modified after Webb and Brush (1978).

Modification of halls

Halls are frequently more complex in shape than the simple “door-way.... with all the corners rounded off” described by Shannon (1970). Cupolas are common in the ceilings of halls, in some cases at, or close to, their terminations. Sometimes a number of halls coalesce along a single narrow to form a large room, as in the Queenslander-Cathedral Cave System (Fig. 10).

Speleogens

A variety of speleogens, generally interpreted as being indicative of slow phreatic solution, occurs in hall and narrows caves. These include bell holes, spongework, rock bridges, roof pendants, wall pockets, blades, symmetrical pits and juts. Most caves contain few, if any, speleogens indicative of rapid flow or vadose incision, such as scallops or floor canyons.

Entrances

The entrances of hall and narrows caves appear to have little genetic relationship with the rest of the cave, and generally appear to have formed after most, or all, of the cave was excavated. Few entrances appear to have acted as inflow points to the caves in the past. Where intermittent streams now sink into the entrances there is clear evidence of the cave having been modified, but not formed, by the action of these streams. Three main types of entrances are recognised: - breakdown entrances, surface lowering entrances and cliff retreat/ incision entrances.

Breakdown entrances are common in hall and narrows caves. Many, such as the entrance to Yessabah Bat Cave (Fig. 3) and the main entrance to Dip Cave (Fig. 8) are developed in the cave ceiling close to, or at, the blind ends of halls. Jennings (1963) recognised that the main entrance of Dip Cave resulted form an advanced (ie. late in the history of the cave) stage of breakdown.

Surface lowering entrances occur where lowering of the ground surface penetrates an underlying cave. Some of these entrances are simple holes in the roof, often at the apex of a cupola. Others, as at Ashford Cave, are more complex consisting of a segment of unroofed cave which remains connected to the cave below it.

Cliff retreat/incision entrances occur where a retreating cliff or by an incising stream intersect a hall or narrow. These are the most common types of horizontal entrances into hall and narrows caves. Some caves have multiple entrances of this type, where the ends of a series of halls are intersected by a cliff-line, while in other cases (eg. Transmission Cave, Fig. 7), the cliff face has intersected a single narrow.

At all three types of entrances, cave structures are truncated indicating that the entrances formed after, rather than during, the excavation of the caves.

Sediments

Many hall and narrows caves intersect palaeokarst deposits, are partly filled with clays and contain remnants of vadose deposits such as flowstone.

Although remnants of gravel deposits occur in some caves, many hall and narrows caves located directly adjacent to major streams do not contain any stream deposits (eg. Transmission Cave at Cliefden (Fig 7) and Ashford Cave (Fig. 11)).

Thick deposits of clays, or more frequently remnants of clay deposits, often occur in these caves. The clays are often finely -laminated and similar in appearance to the “cap muds” described by Bull (1977). It has usually been assumed that either the clays were derived from the surface, or that they consist of insoluble residues derived from solution of the limestone. However since there has been little study of their mineralogy, comments on the origin of these clays is largely based on speculation. Work in progress suggests that at least some of these clays are probably autochthonous. It appears that the bulk of the clay deposits were removed relatively recently in the history of the caves (Osborne, 1978), but it remains unclear exactly how and when this occurred.

The palaeokarst deposits and significant amounts of flowstone appear to have been removed by phreatic solution. Phreatic speleogens are developed on flowstone at Timor Caves (Osborne, 1986), Moparabah Cave, Dip Cave and Ashford Cave. When and how this phreatic solution, particularly of the resolution of the flowstone, took place has yet to be adequately explained and is currently being investigated.

Alteration

Exposed bedrock in many hall and narrows caves shows signs of chemical alteration. As some large halls, particularly those with cupolas, have been used as bat roosts, some phosphatic alteration is the result of interaction between the bedrock and guano. Often, however, the alteration is not phosphatic.

Boxwork, silicification of fossils, and emplacement of dolomite and pyrite occur frequently in hall and narrows caves. The walls of some halls are not smooth, but deeply etched and silicified fossils protrude. Outstanding examples of this type of alteration occur in Flying Fortress Cave (Fig. 13)

(Bauer, 1998) and Grill Cave (Osborne 1993) at Bungonia.

The walls of narrows, which develop where joints penetrate relatively less soluble beds, do not show this etching, but the bedrock exposed in them may be pervasively altered. Bauer (1998) noted that the limestones walls of “the Flattener”, a squeeze (narrow) joining two halls in Argyle Hole Cave at Bungonia, are extensively dolomitised. Resistant spiculite beds, located further inside the cave, are also altered with secondary emplacement of dolomite and pyrite.

Dykes at the end of halls are significantly altered. Gypsum and calcite have replaced feldspars in dykes at Bungonia, while quartz and gypsum have replaced feldspars in dykes in Spider Cave at Jenolan.

Two explanations of this alteration seem possible. One is to propose, by analogy with the changes that occur to limestone in contact with phosphatic sediments, that alteration results from chemical interaction between clay and the bedrock. Osborne (1993) proposed that silicification of bedrock and fossils at Bungonia Caves resulted from such an interaction, considered to relate to a Mid-Tertiary period of deep weathering.

An alternative explanation, outlined by Osborne (1999b), proposed that the cavities themselves, and at least some of the clays found in them, were produced by rising hydrothermal waters. This would explain not only the alteration of the bedrock and the dykes, but also many elements of the morphology of these caves.

Discussion

Hall and narrows caves are common in eastern Australia; consequently, many are described in the scientific and speleological literature. Their characteristic morphology has not, however, previously been discussed. Most commentators have proposed a phreatic origin for these caves, and related their development to periods in the past when water tables were higher, usually before a particular phase of stream incision.

Those who went further than just noting the evidence for phreatic solution encountered significant difficulties. Jennings (1963) commented on Dip Cave at Wee Jasper that: - “the clarity with which the morphology of the cave reflects the geological structure, is almost counterbalanced by the obscurity which hinders any effort to interpret the origin and evolution of the cave.”

The major, although unrecognised, problem was that phreatic water could not have possibly flowed along strike *through* blind halls, so the halls could not have acted as ‘stream passages” or “phreatic conduits”. Nevertheless, Jennings (1963) discussed the direction in which the blind halls in Dip Cave “drained”, and how the evolution of the surface geomorphology caused the cave to come “under the influence of stronger water currents”.

Many caves with hall and narrows morphology in eastern Australia were attributed to solution under conditions characterised by Jennings (1977) as nothephreatic. Nothephreatic solution, as described by Jennings, was thought to take place by the action of slowly flowing or convecting water in a water-filled cave. Jennings (1980) cited Ochtinská Aragonite Cave in Slovakia and Cathedral Cave at Wellington Caves, New South Wales (Fig.1, M) as examples of nothephreatic caves. Frank (1971) had attributed the development of Cathedral Cave at Wellington Caves to solution by “eddy currents in the phreatic zone”

Jennings definition of nothephreatic, and the latter use of the term in the eastern Australian context, assumed very slow and diffuse flow of “a few metres a day” (Jennings, 1985). This differs considerably from the definition of Lowe and Waltham (1995) who defined nothephreatic as “conduit flow, which is always laminar”.

Following Jennings, I considered that the caves at Cliefden, including Transmission Cave (Fig. 7), formed by “sluggish solution of the nothephreatic type” (Osborne, 1978). Similarly, David Branagan and I commented that the larger caves in the Western Slopes region of New South Wales were “structurally controlled nothephreatic networks” (Osborne and Branagan, 1988).

Nothephreatic (*sensu* Jennings) has proved a useful term for grouping caves exhibiting a series of characteristics indicative of solution under slow-moving, water-filled conditions. The term, however, does not imply any mechanism for generating diffuse flow or convection currents, nor does it propose any mechanism by which water in the phreas remains aggressive.

Shannon (1970) proposed that hall and narrows caves at Mt Etna in Queensland resulted principally from vadose solution. His idea was that solution resulted from organic-rich runoff (rainwater inflow) entering the limestone through karren fields. He envisaged that the caves were continuing to form by solution at the terminal sediment plug, as the inflowing water soaked away through the sediment to a postulated lower-level conduit. The “ramifying horizontal caves” (hall and narrow caves), to which many of the more vertical “rainwater inflow caves” connect were interpreted as “former water dispersion and discharge caves". Shannon's mechanism, like the phreatic mechanisms discussed above, involved movement of water, in his case dispersal, through the blind (dead) ends of halls.

Since hall and narrows caves and maze caves are structurally guided networks, mechanisms proposed for the origin of maze caves may help explain the origin of hall and narrows caves. Three, quite different, explanations have been given for the origin of maze caves.

Palmer (1975) proposed two mechanisms by which descending meteoric water could produce maze caves. The first involved solution from surface waters seeping down into joints in the limestone through a porous cap rock, usually an overlying sandstone bed. The second involved flooding during the evolution of a stream cave. Alternatively, Bakalowicz *et al.* (1987) proposed that rising thermal waters excavated large maze caves in the Black Hills of South Dakota. Similarly, Klimchouk (1996) proposed that recharge from a basal, non-karst; aquifer (ie. artesian processes) excavated large gypsum maze caves in the Ukraine.

Except in a few cases, where sandstones and laterites unconformably overly limestone, network caves in eastern Australia do not occur in limestones that are either stratigraphically or topographically overlain by porous cap rocks. At Wyanbene and Bungonia, sandstone and laterite cap rocks appear to have inhibited, rather than promoted, cave development (Osborne, 1996). Thus, Palmer's seeping solution mechanism does not apply.

Few true mazes, or hall and narrows caves, in eastern Australia appear to have formed by flooding during the evolution of a stream cave. Most maze caves in eastern Australia do not contain passages that have formed as streamways. The large elongate passages in these caves are halls, with blind terminations along their principal axis and speleogens indicating solution by slowly convecting phreatic water. While significant streams flow through Exit Cave (Fig. 3), Osborne and Cooper (2001) noted that passage size does not increase systematically downstream of junctions, in fact in some cases it actually decreases. This type of passage behaviour was seen by Bakalowicz *et al.* (1987) as being characteristic of maze caves formed by rising hydrothermal water.

Fundamental questions concerning the origin of hall and narrows caves include:

- how were halls excavated if water did not *flow* along, or out of them?
- how were convection currents generated in the nothephreas?
- how did water become or remain aggressive?
- why is there an association with silicification, dolomitisation and pyrite?
- why do these caves frequently intersect palaeokarst?

These might be explained if the caves were dissolved (at least in part) by rising artesian or hydrothermal waters. Hall and narrows caves have many characteristics similar to those cited by Dublyansky (1980) and Bakalowicz *et al.* (1987) as indicating a hydrothermal or artesian origins in that they:

- have a poor relationship with surface topography
- have poor connections with surface hydrology
- expose and intersect palaeokarst
- have cave walls that show signs of chemical alteration
- have crystal linings and contain unusual minerals
- were dissolved by slowly-moving water
- exhibit a high degree of structural guidance
- have cupolas developed in their highest parts

I used this type of evidence to propose that Jenolan Caves underwent at least one phase of hydrothermal development during their complex history (Osborne, 1999b).

Some hall and narrows caves may have developed under conditions similar (but with tilted bedding) to the "upward recharge from a basal aquifer" process described in gypsum maze caves by Klimchouk (1996). Hall and narrows caves, such as Yessabah Bat Cave, are developed in the Permian Yessabah Limestone west of Kempsey in northern New South Wales. The upper beds of the Yessabah Limestone are strongly silicified (possible aquiclude), while the lower beds are composed of purer, more massive limestone. Cave development is largely restricted to the lower beds. Stratigraphically and physically underlying the limestone are clastic sediments, including shales, sandstones and conglomerates which may have acted as a granular aquifer, feeding artesian water up into the massive limestone.

Research is continuing into the origin of these caves, with evidence for the role of warm, rising water being evaluated. Emphasis is being given to mineralogy, stable isotope studies and the detailed morphology of halls, narrows and cupolas.

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