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Jim England

Vanishing Falls, South West Tasmania

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KARST GEOMORPHOLOGY AND BIOSPELEOLOGY AT VANISHING FALLS, SOUTH-WEST TASMANIA

Rolan. Eberhard, Stefan. Eberhard and Vera. Wong

ABSTRACT

A speleological expedition to Vanishing Falls explored a 2.3 km long cave associated with the underground course of the Salisbury River, and provided the first systematic documentation of karst features and cave ecology in this remote area. A major limestone gorge has been incised below Vanishing Falls by the Salisbury River, although flow through the gorge now occurs only episodically due to the formation of subterranean conduits. Large volumes of meltwater and an abundance of lithic tools during Pleistocene glacial episodes are likely to have facilitated both gorge and cave development. The recent evolution of the system is characterised by the initiation of subterranean drainage from a pool at the base of the falls, and paragenesis in response to large scale cave and valley aggradation. The caves host a fauna comprising at least 30 taxa, of which probably more than 14 are troglobitic or stygobiontic. This fauna exhibits a high degree of troglomorphy, with some species likely to be endemic to the Vanishing Falls karst.

INTRODUCTION

Vanishing Falls is located 80 km south-west of Hobart in the Tasmanian Wilderness World Heritage Area. This spectacular feature was first spotted from the air in the late 1940s, probably by pilot Lloyd Jones. Following an aerial reconnaissance in 1972 (Shaw, 1973), a party on a trip of several weeks duration reached Vanishing Falls on foot. No major caves were found and interest in the speleological potential of the area languished until 1992 when a trip was undertaken utilising a helicopter to transport a small party that spent two weeks at Vanishing Falls (Wong, 1992). The expedition documented an extensive and hitherto unexplored cave system associated with the underground course of the Salisbury River, and made the first collections of cave invertebrates in this remote area.

The catchment of the Salisbury River above Vanishing Falls is an area some 42 km^2 in extent defined by the summits of Precipitous Bluff (1145 m) on the west, and Mt. Victoria Cross (1120 m) and Mt. Bisdee (1005 m) to the east. The base of the falls is at an altitude of approximately 350 m. The nearest meteorological station is Hastings, 19 km to the east, which experiences a mean annual rainfall of 1417 mm and mean daily maximum and minimum temperatures of 16.0° C and 6.1° C respectively (Bureau of Meteorology, 1988). The vegetation at Vanishing Falls consists of temperate rainforest dominated by myrtle (*Nothofagus cunninghami*), with King Billy pine (*Arthrotaxis selaginoides*) prominent along the upper margin of the gorge below the falls.

Geological mapping (Dixon and Sharples, 1986) suggests that limestone at Vanishing Falls is part of an almost continuous belt of Ordovician Gordon Group carbonates that extends southward from Wargata Mina (Judds Cavern) along the valleys of the South Cracroft River and New River to outcrop on the slopes of Precipitous Bluff (Figure 1). The limestone is generally overlain by Permian non-carbonate sedimentary rocks of the Parmeener Supergroup (G. Dixon, pers. comm.). At Vanishing Falls the contact between the horizontally bedded limestone and overlying sediments has been intruded by a sill of Jurassic dolerite.

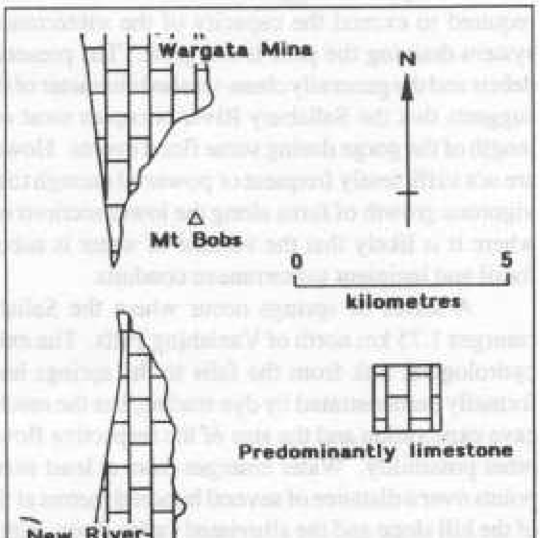

Figure 1. Interpretive geological map showing the possible extent of late Ordovician Gordon Group carbonates in the Mt. Bobs-Precipitous Bluff area. After Dixon & Sharples (1986).

SURFACE GEOMORPHOLOGY

At Vanishing Falls the Salisbury River plunges over 60 m high dolerite cliffs into a 40 m diameter pool where its flow is abruptly lost underground. The contact between the dolerite and underlying limestone is some 10 m above the base of the falls. On the basis of soundings with a weighted line by a wet-suited swimmer, this pool is tentatively concluded to have a maximum depth of 7 m. Extending north from this point for a distance of nearly 2 km is an impressive gorge formed principally in limestone, although cliffs of columnar dolerite extend for several hundred metres along the eastern side of the gorge immediately below the nickpoint of the falls. The mid section of the gorge is characterised by a V-shaped profile with steep sides up to 120 m high including tiers of limestone cliffs in places.

An estimated flow of 1 cumec, representing some 30-50% of the total volume of the river above the falls, was present along the initial section of the gorge at the start of the recent expedition on 16/4/1992. This water was sinking underground through humanly impenetrable crevices between boulders in the river bed down to a point 0.5 km downstream of the falls ("1" in Figure 2), though 18 hours later outflow from the pool had ceased entirely. Only 13.4 mm of rain was recorded at Hastings over the 24 hours prior to the morning of the 16th, and no rain occurred there over the preceding 7 days. The likelihood of similarly low levels of precipitation in the catchment of the Salisbury River suggests that the amount of additional flow required to exceed the capacity of the subterranean conduit system draining the pool is not great. The presence of flood debris and the generally clean-washed character of the riverbed suggests that the Salisbury River occupies most or all of the length of the gorge during some flood events. However, flows are not sufficiently frequent or powerful enough to prevent the vigorous growth of ferns along the lower sections of the gorge where it is likely that the volume of water is subtracted into fossil and incipient subterranean conduits.

A series of springs occur where the Salisbury River resurges 1.75 km north of Vanishing Falls. The existence of a hydrological link from the falls to the springs has not been formally demonstrated by dye tracing, but the results of direct cave exploration and the size of the respective flows allow no other possibility. Water emerges from at least seven discrete points over a distance of several hundred metres at the junction of the hill slope and the alluviated valley floor, with additional outflows becoming operative at high stage. Some of these flows originate from partly-submerged cave entrances, while other springs appear to emerge wholly from colluvium. A large doline that is highly visible from the air is located approximately 60 m higher than the springs and directly over the mapped position of underground passages in Salisbury River Cave. The southern side of the doline is a vertical bedrock wall some 40 m high; the opposite side has been degraded to a gently sloping ramp. A smaller doline of collapse origin is located nearby. This has Parmeener Supergroup bedrock exposed in its upper walls. Several other significant dolines are located midway along the gorge on its upper western slopes.

An additional and rather enigmatic feature is Pungalannar Pool. The pool is elliptical in shape, of uncertain depth, and located on the valley floor within 0.5 km of the Salisbury River resurgence. Its status as a karst feature has not been confirmed.

The toppling of dolerite columns many metres in length appears to be the principal source of the massive amount of dolerite that is present throughout the gorge and which largely obscures the underlying bedrock floor. Clasts of limestone are generally rare amongst the dolerite in the riverbed, although at several points there are limestone blocks up to 8 m in diameter that have obviously fallen from the cliffs above. Sheeting or unloading joints that result from the release of stress accompanying valley erosion (Jennings, 1980, Kiernan, 1982) may well have facilitated the detachment of large blocks from the slopes. A karst tower-like form some 15 m in height and separated from the adjacent cliff by a gap of several metres, seems to be associated with an unloading joint that cuts through a buttress at a bend in the gorge.

The microtopography of limestone surfaces exposed in the floor of the gorge displays considerable variety. Bedrock surfaces subject to mechanical erosion during flood events are mostly of smooth aspect and lack scalloping or other solutional sculpturing. In some cases spectacular coralline fossils 200-300 mm in diameter are exposed, and often these have been preferentially eroded to form concave hollows. Rainwater collecting in these depressions probably results in their further enlargement by chemical means. Bedrock surfaces that have not been smoothed by fluvial processes generally exhibit highly rugose textures influenced by the presence of numerous silty horizons in the limestone. More rarely, classical karren varieties are present. Maanderkarren 1-2 m in length and extending from large solution pans (kamenitsa) have developed in considerable depth at one point, with incipient rillenkarren forms present on the raised edges of the larger runnels. Other examples of rillenkarren are almost exclusively restricted to the unusual context of the surfaces of exposed coral fossils. Rundkarren, a common form elsewhere in Tasmania, is not greatly in evidence.

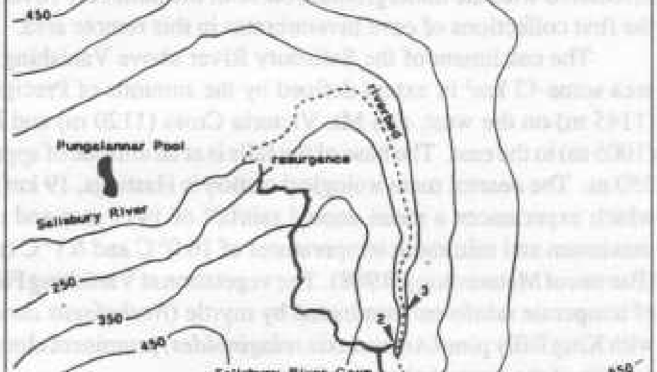

Figure 2. Salisbury River Cave. Surveyed with Suunto compass and clinometer read to the nearest 1.0° and 30 m fibreglass tape to the nearest 0.1 m. Passages upstream of Gorge Entrance were surveyed by pace and compass. Fossil or intermittently active inflow points are indicated by arrows: 1 = Downstream limit of flow on 16/4/92, 2 = Gorge Entrance, 3 = Bushwalkers Cavern.

CAVE DEVELOPMENT

Associated with the underground course of the Salisbury River is a major cave system that was explored for the first time during the recent expedition (Figure 2). 1910 m of passage was surveyed in this cave, with an additional estimated 400 m of passage explored but not surveyed. The major portion of the system consists of a river passage up to 12 m in height and typically 4 m in width, with a basically rectangular cross-section that reflects the influence of horizontal bedding in the host rock. The downstream end of this passage consists of a 200 m long section of canal which is occupied by slow moving water in excess of 2 m deep. The passage upstream of this section is characterised by very fast moving water 0.5-1 m deep, often in the form of small rapids. Sections of open passage are regularly interspersed with short blocky rockfalls that seem to have been caused by lateral meandering by the river and wall undercutting. An entrance mid-way along the Salisbury River gorge (Gorge Entrance; "2" in Figure 2) has obviously acted as a swallet during a major portion of the cave's evolution. It is now stranded several metres higher than the floor of the gorge and well above the level of contemporary flood flows. This section of the cave consists of a broad horizontal gallery 100 m in length that contains an area of profuse and currently active carbonate deposition which is noteworthy in the context of an almost total absence of speleothems elsewhere in the system. A steep slope connects this passage to the active level 20 m below.

The continuation of the main streamway upstream of where Gorge Entrance joins is quite distinct from the lofty passages downstream of this point. The passage becomes relatively low and enters an area of extensive slab breakdown prior to passing underneath the gorge at a depth of only 20-30 m. Beyond this point is a wide, low chamber that leads to the base of a waterfall. This waterfall, which could be seen continuing upwards for at least 15 m above the highest point reached, marked the upstream limit of recent explorations. The moderate gradient of the cave up to this point suggests a steep hydraulic gradient over the intervening 0.6 km of horizontal distance to the base of Vanishing Falls.

The most complex part of the cave lies at its downstream end. Access to the system was initially gained via a flood overflow passage in this area. This passage branches off the main riverway, rising 7 m over a linear distance of 180 m and becoming progressively lower, changing from a spacious elliptical tube to a flattened bedding-plane rift. An area of breakdown and constricted anastomosing development is encountered as the passage approaches the margin of the hill. Foam observed throughout this section indicates that it had been inundated not long prior to the recent explorations. The downstream continuation of the riverway is partly blocked by large collapsed blocks beyond which lies a complex of large passages containing massive accumulations of silt and vegetable detritus. At least one tributary stream joins here, although the Salisbury River itself is not encountered again in this section of the cave. Exploration of this area was very cursory and time did not permit its surveying.

Bushwalkers Cavern is another entrance located a short distance downstream of Gorge Entrance ("3" in Figure 2). This cave consists of a spacious horizontal tunnel on the eastern side of the base of the gorge (Figure 3). Its development has been influenced by a major joint that is clearly visible in the ceiling of the initial passage. 30 m from the entrance is a more open area where a minor tributary showers from above and an apparent continuation has been choked by logs and clastic material. Unlike Gorge Entrance, Bushwalkers Cavern Cave appears to act as a contemporary inflow point for the Salisbury River when overland flow penetrates this far during flood events.

A number of caves of quite different character are located on the western slopes of the gorge in the order of 50-100 m above the riverbed. Several of these take the form of vertical rifts which, in the case of Alley Pot (Figure 4), seem to result primarily from the dilation of unloading joints. The narrow, parallel walls of this cave suggest that only minor modification is attributable to vadose water, though it would appear to offer an efficient route for descending allogenic runoff. Despite the existence of several small swallets near the upper limit of the limestone, overland flow to the base of the gorge is common. This may reflect the abundance of numerous silty horizons in the limestone which discourage the penetration of descending vadose water, though the steep gradient, rapid gorge incision, and slope deposits may also be implicated. In at least one instance, allogenic water is discharged from an entrance ca.60 m above the floor of the gorge. The associated cave (Waterfall Spring Cave) contains 100 m of low passage interspersed with small chambers. This cave appears to have formed as a result of the horizontal deflection of water originating in one or both of two nearby swallets.

At the base of Vanishing Falls is a shelter-type cave that has developed at the contact between the limestone and the dolerite intrusion. It consists of a wide chamber 23 m in length that becomes progressively lower with increasing distance from the main entry point. The ceiling is formed in dolerite while the floor is limestone metamorphosed to a virtual calcsilicate hornfels (Dixon and Sharples, 1986).

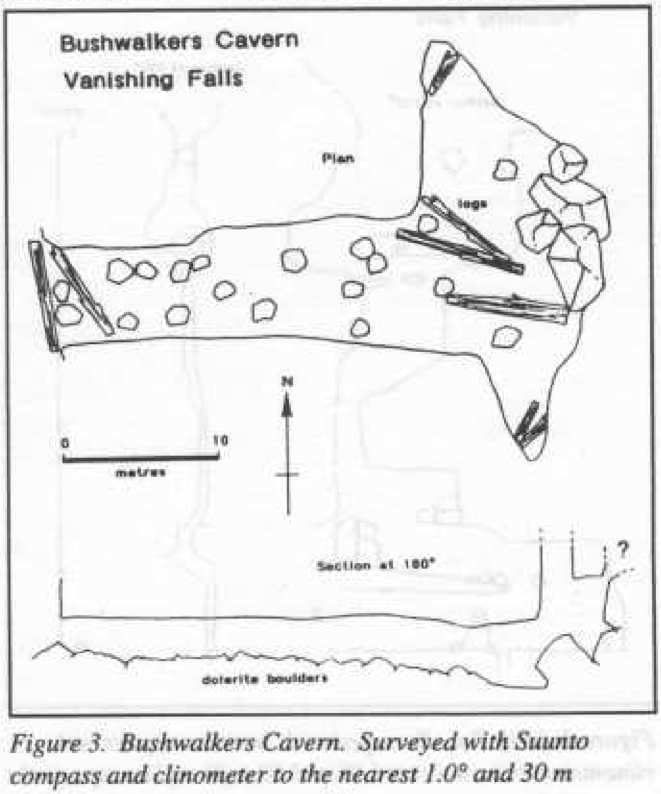

Figure 3. Bushwalkers Cavern. Surveyed with Suunto compass and clinometer to the nearest 1.0° and 30 m fibreglass tape to the nearest 0.1 m.

INFLUENCES ON KARST EVOLUTION

Late Cainozoic climate change, notably the advent of cold conditions that implied a suite of processes quite different to that of the Holocene, has been a major influence on karst evolution in Tasmania. Evidence of at least four glaciations has been identified in central and western Tasmania (Kiernan, 1990a, Colhoun and Fitzsimons, 1990). The impact of these events on karst has been varied and sometimes ambiguous, involving processes conducive to karstification in some instances and destructive or impeding in others (Kiernan, 1982, 1983, 1989, 1990b, 1990c). It is clear that glacial and periglacial processes have been highly significant in the geomorphic history of high altitude areas in the vicinity of Precipitous Bluff. Lewis (1925) and Davidson (1971) found ample evidence of intense glaciation on nearby Mt. La Perouse, as did Colhoun and Goede (1979) in the Picton Range-Mt. Bobs area to the immediate north of Vanishing Falls. Kiernan (1989) has argued that glaciation has been a major influence on karstification in the Lake Sydney-Cracroft area.

No detailed mapping of glacial features has yet been undertaken on Precipitous Bluff itself. However, the north-south orientation of the extensive summit ridge is likely to have encouraged the accumulation of ice in its lee which presumably fed valley glaciers occupying the basin at the headwaters of the Salisbury River. There is evidence that ice descended to below 100 m ASL in the valleys of the Picton and D'Entrecasteaux Rivers, and may even have approached present sea level at South Cape Rivulet (Kiernan, 1987). Thus, it is plausible that glacial ice extended to below the level of Vanishing Falls (350 m) on at least one occasion, possibly during a severe glacial episode in the early Pleistocene or late Pliocene when an ice cap of ca. 6000 km^2 was present in central Tasmania (Kiernan, 1990a). Subsequent glaciations were of a lesser intensity, with late Last Glacial ice restricted to around 700 m at Pine Lake on Mt. Bobs (Colhoun and Goede, 1979) and near Oval Lake in the Southern Ranges (Kiernan, 1987). The influence of these later glacial episodes on karst development at Vanishing Falls is therefore most likely to have been mainly in terms of periglacial effects and meltwater rather than the direct action of glacial ice. Meltwater armed with hard lithic tools available either as glacial or glaciofluvial detritus, or from dolerite rockfalls in the upper section of the gorge, is likely to have been a potent erosive force at times when flows were sufficient to mobilise these as tools for mechanical erosion.

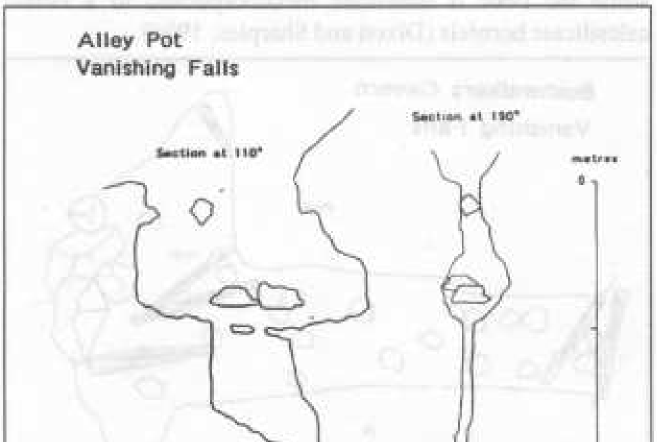

Figure 4. Alley Pot. Surveyed with Suunto compass and clinometer to the nearest 1.0° and 30 m fibreglass tape to the nearest 0.1 m.

While there is no doubt that the modern Salisbury River has the capability of shifting coarse clastic material, several factors suggest that corrasion is less important in effecting contemporary cave enlargement than has been the case in the past. A reduced mobility of clastic material relative to that occurring under the influence of torrential Pleistocene meltwater flows is to be expected. Some corrasion associated with the reworking of allogenic sediments derived from the Gorge Entrance phase is to be anticipated, but the calibre of clastic material now entering the system is probably confined to fine silts such as have accumulated in large quantities at the downstream end of the cave. Passage walls throughout Salisbury River Cave are characterised by the protrusion of numerous thin silty horizons with a relief of several decimetres. These are easily detached or broken and imply a dominance of gradual weathering by chemical rather than physical means. Water samples taken during the recent expedition indicate an increase in the calcium content of the Salisbury River amounting to a modest 7 ppm between Vanishing Falls and the point of resurgence (Table 1), of which at least some is likely to have been contributed by additions of autigenic water. In the context of an estimated baseflow in the range 2-3 cumec, this still implies the removal of considerable limestone. The tannin-stained appearance of the Salisbury River suggests that the water owes some of its aggressivity to the presence of humic and fulvic acids (Ford and Williams, 1989).

	Vanishing Falls	Resurgence
Temperature (°C)	8.6	7.8
Total hardness as $CaCO_3$ (ppm)	12	30
Calcium hardness (ppm)	8	26

Table 1. Temperature and hardness of the Salisbury River at Vanishing Falls and its resurgence 1.75 km away. Hardness determinations by EDTA titration of samples collected on the 28/4/92.

Cave development elsewhere in Tasmania often reflects the influence of steeply dipping limestone beds, with passage alignment typically parallel with the strike. Limestone at the base of Vanishing Falls and in the vicinity of the resurgence dips to the northwest and north at 10° and 11° respectively (Dixon and Sharples, 1986). The roughly north-south orientation of Salisbury River Cave does not exclude the possibility that some passage development has been guided along the strike, albeit that hydraulic gradient and the influence of joints potentially explain the gross configuration of the system. A comparison of rose diagrams of joint direction frequencies in the floor of the gorge and survey leg direction frequencies in the cave offers some support for the role of joints in guiding speleogenesis (Figure 5). The dominance of a north-south and east-west conjugate joint set is clearly visible in the rose diagram for the gorge. Caves on the upper slopes of the gorge such as Alley Pot probably owe their existence to the dilation or vadose enlargement of unloading joints, and Bushwalkers Cavern is developed along a major joint.

Recapture of the Salisbury River by the older conduit associated with Gorge Entrance seems to have engendered a new phase of speleogenesis at the outflow end of the system. Flood overflow passages that provided access to the riverway during the recent explorations appear to be essentially paragenetic, viz. a result of upwards erosion due to the aggradation of cave passages (Jennings, 1987). Paragenesis seems to have been occasioned partly in response to valley aggradation that has completely buried the original resurgence point. A complex of unsurveyed flood overflows at the downstream end of the cave contain some passages that are of a size which suggests that they represent the top level of the main river passage, which is now largely buried by sediment.

CAVE ECOLOGY

All animals living in caves can be called cavernicoles. The ecological classification of cavernicoles consists of three major categories, as defined by the Schiner-Racovitza system (Vandel, 1965). Troglobites are species which are obligatory cavernicoles and which, in nature, are unable to survive except in caves or similar subterranean habitats. Troglobites are often distinguished by morphological specializations called troglomorphisms, which may include loss or rudimentation of eyes and pigment, and attenuation of the body, appendages, or sensory hairs (Holsinger and Culver, 1988). Troglophiles are facultative cavernicoles. They are found living permanently, and successfully completing their life cycles, in caves, but they also do this in suitable epigean or endogean habitats. Trogloxenes are species habitually found in caves but which do not complete their whole life cycle there and must return periodically to the surface or entrance zone for food. A further category are the accidentals, which are species that wander, fall, or are swept into caves. They survive for varying lengths of time, and larval forms may metamorphose to adults, but further generations are not established within the cave. Obligate subterranean species living in subterranean waters may be referred to as stygobionts. Facultative species are termed stygophiles.

With some exceptions, the geographic ranges of troglobitic species are generally small and sometimes island-like (Holsinger, 1988). They tend to correlate with separate exposures of cavernous rocks. In many limestone cave regions, closely related species are found in adjacent karst areas or in cave systems separated from each other by some kind of physical barrier. The restricted distributions of many terrestrial troglobite species imply that they are relicts of formerly widespread epigean faunas. Extinction of the surface fauna and isolation of the cave populations is a favoured explanation for speciation in many temperate zone cavernicoles (Barr and Holsinger, 1985). Inimical climate changes during the late Cainozoic are seen as important in causing surface extinctions. Many terrestrial troglobite species are derived from hydrophilic forest-litter and soil-dwelling ancestors. These species are pre-adapted to life in the cool, wet environment of caves. Therefore, caves may act as refugia for populations when surface conditions are unfavourable. Subsequent genetic divergence of these isolated populations, along with specialization to an obligate subterranean existence, explains the highly disjunct distribution patterns.

The karst areas of southern Tasmania rank among the richest, biologically, in the temperate zone of Australia (Eberhard *et al.*, 1991). The Precipitous Bluff karst, for instance, supports at least 15 species of troglobites. In addition, this area has some of the most highly troglomorphic representatives in several genera, including amphipods (genus *Antipodeus*), beetles (genus *Idacarabus*), harvestmen (genera *Hickmanoxyomma*, *Lomanella* and *Mestonia*) and molluscs (genus *Pseudotricula*). The diversity of hydrobiid molluscs at Precipitous Bluff (6 species) is equal to the highest sympatric diversity seen anywhere in Australia (W. Ponder, *pers. comm.*). Similarly, the harvestmen fauna is represented by 4 species in 3 genera, which is more species than has been found in any other single Tasmanian karst area. Other karst areas in southern Tasmania,

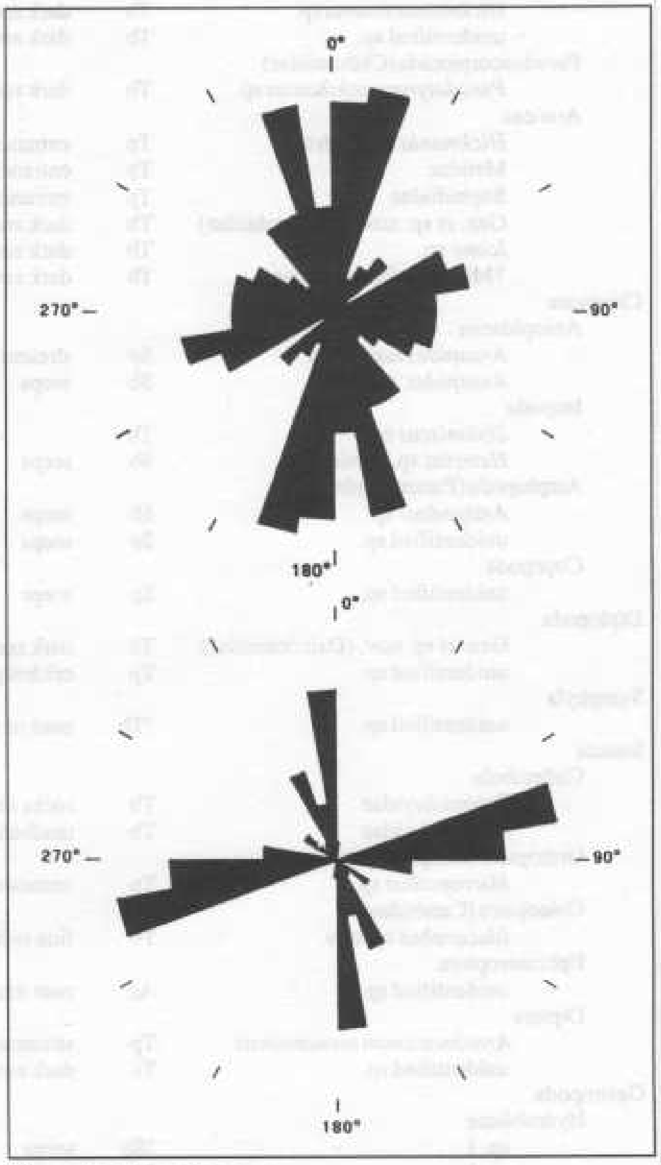

Figure 5. Rose diagrams.
Top: Survey leg direction frequencies in Salisbury River Cave.
Lower: Joints direction frequencies in the Salsibury River gorge on the basis of 46 measured joint strikes.

such as Cracroft and Ida Bay, also have a high biodiversity, the latter area coming close to Precipitous Bluff in terms of numbers of troglobitic species. Precipitous Bluff and Ida Bay have already been the subject of several biological studies, for example: Eberhard and Hume (1987), Eberhard (1990), Eberhard *et al.* (1991), Kiernan and Eberhard (in press), Hunt (1990), Hunt and Hickman (in press), Ponder (1992), and Richards and Ollier (1976). Until recently, however, the biological resources of the Vanishing Falls karst remained unknown, and the first cave species list for the area is given below. The fauna is compared with other nearby karst areas, and its significance and conservation status are discussed.

Taxa	Status	Habitat
Platyhelminthes		
Tricladida (planarians)	?Sb	seeps
Annelida		
Oligochaeta	Sp	mud in streamways
Arachnida		
Opiliones (Triaenonychidae)		
Hickmanoxyomma sp.	Tb	dark zone
unidentified sp.	Tb	dark zone
Pseudoscorpionida (Chthoniidae)		
Pseudotyrannochthonius sp.	Tb	dark zone
Araneae		
Hickmania troglodytes	Tp	entrance - twilight zone
Metidae	Tp	entrance zone
Stiphidiidae	Tp	entrance - twilight zone
Gen. et sp. nov. (Amaurobiidae)	Tb	dark zone
Icona sp.	Tb	dark zone
? Micropholcommatidae	Tb	dark zone
Crustacea		
Anaspidacea		
Anaspides tasmaniae	Sp	streams
Anaspides sp.	Sb	seeps
Isopoda		
Styloniscus sp.	Tb	
Heterias sp. (Janiridae)	Sb	seeps
Amphipoda (Paramelitidae)		
Antipodeus sp.	Sb	seeps
unidentified sp.	Sp	seeps
Copepoda		
unidentified sp.	Sp	seeps
Diplopoda		
Gen. et sp. nov. (Dalodesmidae)	Tb	dark zone
unidentified sp.	Tp	cricket guano
Symphyla		
unidentified sp.	?Tb	mud or rocks in the dark zone
Insecta		
Collembola		
Entomobryidae	Tb	rocks near seeps
Oncopoduridae	Tb	mudbanks
Orthoptera (Rhaphidophoridae)		
Micropathus sp.	Tp	entrance - dark zone
Coleoptera (Carabidae)		
Idacarabus sp. nov.	Tb	fine sediments in the dark zone
Ephemeroptera		
unidentified sp.	Ac	near main stream - dark zone
Diptera		
Arachnocampa tasmaniensis	Tp	streamways
unidentified sp.	Tx	dark zone
Gastropoda		
Hydrobiidae		
sp. 1	?Sb	seeps
sp. 2	Sp	seeps and streams

Table 2. List of invertebrate taxa, including their ecological status and habitat, recorded from caves in the Vanishing Falls area.
Abbreviations: Tb = troglobite, Tp = troglophile, Tx = trogloxene, Sb = stygobiont, Sp = stygophile, Ac = accidental.

FAUNA LIST & DISCUSSION

Field work was conducted in the Vanishing Falls area from 16-30 April 1992. Some taxa could be readily identified without having to collect specimens. Where collection of specimens was necessary, this was limited to the minimum number of individuals required for identification. In most cases this amounted to the taking of only one, or a few, individuals. At all times, particular care was taken to ensure that no one taxon, or cave, was subject to over-collecting. Specimens were collected by hand-picking directly from the substrate, aided only by forceps, small brushes, pipettes or hand nets. The collection is held with other cave fauna material at the University of Tasmania Zoology Department.

The cavernicolous fauna of the Vanishing Falls karst consists of at least 30 taxa, comprising 1 platyhelminth, 1 oligochaete, 1 symphylid, 2 molluscs, 2 diplopods, 7 insects, 7 crustaceans and 9 arachnids. Nearly half of these taxa (14) are troglobitic or stygobiontic, while 2 others may possibly be so. Like other karst areas in southern Tasmania, there is high biodioversity, including cave obligate species. All the Vanishing Falls populations of troglobites or stygobionts can be classified as 'rare' under the International Union for the Conservation of Nature classification scheme. The conservation status of these species appears to be adequately protected at the present time due to Vanishing Falls' remoteness and its location within the Tasmanian Wilderness World Heritage Area. However, the taxonomy of many of the groups remains poorly known and further work needs to be undertaken.

All the groups recorded are characteristic inhabitants of the different cave habitats sampled. Collectively, they represent a typical invertebrate cave community found in Tasmania. However, this survey could not cover all the possible types of habitat available to cave invertebrates and there are several notable absences from the list. These absences include the syncarid *Eucrenonaspides*, which is unusual because it is known to occur at Precipitous Bluff, Cracroft and Ida Bay. These animals are rare and cryptic however, as are the trechine cave beetles. Trechines were not recorded either, but they do occur at Ida Bay and Precipitous Bluff. The harvestmen fauna at Vanishing Falls comprises at least two species, including the widespread cave genus *Hickmanoxyomma*. A genus which was not recorded is *Lomanella*, though it is present at other nearby karst areas. Amongst the spiders, representatives of

Olgania and *Tupua* were not recorded. A conspicuous new genus of hydrobiid, *Pseudotricula*, (Ponder, 1992) was not seen either, so this unusual snail appears to be confined to the Precipitous Bluff caves. Further searching may well reveal the presence of some, or all, of these groups at Vanishing Falls.

Like the Precipitous Bluff fauna, the Vanishing Falls fauna is of particular interest due to the comparatively high degree of troglomorphy exhibited by some taxa. The implication is that these taxa have been isolated in caves for a longer period of time than their less troglomorphic congeners from other areas. The cave beetle, for instance, is a new species in the genus *Idacarabus*. It shows a high degree of troglomorphy, comparable with, or more troglomorphic, than *I. longicollis* from Precipitous Bluff. Similarly, the amphipod *Antipodeus* is highly troglomorphic because it lacks all pigment and eyes, and possesses relatively elongate appendages. Entomobryid springtails collected at Vanishing Falls also appear highly troglomorphic, having very long appendages - the antennae and claws in particular.

Aquatic habitats at Vanishing Falls were found to be rich in both species and individuals. One small seepage-fed watercourse in Salisbury River Cave, for example, contained a total of 6 taxa including planarians, syncarids, amphipods, heteriids and two species of hydrobiid molluscs. The hydrobiid fauna is widespread and abundant in the caves at Vanishing Falls, but it appears to lack the level of diversity found at Precipitous Bluff (6 species). A species of small, white planarian is common in seepage habitats, and it may be a stygobiont. At least two forms of *Anaspides* were found underground, an epigean form with normal pigmentation, plus a non-pigmented form. One vertebrate was recorded underground, a galaxiid fish sighted in Salisbury River Cave.

More so than mainland Australia, the Tasmanian cave fauna shows a pattern of similarity with the cave faunas of other periglacial regions such as New Zealand, Japan, United States and Europe (Hamilton-Smith, 1967). The geomorphic evidence indicates that profound environmental changes occurred during the late Cainozoic in many Tasmanian karsts; some of these changes were partly facilitated by vegetation changes on the surface that were driven by climatic change (Kiernan and Eberhard, in press). The evolution of terrestrial cave species at Vanishing Falls, and elsewhere in Tasmania, is likely to have been strongly influenced by these climatic changes. The vicariant distributions of species in genera such as *Idacarabus* and *Hickmanoxyomma* support the Pleistocene climatic-effect theory (Barr, 1968) for the origin of terrestrial troglobites in temperate regions.

ACKNOWLEDGEMENTS

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RADON HAZARD IN CAVES: A MONITORING AND MANAGEMENT STRATEGY

R G Lyons

ABSTRACT

Radon is well known to accumulate to hazardous levels in some buildings and mines associated with uraniferous rocks but, because of the low radioactivity in most limestone rocks, dangerous levels were not anticipated in caves. The potential health hazard of radon in caves was first mooted in 1975 at the National Cave Management Symposium, New Mexico, but has recently become a topic of considerable concern. Factors governing the accumulation of radon in caves are discussed. Preliminary measurements in some Australian caves show levels which vary by factors of 4 (seasonal) and 75 (diurnal), with the upper levels approaching recommended maximum exposure levels for some tourist cave guides. A workshop comprising interested scientists and cave managers was held in Canberra in April 1992. This meeting outlined a 3-tier research program designed to assess the seriousness of this problem and agreed that funding should be sought to action it. The usefulness of gamma spectrometer measurements to estimate radon concentrations is also discussed.

INTRODUCTION

Radioactivity in the environment is a cause of increasing concern to the general public: radon in particular has been highlighted as a potential hazard in houses, mines and caves. Environmental radiation arises from cosmic sources and from the decay of radionuclides, either naturally occurring, concentrated by industrial processes or produced artificially in nuclear reactions. Radiation from radionuclides is of three principal types, alpha, gamma and beta. Of these, only gamma radiation penetrates more than a few millimetres into solids and it is therefore usually the only type of radiation of concern for human health. However, if the radioactive substances are ingested, inhaled, or are in close contact with the body, alpha and beta radiation, which deposit their energy in a very small distance (a few micrometres or millimetres, respectively) may cause serious damage leading to an increased risk of cancer.

Cosmic radiation is negligible underground because most of it is absorbed by the overlying rocks before reaching the caves; more than 98% will be absorbed by 10 metres of rock. Almost all the radiation in caves arises from the decay of naturally occurring uranium and potassium. The decay chain of the most common uranium isotope, ^{238}U, is given in Table 1.

Radionuclide	Energy (MeV)	Type of Radiation	Half-life
^{238}U	4.2	alpha	4.5×10^{9} yrs
^{234}Th	0.2	beta	24 days
^{234}U	4.8	alpha	2.5×10^{5} yrs
^{230}Th	4.7	alpha	8.0×10^{4} yrs
^{226}Ra	4.8	alpha	1.6×10^{3} yrs
^{222}Rn	5.0	alpha	4 days
^{218}Po	6.0	alpha	3 min
^{214}Pb	0.2	beta	27 min
^{214}Bi	1.5	beta	20 min
^{214}Po	7.7	alpha	1.6×10^{-4} sec
^{210}Pb	0.2	beta	22 years
^{210}Bi	4.9	beta	5 days
^{210}Po	5.3	alpha	138 days
^{206}Pb	STABLE		

Although radiation from radon itself is a relatively small percentage of the total radiation dose received from the environment, its health implications may be considerable. While the other decay products of uranium are solids, radon is a gas and therefore capable of migrating from the parent matrix into ambient air where it forms efficient condensation nuclei and is also readily adsorbed to particulate matter. These particles may then be inhaled and, depending on their size, may lodge in various parts of the lungs. Very coarse and very fine particles are least hazardous, because coarse particles are generally filtered by the nasal hairs while fine particles are exhaled freely. Particles of intermediate size (<4 nm, >10 µm) which are more likely to lodge in the lungs are considerably more hazardous because the alpha radiation emitted by radon daughters is brought into intimate contact with body tissue.

Radon dosimetry is very complex, determined not only by the concentration of radon in the air, but also by whether the daughter products are in equilibrium with radon, the size of the particulate matter in the air, the percentage of radon attached to particles, and the response of different tissues to radiation (the relative biological effectiveness of the absorbed dose). The basic unit of radioactivity is the Becquerel, which is one disintegration per second. Health guidelines for recommended maximum exposures over various times are usually expressed in milliSieverts (mSv), which are a measure of the total amount of energy absorbed by the body, or alternatively as working levels (WL), which are a measure of the radiation dose related to recommended maximum exposure times. These times are usually expressed as working level hours (WLH), where 1 WLH represents the dose received by someone exposed to a dose rate of 1 WL for 1 hour.

Table 1. The decay chain of ^{238}U. Major branches only of the decay chain with decay energies 0.1 MeV are shown. All elements are solids except radon, which is an inert gas. Data from Nambi and Aiken (1986) and Friedlander and Kennedy (1955). The decay chains for ^{235}U and ^{232}Th are similar but the radon isotopes in these chains have much shorter half-lives (<4 seconds and <1 minute for ^{219}Rn and ^{220}Rn, respectively), which substantially reduces the chance of radon reaching the cave atmosphere.

The exact relationship between these measurement systems depends on assumptions concerning the factors outlined above, but as a general rule, the relationship is usually taken as:

$$1WL = 0.0735 \text{ mSv} = 3.8 \text{ kBq.m}^{-3}$$

Using these conversions, an employee working for 170 hours in an environment of 1 WL would accumulate a dose of 12.5 mSV, which is one quarter of the recommended maximum yearly exposure for a licensed radiation worker under British regulations (Table 2). The maximum permitted dose of 680WL would be reached, for example, by a worker exposed to 1WL for 680 hours, or 2WL for 340 hours, or 40WL for 10 hours plus 1WL for 280 hours. Typical outdoor levels are very low (0.001 WL) while indoor levels are higher (0.005). These are "background" levels and correspond to yearly doses of 0.7 and 3 mSv respectively. In terms of health, the increase in the risk of lung cancer for a non-smoker exposed continuously to an average level of 0.1 WL is the same as that caused by smoking 1-2 packs of cigarettes a day (US Environmental Protection Agency).

	Dose	WLH
	(mSv per year)	
Employee	50	680
Trainee	15	200
Other	5	58
Statutory limits on radon daughter concentrations (UK)		
0.03 WL	Ionizing regulations apply	
0.05 WL	Government action level for radon in houses	
0.10 WL	Controlled area to be designated	

Ionizing Radiation Regulations, (1985)
National Radiation Protection Board

Table 2. Radiation exposure guidelines and regulations in the United Kingdom. In Australia, exposure to radiation is controlled through State and Territory regulations based on NHMRC recommendations (1980, 1985) which are, in turn, based on the International Commission on Radiological Protection (ICRP) recommendations (1977). Standards are currently being revised downwards ie. maximum permissible exposures are being reduced and IRCP (1991) recommend a maximum of 100 mSv in any 5 year period. NHRMC (1991) endorse these proposed revisions.

While it is reasonable to expect radon to accumulate in houses with poor ventilation built on uraniferous rocks, it was quite unexpected to find potentially hazardous concentrations in caves in limestone which generally has relatively low uranium concentrations. The first alarm bells were sounded in studies of Carlsbad Caverns (Van Cleave, 1975; Ahlstrand and Fry, 1976; Yarborough, 1976) and, more recently, by Gunn (1988), Gunn et al., (1991), and Hyland and Gunn (1992) who drew attention to the problem in caves in the United Kingdom and elsewhere. Concentrations in excess of 40 WL were recorded in Giants Hole, Derbyshire, and values typically ranged around 0.3 WL, well above the 0.05 WL at which UK Ionizing Radiation Regulations come into effect. At 0.3 WL, the maximum yearly permissible dose for an employee would be reached with 200 hours of exposure while, in Giants Hole, a mere 6 hours exposure would suffice (in fact, the exposure for the cavers collecting this data exceeded 6 hours). It should be noted that levels such as this will NOT cause acute radiation sickness but may lead to significantly increased risk of developing lung cancer in the future.

These data raise the question of whether tourist and wild caves in Australia may also pose a health problem. Management strategies such as limitation of access, closure of caves, ventilation, limitation of working hours for employees, have significant implications for tourism and recreational use as well as possible legal and environmental ramifications. Because the data may vary within caves by more than two orders of magnitude and even at the same site at different times by more than one order of magnitude, and because the collection of data can be logistically very demanding, monitoring of caves is not a trivial exercise. This paper sets out the following:

a) a summary of some of the factors governing the accumulation of radon in caves, in order that monitoring programs can be targeted to the areas most likely to present problems,
b) Australian data to date and
c) proposals for a tiered dosimetry program.

PRINCIPLES OF RADON ACCUMULATION IN CAVES

The isotope generally considered to be most likely to pose a hazard is ^{220}Rn, the ^{238}U daughter, as its half-life is sufficiently long for its diffusion into air to be significant and sufficiently short to produce daughters on a human time scale; if the half-life is very short, the radon will have decayed before it reaches the cave air, and if it is too long, the daughter products will not build up to sufficient levels to give a high dose. Recently ^{222}Rn has also begun to receive attention as, although diffusion is less likely because of its shorter half-life (55 seconds cf 3.8 days), the dose received from its daughters may well be greater because of the greater likelihood of the daughters being in equilibrium.

The concentration of radon in cave air is a function of the amount of radon reaching the air and its subsequent dilution. Factors governing the amount of radon reaching the air are the concentration in the surrounding materials, the emanation rate from the materials into pore spaces or cracks within the matrix, and the rate of diffusion of radon through the pore spaces towards the surface (Figure 1). The net amount of radon reaching the air will be the total contribution from all the materials making up the cave environment (rocks, sediments, water and speleothems). Dilution factors to be considered are surface area/cave volume ratio, air movement and cave ventilation, and the loss of radon from the air by plate-out on the cave surfaces. Consideration of these factors in turn can indicate likely areas for high radon concentrations.

(i) Concentrations in cave surrounds. Radon can be expected to be in equilibrium (i.e. to be decaying at the same rate) with its parent uranium in limestone rock, which generally has a low uranium concentration, typically a few ppm. Concentrations are usually several times higher in sediments because thorium adheres to clay particles and thus accumulates. Where uraniferous intrusions are present in the local geology exceptionally high values exceeding 100 ppm have

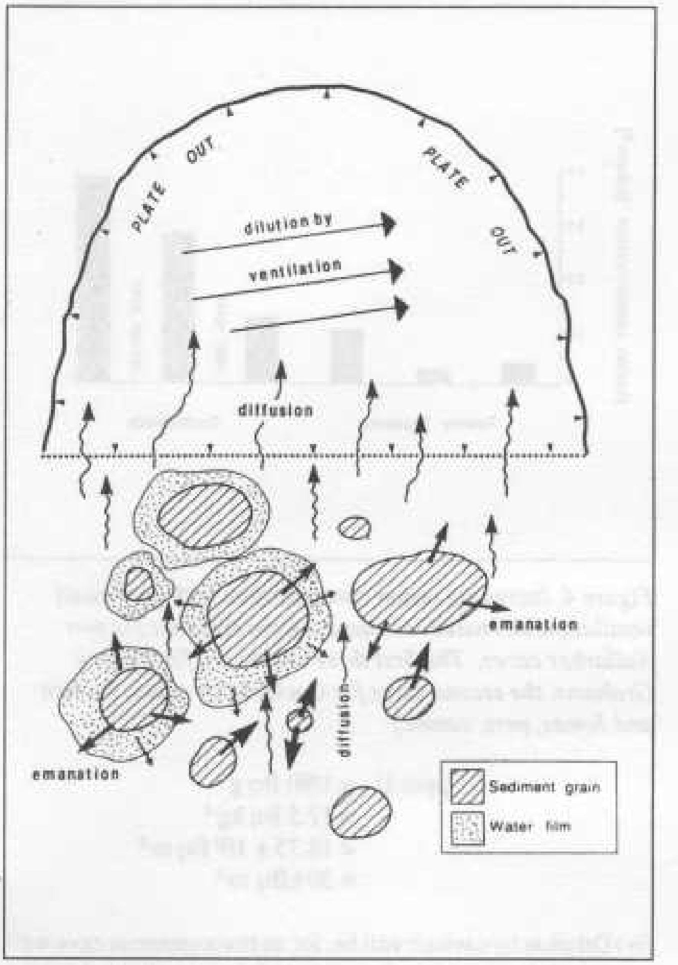

Figure 1. Model of processes affecting radon concentration in cave atmospheres, showing emanation from grains, diffusion through water films and pore air, diffusion into cave air, dilution by ventilation and plate-out.

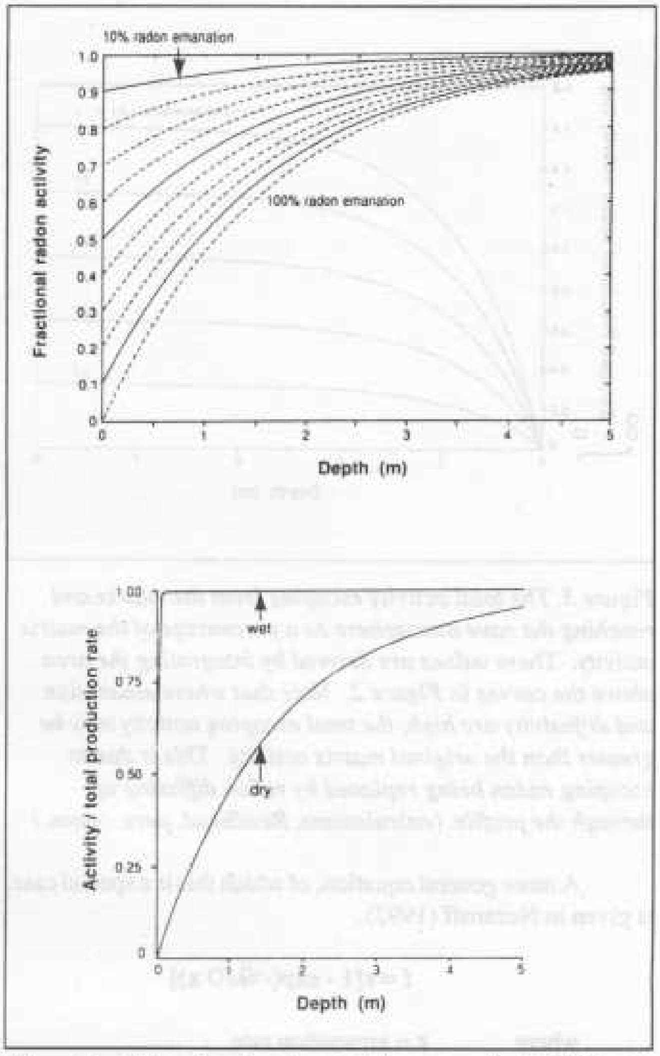

Figure 2. a) Fractional radon activity curves for U-238 series for different emanation rates, redrawn from Readhead (1984). Calculations assume the sediment is dry. The radon diffusion coefficient was taken as 5.4×10^{-2}, which was calculated for buiding sand with a density of 1.4 g cm^{-3}, with a 39% porosity filled with air with a 4% moisture content (Tanner, 1964)

b) Fractional radon activity for two different moisture contents. For wet soil, the amount of radon reaching the atmosphere is negligible. (redrawn from Readhead, 1984)

been observed (Lyons, unpublished data). Shales are also often comparatively high in uranium so sites with shale rock or sediments derived from shale can be expected to be higher in radon. As much as 3-5 m depth of the matrix may contribute radon to the atmosphere, so we would expect sites with significant volumes of sediment to be higher in radon than sites with predominantly rock surrounds. The levels of radon in water may vary by several orders of magnitude, depending on the rock through which the water has passed (Prime *et al.*, 1991). Thus flowing water may increase the radon level in the air through out-gassing or decrease it by solution, depending on the relative concentrations in the air and water.

(ii) Emanation is a function of the material, the size of the grains and the extent of fissuring in the case of rock, with more finely divided material such as silts and clays having higher emanation rates. Rock usually has low emanation rates. Lyons et al (1990) showed that speleothems (stalagmites and stalactites) have negligible emanation except in the unusual case of very finely divided crystals. Thus sites with a high percentage of rocks and speleothems can be expected to be less at risk.

(iii) Diffusion increases with the percentage and connectedness of the pore space. It decreases with increasing moisture content because the moisture present reduces the connectedness of the pore spaces as well as dissolving radon readily. Dry, well sorted sand size sediments, particularly aeolian deposited, will have higher diffusion coefficients and hence contribute proportionately more radon to the cave atmosphere.

External weather patterns may also influence the rate of diffusion because diffusion will be greater when the cave air is at a lower pressure than the pore air. For example, a pressure drop due to the passage of a low pressure system may be reflected in increased radon diffusion.

The set of curves in Figure 2 describe the fractional radon remaining in the matrix for different emanation rates and conditions as a function of depth, according to the following equation (Tanner, 1964). (The fractional radon is the activity of radon after allowing for emanation and diffusion divided by the activity if emanation and diffusion did not occur).

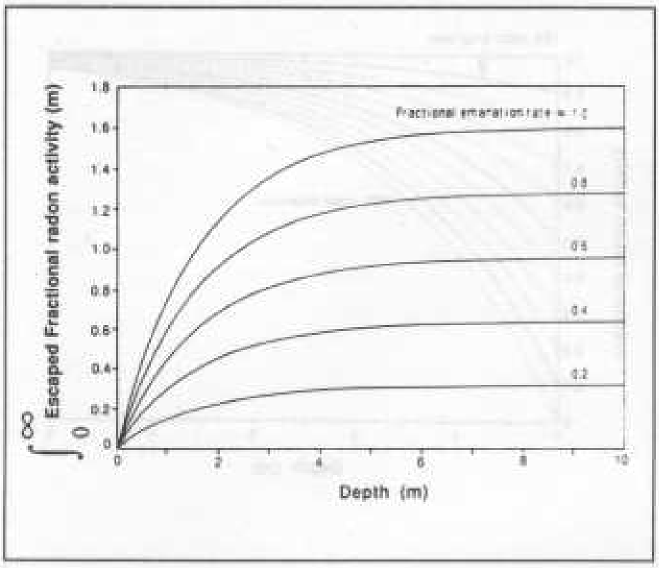

Figure 3. The total activity escaping from the matrix and reaching the cave atmosphere as a percentage of the matrix activity. These values are derived by integrating the area above the curves in Figure 2. Note that where emanation and diffusivity are high, the total escaping activity may be greater than the original matrix activity. This is due to escaping radon being replaced by radon diffusing up through the profile. (calculations, Readhead, pers. comm.)

A more general equation, of which this is a special case, is given in Nazaroff (1992).

$$f = \varepsilon[1 - \exp(-\sqrt{\lambda/D}\, x)]$$

where ε = emanation rate
D = diffusion coefficient
λ = decay constant

The total amount of radon activity which has escaped into the cave air, for an infinite depth matrix, (Figure 3) is given by:

$$A = a \text{ Integral } (1-f)dx$$
$$= a\,\varepsilon\,(\sqrt{\lambda/D}) \text{ in Bq m}^{-2}$$

where a = matrix activity, no escape
A = total escaping activity

Note that, while the *rate* of diffusion decreases with the depth of the sediment for any particular depth, the *total* fraction of radon diffusing into the cave air increases with increasing total depth and may be considerably greater than 1. This occurs because the radon that escapes from near the surface of the sediment is replaced by radon diffusing from greater depths, a "shuffle effect". Using the parameters given in the figure caption for a typical sediment, the maximum likely activity reaching the cave air is 1.6 x the original activity in the matrix. As an example, consider the amount of activity passing through the surface of a sediment which has a uranium concentration of 1 ppm, a density of 1.5 kg m^{-3}, and an emanation rate of 1 (i.e. an integral escaped fractional activity ratio of 1.6)

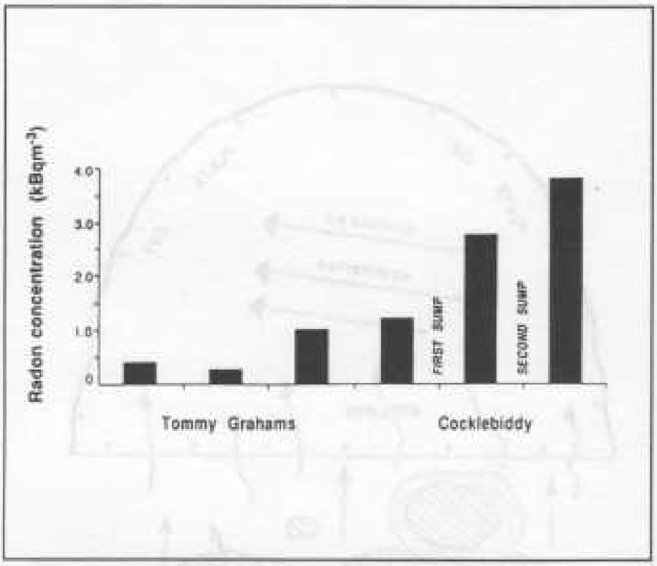

Figure 4. Increased radon concentration with decreased ventilation/increased remoteness from entrance for two Nullarbor caves. The first three values are for Tommy Grahams, the second three for Cocklebiddy (data, Basden and James, pers. comm.)

$$\begin{aligned} 1 \text{ ppm U } &\equiv 1/80 \text{ Bq g}^{-1} \\ &\equiv 12.5 \text{ Bq kg}^{-1} \\ &\equiv 18.75 \times 10^{3} \text{ Bq m}^{-3} \\ &\equiv 30 \text{ kBq m}^{-2} \end{aligned}$$

(iv) Dilution by cave air will be, for an homogeneous cave wall material, proportional to the surface area divided by the volume, i.e. approximately proportional to 1/d where d is the diameter of the cave passage. In the example above, radon concentrations in a cave passage 2 m diameter might reach 4 WL. An approximate calculation of this type confirms the plausibility of the high values being observed in caves even though they were initially greeted with scepticism.

(v If there is significant ventilation, the radon concentration will be further diluted by a factor of $1/(1+v)$, where v is the velocity of the cave air, because the effective volume is greater than the actual volume. Downstream effects may also be significant, for example, dilution may be most noticeable close to the entrance before the air picks up radon as it passes through the cave. Where ventilation is restricted radon levels can be expected to be higher. For example, the level of radon in Cocklebiddy Cave, WA, increases with the distance between the sites and the entrance, (Figure 4, data Basden and James)

(vi) Radon and the particles to which it is attached may be "plated-out" on the cave surfaces, thus reducing airborne concentrations. There is little if any quantitative data on this reduction, but plate-out is likely to be greater when cave walls are damp because radon dissolves readily in water.

Radon concentrations can therefore be expected to be greater in localities where there are greater uranium concentrations (perhaps in areas with mixed rock types). Suspect sites would have a higher proportion of sediments (both with respect to area and depth), of greater porosity and less moisture and be

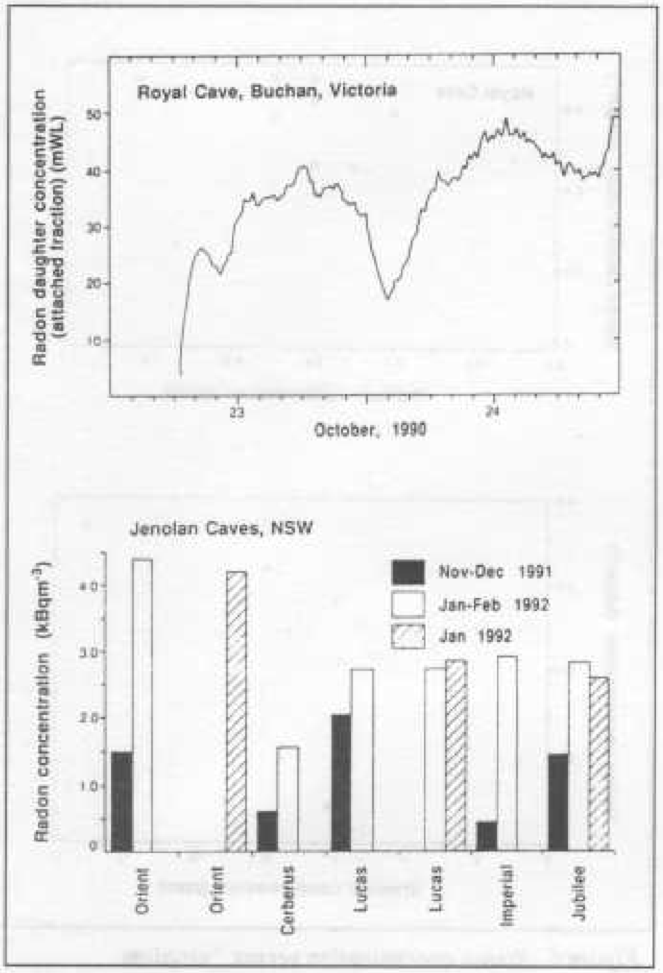

Figure 5. a) Diurnal variations in radon concentrations, Royal Cave, Buchan, Victoria. (redrawn from Solomon et al., *1991)*
b) Seasonal variation in Jenolan Caves (data, Basden and James, pers. comm)

found in smaller cave passages with little ventilation, perhaps blind passages or those sufficiently removed from entrances for the air to have acquired significant radon on its passage into the cave. Sites with more speleothems, rock and water, and with better ventilation, are less likely to have problems with excessive radon.

External factors may also affect the accumulation of radon. A drop in barometric pressure may lead to increased diffusion from the sediments as well as a change in cave ventilation. A difference between the external and ambient cave temperature may also drive a cave air circulation on a diurnal or seasonal basis, affecting both the dilution and spatial distribution of radon. These external factors mean that, even where high risk sites have been identified, the radon concentration may vary significantly, by as much as an order of magnitude, on a diurnal, intermittent or seasonal basis (Figure 5).

RADON IN AUSTRALIAN CAVES

Solomon et al. (1991) published the first data on Australian caves on Buchan Caves in Victoria, using a variety of methods to determine the concentration of radon, radon daughters, aerosol size and unattached fractions of radon daughters.

Region	Range (WL)	Mean (WL)	Number of observations
Nullarbor (3 caves)	0.04 - 0.50	0.19	14
Victoria			
Buchan	0.01 - 0.08	0.06	18
New South Wales			
Jenolan (3 caves)	0.05 - 0.53	0.33	15
Wombeyan (3 caves)	0.03 - 0.42	0.14	4
Abercrombie	0.02 - 0.03	0.03	2
Yarrangobilly (4 caves)	0.23 - 0.90	0.43	12
Western Australia (5 caves)	0.02 - 0.16	0.05	6

Table 3. Radon measurements in some Australian caves. Data have been compiled from data supplied by Basden, James, Holland, Lyons, Solomon, and Spate. Because the data have been obtained by different methods which have necessitated different assumptions, and because radon concentrations are known to vary substantially with time, this summary cannot be definitive, but highlights some potential problem areas and the need for more intensive investigation (cf Table 2).

The derived dose to tour guides for the period 1990-1991 when actual occupancy times were taken into consideration ranged from 0.08 to 2.8 mSv with an average dose of 1.7 mSv. This is well within the current guidelines (Table 2) but not negligible. Results from other Australian caves (Table 3) are generally higher, though none are as extreme as those reported in Gunn (1991). Given the variability observed in Royal Cave in Buchan (a diurnal factor of 75, (Solomon *et al.*, 1991)) and Jenolan Caves (a seasonal factor of four, reported by Basden and James (unpublished data)), these figures are no basis for complacency. Neither are they an immediate cause for alarm for recreational cavers. The highest values occur beyond the sumps in Cocklebiddy, where cavers are not likely to spend significant time, and in tourist caves in New South Wales. Cave tourists will be exposed for very limited periods of time and their risk will be minimal. However, cave guides and other cave workers such as electricians will be exposed for longer periods. The existing data for these caves is not sufficiently detailed to estimate actual doses but, using reasonable assumptions to convert from radon concentrations in the air to inhaled dose, the dose to guides in Jenolan, for example, may be more than five times that received by guides in Buchan, given the same working conditions. Thus it is imperative that these caves be targeted for further research to determine the extent of the problem and what management methods, if any, are required to address it.

PROPOSED DOSIMETRY PROGRAM

In April, 1992 a Radon Workshop was convened in Canberra, to discuss the current state of knowledge of radon levels in tourist and wild caves and assess implications for further work. A list of participants is given in the Appendix. It was agreed that radon efforts should be coordinated and that funding should be sought for a 3-stage dosimetry program as proposed by Whittlestone, as follows:

Stage 1 Assess order of magnitude of radon levels at many sites.
Passive monitors, eg charcoal cups, track edge detectors
Dose accuracy target: factor of five

Stage 2 Make closer assessment of sites which may be a problem
Measure radon daughters - attached and unattached fractions (50% cut at 5 nm diameter) Active methods such as an alpha detector looking at a continuously pumped filter
Dose accuracy target: factor of two

Stage 3 Any doubtful sites, make accurate measurements to form basis of a personnel monitoring program
Make activity-size distribution measurements over periods indicated by other stages to be critical
Dose accuracy target: 30%

It is recommended that all measurements be referenced to the Australian National Radiation Laboratory with periodic checks by the Australian Nuclear Science and Technology Organisation.

The uncertainty limits suggested for each stage highlight the difficulties inherent in radon dosimetry in caves. As well as the temporal and spatial variability in cave concentrations, problems include difficult access, provision of a suitable power supply, high humidity, and the length of time required for reliable measurements to be obtained, necessitating repeat visits to caves which may be remote. Because gamma radiation measurements can be taken on site in a relatively short period of time and in that a substantial amount of data on gamma radiation has already been collected (Lyons, unpublished data), it is worth considering whether these might provide a preliminary stage, to within an order of magnitude, which would enable better targeting of funds and effort.

GAMMA DOSIMETRY AS A SURROGATE VARIABLE

It is reasonable to expect that "radon-prone" sites as identified above may also be expected to have a relatively high gamma radiation level, due to higher uranium concentrations in the sediments and increased dose due to the "shuffle effect" discussed above. The correlation between these factors and actual radon concentrations in the air will not necessarily be high and will be further complicated by plate-out on the cave surfaces, which will contribute to the gamma dose but not the actual radon dose. A desirable effect of plate-out might be to provide an averaging effect over time, smoothing the excessive variability obtained by taking spot measurements.

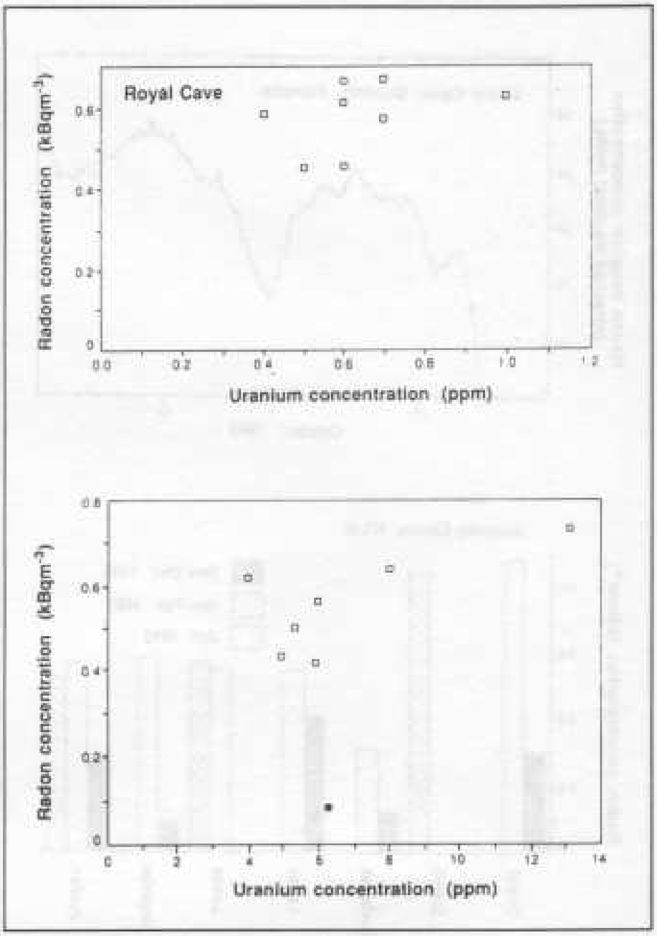

Figure 6. Radon concentration versus "uranium concentration", estimated using field gamma spectrometry.
a) Thampanna Cave, Nullarbor. Radon concentration estimated using track edge detectors (TED) supplied and analysed by NZ National Radiation Laboratory.
b) Royal Cave, Buchan. Radon concentration (PAEC) estimated by Solomon et al., *1991. The infilled square is data for a site close to an entrance and, if the cave was breathing in when the radon measurements were taken, probably reflects external conditions*

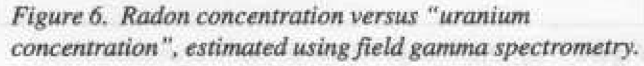

Figure 7. "Uranium concentration" estimated using field gamma spectrometry, for Royal Cave, Buchan as a function of time measurement was taken. The infilled square represents a site in a large chamber where air velocities are reduced and more plate-out could be expected. Plate-out would increase the spectrometer estimate but not the concentration of radon in the air.

Gamma dose estimates were obtained using a GR-256 gamma spectrometer with a 75 x 75 mm NaI crystal and a 256 multi-channel analyser for spectral storage, manufactured by Exploranium. Comparisons are shown in Figure 6 for sites from two caves. Radon measurements for Royal Cave in Buchan are taken from Solomon *et al.* (1991); it should be recognised that these data were collected at different times and that exact site equivalence is not assured. A poor correlation is thus to be expected. Radon data for Thampanna Cave were collected over a five day period, using track edge detectors (TED) supplied and analysed by New Zealand National Radiation Laboratory, according to the method described in Robertson and Tucker (1980). Gamma measurements were taken for the same sites when the TED were collected at the end of their exposure time.

The scatter in the radon measurements is not large, the data for each site mostly lying between 400 and 700 Bq/m^{-3} (The exceptionally low value in Royal Cave is close to an entrance and presumably reflects the low concentration in air entering the cave at the time of measurement.) Because all that is required is a prediction within an order of magnitude, the poor correspondence in each cave is not too discouraging. However, both caves recorded similar radon concentrations, admittedly by different methods not cross-calibrated with each other in any way, yet the gamma spectrometer estimates differ by an order of magnitude. While more data is being processed, this discrepancy does not look promising.

However, the gamma spectrometer results plotted against the time at which the measurements were taken (Figure 7) show an obvious trend. During the overall period of measurement it was noted that the draught of air, which was strong at the beginning of the period, dropped to zero and eventually reversed weakly. It is possible that the spectrometer is in fact picking up a real increase in radon concentration due to the reduction in ventilation, such as was observed by Solomon *et al. (1992)* over a similar time period (Figure 5a)

CONCLUSION

Radon measurements so far carried out in Australian caves show levels which indicate the need for further dosimetry but are not as alarming as those reported for some caves in the United Kingdom. The only detailed study which estimated exposure for tourist guides in Buchan Cave, Victoria, yielded annual dose estimates of less than 20% the recommended maximum yearly dose for licensed radiation employees. However, other caves in New South Wales and the Nullarbor region show higher radon concentrations. While the caves in the Nullarbor are rarely visited, those in New South Wales are tourist caves and the guides employed may spend significant time underground. In view of the known variability in radon concentrations and the limited data available, there is no room for complacency and further study is required. In particular, effort needs to be coordinated for maximum efficiency, and funding sought for the 3-stage dosimetry program outlined above.

ACKNOWLEDGEMENTS

The cooperation of cave management and guides across Australia has been essential to this work. Thanks are due to Dr M.L. Readhead, Defence Science and Technology Organisation, for helpful discussions and for calculations of radon activity ratios. The assistance of Dr Ken Basden and the New Zealand National Radiation Laboratory in providing and analysing TED is gratefully acknowledged. The work was supported by a University of New South Wales Postdoctoral Fellowship and by a Special Rectors Grant, Australian Defence Force Academy.

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AN UNUSUAL SUBJACENT KARST DOLINE AT EAST BUCHAN, VICTORIA

Adrian G Davey and Susan White

Abstract

A small subjacent karst doline is described which is expressed in surface outcrop of volcanics overlying limestone. The doline is close to the fault contact between the karstic and non-karstic rocks. Stratigraphic inversion resulting from thrusting of the volcanics over the limestone on an inclined fault plane gives the unusual result of a surface doline form expressed in rocks which are older than the underlying karst rocks, solution of which is responsible for the surface form.

INTRODUCTION

There are at least four or five hundred temperate karst features developed in the Middle Devonian Buchan Group carbonates (Teichert & Talent 1958) of East Gippsland, Victoria (Davey & White 1986). One of the more unusual of these is a small subjacent karst doline. This landform has the code number EB-X167 (Davey & White 1986) in the reference system of the Australian Speleological Federation - ASF (Matthews 1985). The doline has its surface expression in rocks of the Snowy River Volcanics (Teichert & Talent 1958). Its origin, however, must be from solution of underlying carbonates. Subjacent karst as used here (Martin 1965, cited in Jennings 1971), or alternatively interstratal karst (Quinlan 1968), refers to in-situ development of karst forms in non-karstic rocks which overlie karst rocks (Jennings 1985). The karst forms in such cases are due to subsidence and/or collapse of non-karstic materials into solution-formed cavities beneath.

The Buchan Group of predominantly carbonate sediments is generally downfaulted in a complex pattern into the older and much more extensive Snowy River Volcanics, especially here at the south-eastern margin of the outcrop of Buchan Basin sediments. The site is on the southern slopes of the valley of Back Creek, a tributary of the Buchan River. The doline is located on a moderate hillslope (10°), upslope from the fault contact between the volcanics and the Buchan Caves Limestone.

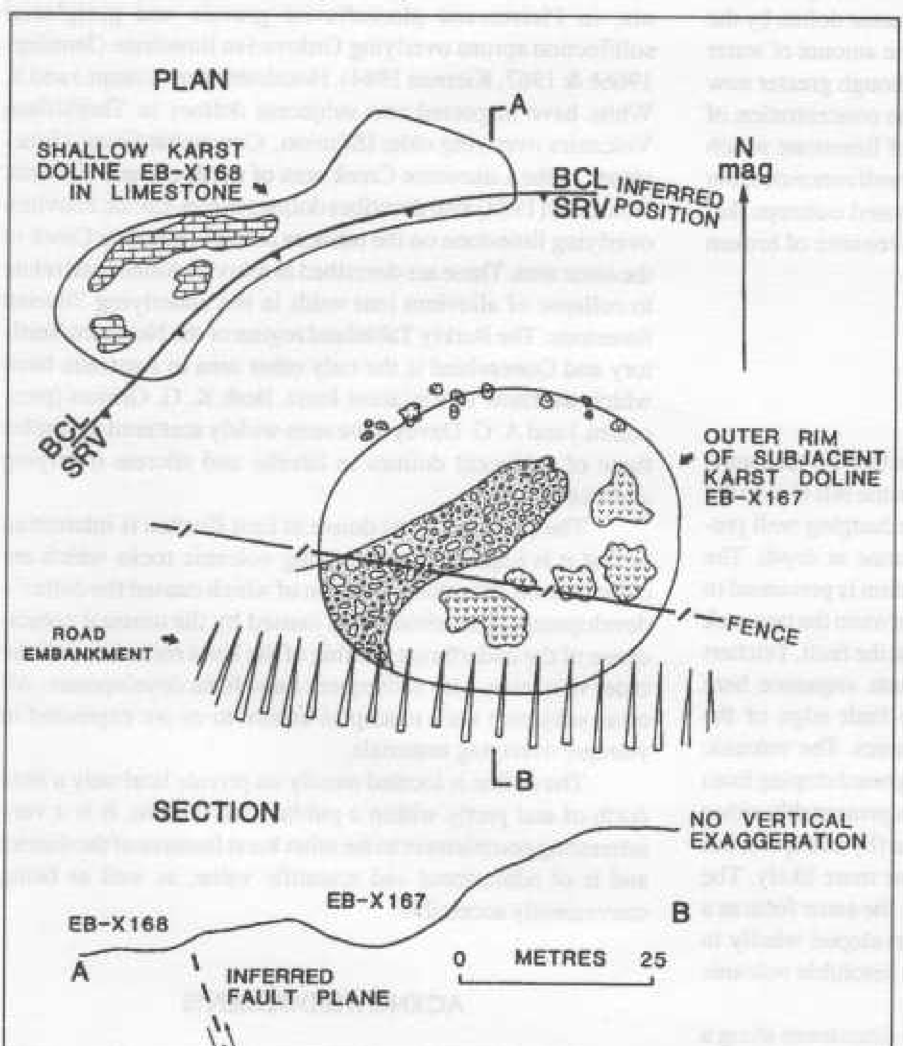

Figure 1. Sketch plan and section of subjacent karst doline EB-X167 and its context, East Buchan, Victoria

DESCRIPTION

The doline is a not quite circular feature, 5 metres deep and about 35 m in diameter (Figure 1). The uphill wall of the doline is relatively steep, with much gentler slopes from the floor up to the downhill rim. Irregular outcrops and large rocks of the volcanics occur around the backwall and on the south-eastern side of the doline. The rim consists of discontinuous outcrop of volcanics, apparently in situ, but probably disturbed. Thus the doline appears to have volcanics all around it. Identifiable outcrop of Buchan Caves Limestone at the surface is about 20 m away down the hillslope from the lower rim of the doline, in another shallow doline EB-X168 (Figure 1).

The doline appears to be developed where the fault contact between the carbonates and volcanics, as shown on geological mapping by Teichert & Cottle (1946), takes a 30° bend at a spur. The surface contact between the volcanics and limestone is expressed in an elongate irregular depression of subdued expression (EB-X168) running along the contact (across the slope) downhill of the subjacent doline EB-X167 (Figure 1). There is irregular outcrop of Buchan Caves Limestone in the northern (downhill) slopes of this other shallower doline EB-X168. The original minor drainage line on the hillslope fed into this depression, and piping is still occurring in the volcanics-derived soils at its head.

The floor of the basin of the subjacent doline is partly filled to 0.5 m depth or more with recent gravelly sediment, with a minor streamsink into a wombat burrow at the bottom. The clastics are locally derived by hillslope wash, latterly at least from the adjacent Buchan-Orbost Road which cuts across the upper slopes of the southern wall of the doline (and which dates on this alignment from about 1935). Some of the gully flow which previously drained into the shallow elongate doline on the contact is now diverted into the subjacent doline by the accumulation of sediment from the road. The amount of water sinking in the doline is relatively small, although greater now than under natural conditions because of the concentration of runoff from a road culvert. Any exposure of limestone which might otherwise appear in the doline floor is well concealed, but it seems likely from the distribution of exposed outcrops that the floor of the doline beneath the clastics consists of broken volcanics.

DISCUSSION

We interpret the fault contact between the two rock units as dipping under the surface volcanics, into the hill (i.e. to the east-south-east). Solution beneath the fault hanging wall presumably created initial voids in the limestone at depth. The precise depth is undetermined, but the solution is presumed to have been concentrated along the contact between the two rock types in the zone of shearing and fracturing at the fault. Teichert & Talent (1958) suggest that the carbonate sequence here becomes thicker towards the east, at the fault edge of the Buchan Group sediments against the volcanics. The volcanic rocks above the void have moved down by upward stoping from the void beneath, probably to fill it. This was presumably either progressive (by subsidence) or catastrophic (by collapse), but it is difficult to tell which. The former is the more likely. The result is a doline at the surface, of precisely the same form as a subsidence or degraded collapse doline developed wholly in limestone, but expressed here in relatively insoluble volcanic rocks instead.

Solution is probably occurring in the limestones along a considerable length of the contact in this general area. There are substantial banks of tufa nearby at the perennial spring EB-49R. This is located on the southern bank of the Buchan River, at the limestone-volcanics contact, some 1600 m ENE of the doline described here. The water of this spring discharge is sufficiently saturated with respect to calcium carbonate to indicate prolonged contact with the limestone rather than direct transmission from surface streams (Ellaway & Finlayson 1984). The configuration of topography and geological contacts at this eastern extremity of the main Buchan Basin outcrops suggests a contact route for at least some of the outflow to the EB-49R spring. We have not, however, attempted any tracing of such hydrological linkages.

Subjacent karst is not widely reported in Australia. The classic Australian example is The Big Hole, in the Deua National Park on the south-eastern tablelands in NSW (Jennings 1966a&b). The Big Hole (15P-2D in the ASF reference system, Matthews 1985) is exceptional among dolines generally because of its very high depth/width ratio of between 2: 1 and 3.5: 1 (Jennings 1966a), whereas the East Buchan doline described here has a D/W ratio of only 1: 7, a typical mid-range figure for Buchan area dolines. The Australian karst index database (Matthews 1985) contains no references to subjacent karst other than for The Big Hole. Other documented Australian examples known to us are dolines at Mole Creek in Tasmania, in Pleistocene glaciofluvial gravels and periglacial solifluction aprons overlying Ordovician limestone (Jennings 1966b & 1967, Kiernan 1984). Houshold (pers. comm.) and S. White have inspected two subjacent dolines in Thorkidaan Volcanics overlying older [Silurian, Cowambat Group] limestones in the Limestone Creek area of north-eastern Victoria. Houshold (1984) also describes dolines in non-karstic alluvium overlying limestone on the terraces along Limestone Creek in the same area. These are described as alluvial dolines and relate to collapse of alluvium into voids in the underlying Silurian limestone. The Barkly Tableland region of the Northern Territory and Queensland is the only other area in Australia from which we know of subjacent karst. Both K. G. Grimes (pers. comm.) and A. G. Davey have seen widely scattered examples there of subjacent dolines in laterite and silcrete overlying carbonates.

The subjacent karst doline at East Buchan is interesting in that it is expressed in overlying volcanic rocks which are older than the limestone, solution of which caused the doline's development. This situation is caused by the unusual coincidence of the underthrust faulting of the karst rocks beneath the older volcanics, with subsequent karst form development. All other subjacent karst examples known to us are expressed in younger overlying materials.

The doline is located mostly on private land only a little north of and partly within a public road reserve. It is a very interesting complement to the other karst features of the district and is of educational and scientific value, as well as being conveniently accessible.

ACKNOWLEDGEMENTS

This subjacent karst feature was documented by us while we were undertaking a study (Davey & White 1986) commissioned by the Caves Classification Committee, a body which advised the Victorian Minister for Conservation, Forests & Lands.

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