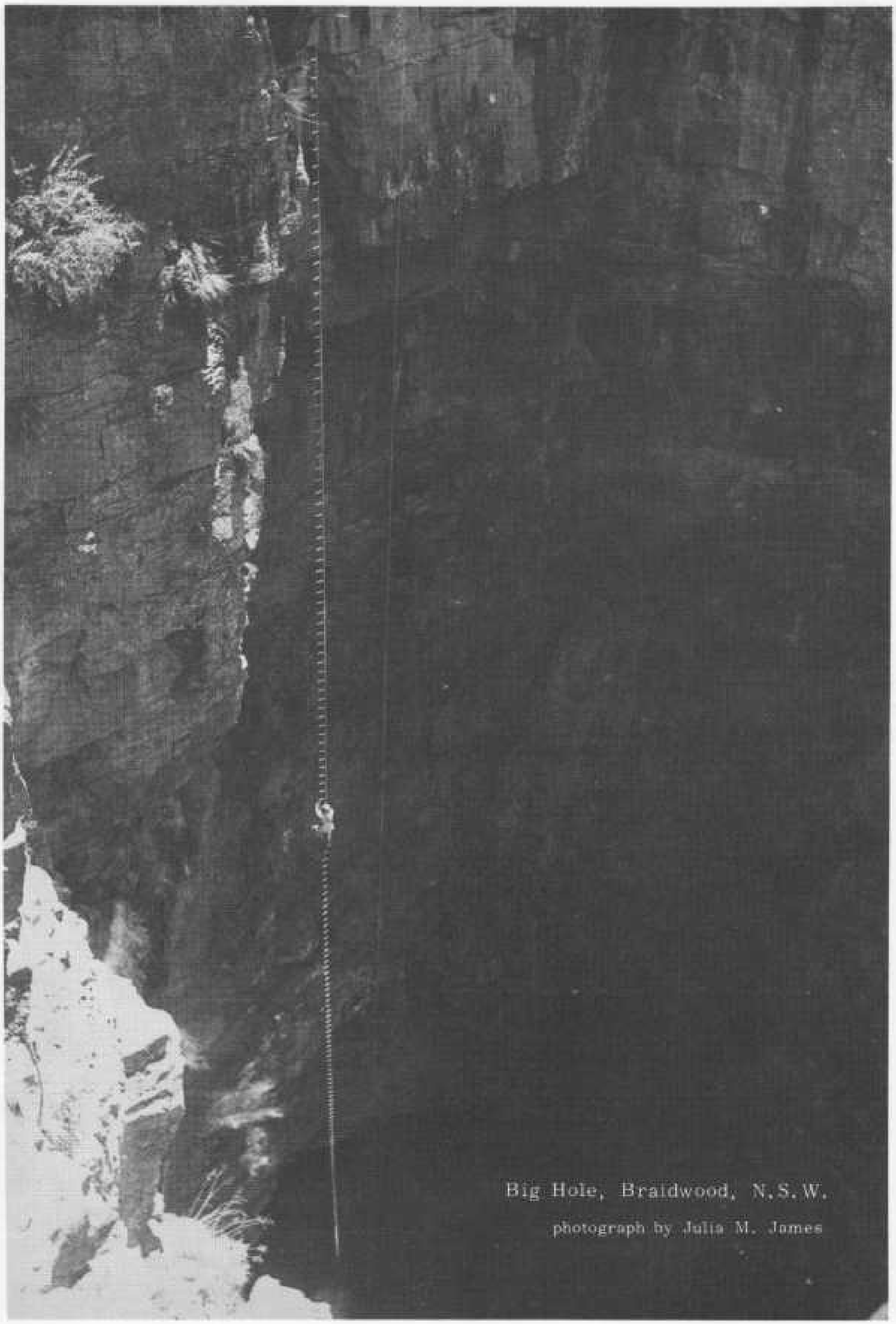
VOLUME 20(2) 1982

Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Big Hole, Braidwood, N.S.W.

photograph by Julia M. James

HELICTITE

Helictite was founded by Edward A. Lane and Aola M. Richards in 1962.

This Journal was (and is) intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia in the truest sense — Australia, New Zealand, the near Pacific Islands, New Guinea and surrounding areas, Indonesia and Borneo.

In 1974 the Speleological Research Council Limited agreed to support the Journal with financial assistance and in 1976 took over full responsibility for its production.

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Cover Photograph: Big Hole, near Braidwood, N.S.W., an example of subjacent karst. See the paper by J.N. Jennings, page 37.

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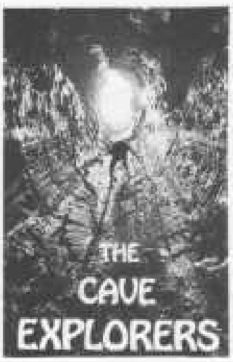
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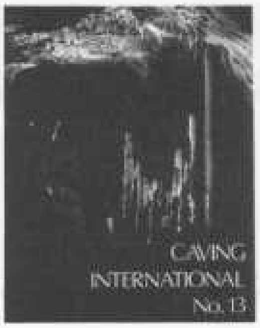
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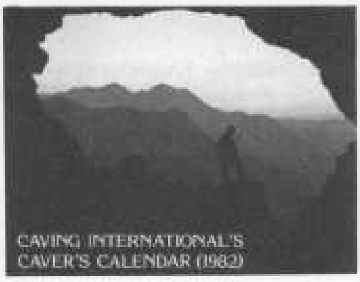
CAVING INTERNATIONAL'S
CAVER'S CALENDAR (1982)

REVIEW

THE GEOMORPHOLOGY OF THE GREAT BARRIER REEF : Quaternary Development of Coral Reefs

by D. Hopley. Wiley, New York 1982. Pp. xiv + 453

The Great Barrier Reef is much the largest and most varied of its kind in the world; indeed, J.A. Steers, an eminent student of it, insisted that it should be 'Reefs' not 'Reef' and thought 'Barrier' gave a misleading single notion concealing its complexity. This large book treats of the Queensland reefs as physical features, their varieties with their distributions, the processes at work upon them, the components in their makeup, and their histories. Since the materials of which they are built are of animal and plant nature, both living and dead when incorporated, the biology of the reefs must come into this study but it is considered here only to the extent that it contributes to an understanding to the physical forms and patterns. This touchstone can be illustrated by a minor but subtle effect. One doesn't have to walk too much over a reef flat when it is being flushed over by the sea before one spots lanes or patches of oily iridescence on the water surface. This is caused by the breakdown of coral mucus and has the significant effect of damping down wave action within certain limits of wind stress.

A considerable amount of research relevant to this theme of the geography of reefs has been done in the last two decades, the Australian contribution coming mainly from the University of Queensland, the Commonwealth Bureau of Mineral Resources and the James Cook University (there are the manifold efforts of the author and his research students). Direct work on the Great Barrier Reef and the implications for it of results from elsewhere are synthesised here with a clarity and judiciousness which will ensure that it will in large measure replace Maxwell's Atlas of the Great Barrier Reef and that it will become necessary reading for serious students of coral reefs through the world. With a book of this size there is bound to be a longish interval between the author putting down his pen and publication. It is unfortunate that J. Chappell's synthesising hypothesis (1980) on the controls over coral form must just have escaped incorporation.

In what ways are coral reefs of interest to speleologists and how does this book stand in relation to them?

An obvious source of interest rests on the fact that many kinds of limestone - the host rock for most caves - can be seen in course of formation here and the differing natures of limestone affect cave development in many ways. Indeed, some 20 years ago, when Ed Slater and I were planning to make a film about caves (abortively, needless to say), we were agreed that it should start off in the Great Barrier Reef with the organisms and the mechanical processes making limestone. This new book will by no means replace for cavers books directly concerned with the petrology of carbonate rocks and their genesis, such as that of Bathurst. Nevertheless by revealing the complexities of organic growth and destruction and transfer of biogenic sediment on reefs, it will certainly lead us not to expect simple lithologies where caves have formed in ancient reef systems.

The overall structures of reefs have important effects on karsts which develop in reef rocks as is the case with the Limestone Ranges of the Kimberleys in the opinion of most geologists still, although there is a divergent school of thought, which thinks the carbonate sediments accumulated in simple shoals and were subjected to tectonic stresses producing structures mistaken for those of barrier and patch reefs. Not many deep bores have been put down in the Great Barrier Reef and Hopley does not study their data afresh, concerning himself mainly with its late Quaternary history, so that in this respect it brings little of new.

Another concern cavers have is whether caves may be primary features of reefs, left as voids in reefs as these accumulated. Ollier and his associates have, however, failed to find any caves which they would interpret in this fashion amongst the caves of the Trobriand Isles and other emerged reefs off Papua New Guinea, on which they have reported in a number of papers in Helictite. Iliffe (1981) describes caves of this nature still occupied by the sea in the fringing reefs of Bermuda but they are apparently quite simple in form, vertical fissures only tens of metres long. Siminar features are probably widespread in the Great Barrier Reef but Hopley does not add to the information on this in Davies et al. (1976), which he cites.

The converse situation of interest is the drowning of normal karst caves formed in reefs when they were emerged; such are likely to provide a greater field of activity for the sporting cave diver as well as evidence of considerable interest for the karst geomorphologist. Dill (1977), for example, has inferred tectonic tilting of reefs from the present geometry of submarine caves of subaerial origin in them. Again, Hopley has no such systems to report from the Great Barrier Reef as yet. What the prospects are, however, may be gauged to some degree with this book from a major concern of his, which independently comprises a topic of interest to the speleologist.

It was nearly at the beginning of this century that the alternate lowerings and raising of sea level caused by Pleistocene glaciations were first at all adequately recognized as important in the development of coral reefs, by R.A. Daly. But it was not until its second half that the role of karst action while the reefs were exposed to the atmosphere began to be appreciated by F.S. MacNeil. Later, E.G. Purdy elaborated ideas about this on the basis of the Caribbean evidence and laboratory experiments, and argued that many aspects of the Great Barrier Reef were controlled by it. The effects of changing Quaternary sea levels are a recurrent theme in Hopley's book and in particular he reasses the applicability of this 'antecedent karst' hypothesis to Queensland's reefs.

About the only feature that he regards as ineluctably a consequence of karst are the 'blue holes' - collapse dolines here much smothered by later sediment, though he also thinks that the high reef flat rims along many passes between reefs are best explained as solution rims such as embank river valleys through the Puerto Rico karst. Reticulate reefs likewise he thinks are more likely to have grown upon fields of shallow solution dolines than to be due to marine erosion as Maxwell thought. "Spur and groove" relief of windward hardline reef margins could be in part due to subaerial weathering but is more likely to be caused by differential coral growth plus some marine erosion. He is even more sceptical about 'bommies' growing on karst towers and about the inner steamer channel following a karst margin plain. As further evidence comes from seismic traversing, closer sounding and shallow drilling, these matters should receive more clarification. At present David Hopley has surveyed these matters most carefully and if they can't buy a copy, speleologists should try to ensure that this book is lodged in the public library they frequent.

J.N. Jennings

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PRINCIPLES AND PROBLEMS IN RECONSTRUCTING KARST HISTORY

J.N. Jennings

Abstract

Principles and problems in the reconstruction of karst history, apart from methods of absolute dating, are discussed and illustrated on the basis of Australian examples as far as possible, but with recourse to overseas where necessary. Relict, buried, exhumed and subjacent components, and compound histories are considered. Connotations for the less consistently employed terms, fossil karst and palaeokarst, are recommended.

INTRODUCTION

Reconstructing the history of karst caves and their associated landforms and drainage has generally been difficult in Australia. The rocks in which they are formed are frequently old and the regions in which they are situated have been land for a long time and have not been disturbed by earth movements in geologically recent periods. These factors make it difficult to date events in the evolution of caves even when these can be placed in sequence.

In recent decades new tools have been developed to make chronology easier; the chief ones are radiocarbon dating of organic cave deposits and speleothems, potassium/argon dating of Cainozoic basalts in the regional landscape, uranium/thorium dating of speleothems, palaeomagnetic investigation of iron-rich palaeosols and cave sediments. These have now been used in Australia with some success (though not all have reached publication state).

With these aids, it is likely that we shall enter into a phase of greater attack on the history of our caves. Even with the help of these new dating methods, many difficulties in interpreting evolution will occur because of special complexities which arise in karst development and to a degree also from confusion in terminology. It is intended here to review the concepts involved and to illustrate some of the complexities in the hope of helping forward this aspect of Australian speleology. As far as possible Australian examples will be employed but since such studies have lagged behind here, it will be necessary to draw on overseas material to present a wider range of happenings to which karst is subject and which may be encountered here also in the future. The oldest karst phenomena found so far are infilled caves and dolines within early Proterozoic dolomites of ca.2,300 my age in the Transvaal, South Africa (Martini 1981). Northern Australia has Lower Proterozoic carbonate rocks so mining operations could reveal comparably ancient features here.

RELICT KARST

Karst is like other terrain in that it may have three historical components-active, relict and exhumed landforms. Active landforms have been formed by the processes still at work on them today. The nature of these processes depends on present climate and vegetation, present sea level position, present internal conditions of the earth controlling volcanic activity and tectonic movement, including earthquakes. However, these modern processes operate upon relief and rocks, which are the product of past earth movements, sea levels, bioclimates, etc., and which have not everywhere been brought into adjustment yet. Therefore there survive till today landforms which are essentially a response to former conditions that hold sway no longer; these are relict (or inherited) landforms.

This contrast is readily appreciated at Cooleman Plain, New South Wales, where most of the caves are found in gorges which are cut sharply, if not very deeply, into a remarkably level plain at about 1270 m a.s.l. (Figure 1). Surrounding igneous ranges rise 300-400 m above this plain which is developed strictly in the Silurian Cooleman Limestone, even overlying Silurian Blue Waterhole beds forming undulating hills with 50 m relative relief. The gorges are still being deepened by river action, though this is intermittent above the Blue Waterholes, karst springs which constitute the perennial head of Cave Creek near the drainage outlet of the Plain. On the flat interfluves on the limestone, there are patches of river gravel to be found and more widely ironstone gravels and ferruginous sandstone covers. The latter belong to a former widespread palaeosol, probably enriched in iron by lateral soil water movement from the igneous rocks encompassing the plain.

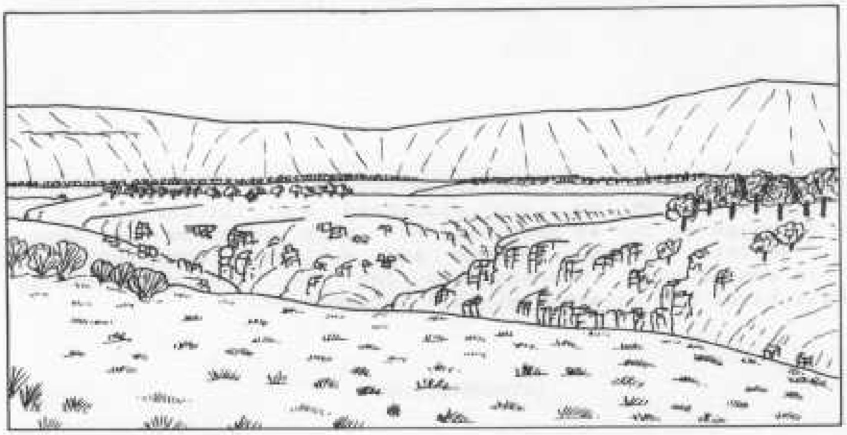

Figure 1 Contrast between active and relict landforms shown by dissection of the Tertiary planation surface of Cooleman Plain, New South Wales, at the junction of the North and South Branches of Cave Creek. Igneous rim of the Currangorambla Range behind.

The age of this relict erosional surface has not yet been determined at all precisely. The best clue rests in Lower Miocene basalts, which were poured down a former valley floor of the nearby Yarrangobilly River. The basalts in place lie at about 1150 m a.s.l. but the limestone valley floor was lowered some 100 m more prior to the gorge cutting by the Yarrangobilly River. Whether the formation of the old surface at Cooleman Plain ended prior to the Lower Miocene basalts or continued after that event as did the lowering of the old Yarrangobilly valley floor, remains uncertain as yet (Rieder et al. 1977).

Timing the gorge cutting at Cooleman Plain is even more difficult. There are cold climate deposits close to and at the bottoms of the gorges, which probably belong to the Late Pleistocene (30,000-15,000 B.P.) so that not much incision is later than that. Some 60 km down the Goodradigbee River, into which Cave Creek flows, are the Wee Jasper Caves. Recent unpublished palaeomagnetic work on these caves (Schmidt et al. in preparation) makes it evident that less than 1 my ago, the Goodradigbee River was within 25 m of its present channel level. Extrapolation from this information to Cooleman Plain is difficult, especially because tributary valleys may respond to rejuvenation more slowly than major valleys in a drainage system.

The active- relict dichotomy applies to constructional as well as erosional landforms. Along Davey Creek at Cliefden, New South Wales, there are remnants of old tufa dams alongside those being built today. These could be local effects of competition between dam building and stream incision. In the Monaro, New South Wales, however, there are calcareous tufa deposits formed by springs now defunct such as at Bunyan where the waters came from Tertiary basalts formerly. A.B. Costin (pers. comm.) has dated three such tufas, ranging between 37,000 and 17,000 B.P. These are relict forms, probably indicative of greater effective precipitation so that more waters passed through the rocks and picked up ions for depositing them. At Davey Creek dating might show that there have been discrete periods of tufa deposition there also, which could have had external causes, making earlier dams relict.

Relict surface landforms in karst seem to persist longer and with greater perfection than landforms developed in most other rocks through the strong tendency of water to go underground and leave an outer shell no longer subject to fluvial erosion and its concomitants. This is termed karst immunity.

With caves in karst, it has been recognised that there are some complications affecting terms; for example, take the notion of 'active' when applied to a cave. Flowing water is the main agent of cave excavation by solution and mechanical action. However, drips and films of water tend to fill up a cave with speleothems, though this is only likely to be substantial when streams are ceasing to enlarge the underground space.

Underground rockfall (or cave breakdown) also tends to fill up a cave because it occupies more space than undisturbed bedrock. At the same time, this process provides cave streams with abrasive tools, which need rapid renewal because of limestone solubility. Fragmentation also exposes a greater surface area to solution. Thus a cave stream may keep pace with breakdown and a rough equilibrium may be established between the two actions. Or it may dissolve and transport more rockfall than arrives and the cave continues to enlarge.

Some of the preceding considerations led to certain distinctions in speleological terms (Jennings 1968, 1979; Monroe 1970). Active cave for one with a stream in it is contrasted with dry cave where this is lacking; live cave with a stream and/or drips is opposed to dead cave without either kind of water activity. An active cave may not have a stream flowing in it all the time, even where there are favourable water balances all the year round. Whereas a surface stream can spread over its floodplain or rise indefinitely when in spate, a cave stream is confined by the passage walls and roof. Therefore it will reoccupy higher passages for a long time in its evolution. Caves are like three-dimensional braiding river systems.

Wherever relief and hydrology permit, water tends to find lower ways through karst and to enlarge them so that eventually earlier, higher routes are replaced at all stage of flow. In speleological literature, such dry or dead caves and passages are more often termed abandoned than relict. This is logical since a vertical sequence of caves in an area or of levels in one system need not imply any general change in external conditions, either climatic or tectonic. They may all be the product of incision following a single uplift. A succession of halts in uplift or cyclical climatic changes is not necessary to explain them, though indeed these may be the cause in particular cases, when the high, dry levels are truly relict.

Thus at Yarrangobilly, N.S.W., in the tourist caves area, there is a descending sequence of Jersey-Jillabenan, Glories-Harrie Wood, Mill Creek Swallet-River-Federation Caves, which points to a threefold history of the Mill Creek and Rules Creek drainage. However, there is little surface geomorphology to correlate with this (Nicoll 1977) so that it could all be the product of a single, initial uplift.

However, when caves are found in the tops of hills and without sensible relationship to the surface topography, there is a strong case for regarding them as relict in the full sense of the term, even without deposits that indicate different controlling circumstances at the time of their formation. Such is the case, for example, with Durins Tower Cave at Wombeyan, New South Wales, lying as it does practically at the highest altitude of the marble here (Jennings et al., in press).

BURIED KARST

Buried landforms do not form part of the natural landscape; they are only seen transected in quarry faces and natural cliffs or revealed in mining or inferred from drill records and geophysical traverses. Knowledge of them may, nevertheless, be necessary for the understanding of the overall development of the karst and in the management and exploitation of its resources.

A most extensive buried surface is represented in the disconformity at the top of the Eocene limestones in the Nullarbor Plain of Western Australia and South Australia (Lowry 1970). These rocks were exposed to subaerial erosion for about 11 my in the Oligocene and then buried by Lower Miocene limestones. The result can be seen in deep cave walls; the erosion surface is flat and the top 2-3 m of underlying rock is hardened by weathering and penetrated to about 0.6 m by tubes 2-3 cm in diameter of uncertain origin.

Much later, in the Pleistocene, marine erosion cut back into an uplifted Nullarbor Plain to remove the upper part of the limestone sequence along the coast. Fresh, thin marine limestone, the Roe Calcarenite, was laid down over parts of the planation surface. Emergence resulted in a coastal plain between Eucla and Eyre, the Roe Plains, where the unconformity lies at shallow depths. Indeed, in the middle around Noonaera the extremely flat marine erosion surface of the Eocene Toolinna Limestone is exposed and has suffered little change since it formed. The associated sea cliffs inland - which constitute the Hampton Range - have been much modified in profile, however. In their upper part they have been worn down by subaerial weathering and below they have been buried by colluvium and aeolian sands (Plate 1). These changes probably belong largely to the Last Glacial low sea level time and so in this respect the old cliffs are relict from that time. In plan, however, they have changed little, notched here and there by short valleys, some of which are hanging, e.g. at Moodini Bluff, and in this other respect they are relict from earlier in the Pleistocene.

Buried marine erosional features are also characteristic of the karst of the Southeast of South Australia according to Marker (1975). The Oligocene-Miocene Gambier Limestone was cliffed and benched at different levels in the Pliocene and Pleistocene and then largely buried by Pleistocene sediment, especially by dunes of calcareous sand which consolidated into aeolian calcarenite. The distinction between primary dune depressions in this later limestone and closed karst depressions in the whole carbonate sequence is not always easy to make and it is not clear whether Marker has allowed sufficiently for this when dividing the karst into different subregions. The innermost marine cliffline lies along the Kanawinka escarpment, which is in part a fault scarp. This complexity has given rise to divergent interpretations of the history of the Naracoorte caves which lie close to the Kanawinka escarpment. Wells (1975) considers that some of these caves formed prior to a Pliocene marine transgression. Because of the absence of marine sediments in them, Marker (1975) thinks they formed subsequently to the Pleistocene marine transgression of about 700,000 B.P. which reached Naracoorte.

Old soil and weathering profiles sometimes survive on buried landscapes though this has not been well demonstrated in Australia so far. In the U.S.A. a Late Mississippian (Early Carboniferous) disconformity extends through the Middle West into the Rocky Mountains. In the state of Missouri, this is marked by fire clays and chert breccia, both residual weathering products, on limestones. Different clay minerals indicate a gradient of reduced leaching from S to N, the north being low, marshy terrain near the coast at that time (Keller et al. 1954). Shales and sandstones have buried the old surface with its soils.

Closed depressions so characteristic of karst are ready receivers of sediment and prone to burial, e.g. in middle Poland quarrying has revealed dolines with fills of various ages from Upper Triassic to Quaternary (Gilewska 1964).

The best Australian example so far has been detected by drilling near Alexander Creek northwest of the Napier Range, Western Australia (Westblade 1980). Here Devonian limestone has been planed off at about 80 m a.s.l. and contains a completely filled closed depression about 250 m by 200 m and more than 100 m deep. Sands make up most of the fill but near the surface

Plate 1 Hampton Range and Roe Plains at Mundrabilla, W. Australia. The Plains are a Pleistocene marine erosion surface, here cut in Eocene Toolinna Limestone and partly buried by a thin Pleistocene marine limestone (Roe Calcarenite). The Range is the former sea cliff in Eocene and Miocene limestones, worn back by subaerial weathering above and covered by colluvium below.

these are overlain by horizontally bedded clays, silts and lignite. Pollen and spores point to a Lower Tertiary age. Thus this large hole was totally filled with river, lake and swamp deposits. From Westblade's data it can be inferred that this is a buried doline. The shape of the bedrock cavity is more suggestive of a collapse than a solution doline (contrast this with Sando (1974) who finds evidence for solution dolines in the Late Mississippian disconformity mentioned above). In the area northwest of Napier Range, there are even larger filled dolines apparent from the topographic map. Aggraded poljes in Yugoslavia contain economically important lignite deposits, whilst some Jamaican poljes have bauxite of economic size.

Caves with complete fills of sediment are encountered in mining and quarrying: the oldest so far recorded from Australia is that filled with Devonian sediments exposed in a quarry near Devonport (Burns 1964). It was excavated in Ordovician Gordon Limestone. The fill is of varied nature and it is claimed that both phreatic and vadose conditions are represented by different sedimentary characteristics, though the evidence for this is not very convincing.

Similar cave fill occurs in natural outcrop near Mountain View homestead not far from Wellington, N.S.W. (Crook & Powell 1976). It is a coarse breccia with a red ferruginous matrix in a cavity in the Lower Devonian Garra Formation limestone and is associated with other karst features at the angular unconformity with the overlying sandstone of the Upper Devonian-Carboniferous Catombal Group. It is worth mentioning here because the authors refer to the occurrence as a 'palaeocave', a term I have not encountered elsewhere.

A most interesting record of filled caves is that from the Canadian Lead in the Gulgong Goldfield, N.S.W. (Jones 1940). Here limestone along a valley floor has been buried beneath thick alluvium. Not only is the surface of the limestone highly irregular from solution but the gold-bearing gravels were traced into caves inside the limestone, a shaft reaching 70 m from the surface without bottoming the fill. One cave chamber had horizontal dimensions 34 m by 13 m, with a triangular cross-section wider at the top. The gold was found at intervals in ferruginous clay. Bones of extinct giant marsupials are attributed to Tertiary genera. Not far away similar alluvial deep leads are capped by Tertiary basalts so the filled caves are certainly of Tertiary age.

Though on a ridge, some of the Wellington Caves, New South Wales, were completely filled with bone-bearing beds. These bones brought Australian caves their first scientific importance because they helped to show that life had evolved independently in different parts of the world. Even the youngest unit is almost at the limit of radiocarbon dating (Frank 1971); on the other hand none of the fossils suggests a Tertiary age and the cave ridge lies low in the landscape. Therefore the fill is likely all to be Pleistocene. The sedimentary structures of the fill have recently been shown by R.A. Osborne to be more complex than Frank documents, with characteristics peculiar to the cave environment.

Cave roofs are liable to be removed by erosion so that it may be difficult to ascertain whether a truncated body of sediment in limestone is a remnant of a filled cave or only from a buried doline. At the main Peking Man site at Zhoukoudian near Beijing in China, a sandy flowstone with bat bones in it capped the fill and this implies that there had been a cave roof over the whole formerly (Black et al. 1933). The fauna indicated a Middle Pleistocene age for the fill and the cave. Likewise the Middle Pleistocene fill exposed in a quarry at Westbury-sub-Mendip in Somerset, England, is regarded as occupying part of an unroofed cave because of bat bones, other bones suggesting a carnivore's den, small bones from owl pellets, and breccia of cave type (Bishop 1974).

Breccias by themselves may not be diagnostic. The breccias found in caves have sometimes worked down from the surface through fissures. Also the 'gash-breccias' in fissures in Pembrokeshire sea cliffs in Wales, which were long regarded as cave fillings, are now interpreted as fault breccias (Thomas 1971). There is a fault breccia in, for example, Queenslander Cave, Mungana, northeast Queensland.

Intra-formational or penecontemporaneous breccias due to movement of sea floor sediment prior to consolidation are also found in cave walls and can be confused with cave breccias. Stylo-breccias due to pressure solution of bedrock carbonate are more distinctive, e.g. when they show intergrowth of larger rock components, and should not lead to confusion so readily.

At Wombeyan, New South Wales, in Steetley's Quarrries, bodies of sediment are encountered in retreating faces from time to time but detailed sedimentological work to determine whether they filled open shafts and fissures or else had been roofed in has not been done. In one case at least, such fill ran laterally into a genuine cave, which quarrymen entered for some distance so there is the possibility that parts of caves were completely filled here. Nine extinct species of marsupials, including giant kangaroos and diprotodontids, and an extinct bird, are taken to mean that that particular fill must be more than

18,000 years old (Hope, in press).

Buried karsts can be extremely difficult to recognise as the fascinating case of the Middle Palaeozoic unconformity in eastern Tennessee demonstrates (Society of Economic Geologists 1971). This unconformity has been subjected to vigorous folding and thrust faulting so it was only after much mining that the true nature of mineral occurrence in relation to the unconformity was recognised. There are elaborate network caves filled with zinc-rich breccias (Fulweiler & McDougal 1971), Fig.2. This karstic zone associated with the unconformity favoured water movement; it was a palaeoaquifer (Harris 1971). Solution breccias accompanying disconformities can persist in influencing groundwater circulation (e.g. Rudnicki 1973) and understanding of them may assist water management.

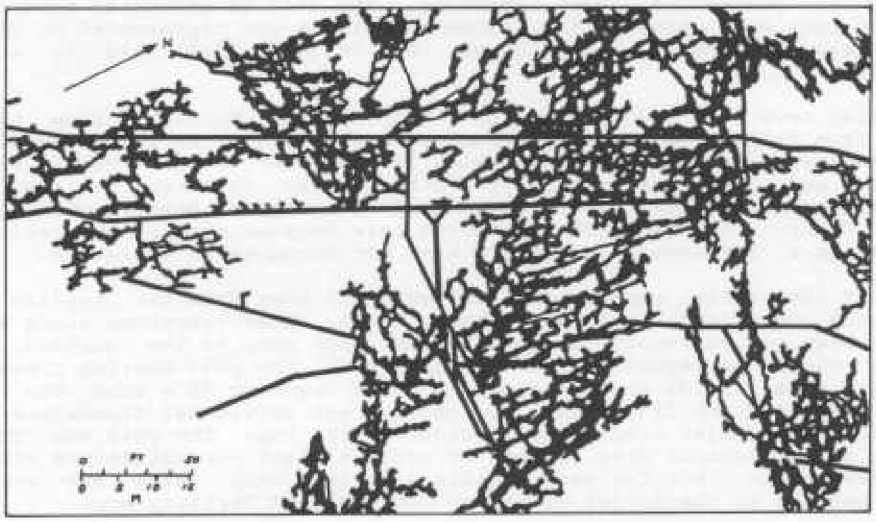

Figure 2 Plan of part of the workings of Jefferson City zinc mine, Tennessee. Zinc-rich dolomite breccia filled a phreatic maze in the Ordovician Kingsport Limestone. Two levels of the network, not distinguished here, partly overlie one another. The straight elements are mine adits. Drawn from Fig.6 of Fulweiler & McDougal 1971.

In Australia mining in subsurface brecciated carbonate rocks has happened at many places. Only latterly have links with karst history been recognised as with the Lawn Hill silver-lead field in NW Queensland, where Lead Hill Mine was worked in mineralised collapse breccia with the minerals leached from adjacent siltstone and dolomite (Grimes & Sweet 1979).

EXHUMED KARST

Exhumed (or resurrected) landforms are those which once formed part of a former landscape that developed in relation to past morphogenetic conditions, often quite different from those prevailing today, which were then buried by younger accumulations of sediment or volcanic materials, and which finally were restored to surface expression by erosional removal of these accumulations. Exhumed landforms are usually recognised as such because exhumation has been incomplete. Where it is total, the issue is more uncertain; Ford (1964) provides an instance in karst of this.

Undissected limestone relief has been exhumed at the southern end of the Lawford Range at the southeastern end of the Limestone Ranges of the Kimberleys (Figure 3). Here the Permian Grant Formation buried the Devonian Bugle Gap Limestone, both marine rock systems. Now the Ngumban Cliffs, a cliffed escarpment in lateritised, horizontally bedded quartz sandstone, looks across an alluviated vale along the contact towards a steep, primary depositional slope of the limestone which forms a gently sloping plateau above. On that gentle surface rest undisturbed outliers of the red sandstone.

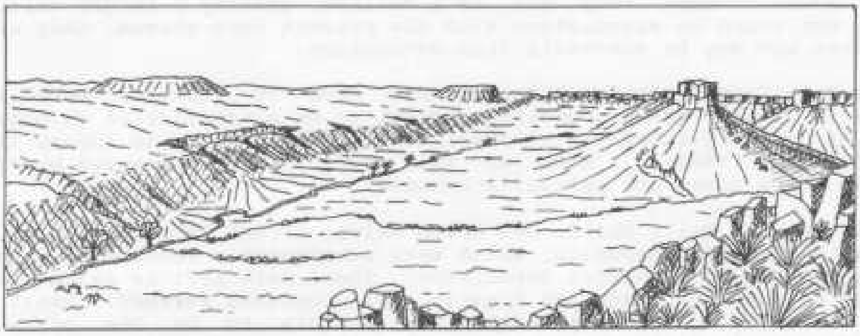

Figure 3 The southern end of the Lawford Range, Western Australia. On left is an undissected surface of steeply dipping Bugle Gap Limestone (Devonian). This supports undisturbed outliers of Grant Formation quartz sandstone (Permian). On right the Ngumban Cliffs are an escarpment of the lateritised, horizontally bedded Grant Formation sandstone. Between is an alluviated vale along the contact.

The most remarkable exhumed karst yet recognised in Australia is that eas of Gascoyne Junction in Western Australia (Graaff et al. 1977). Fields o towers up to 30 m high and rectangular patterns of corridors up to 20 m wide were dissolved out of calcarenites of the Lower Permian Callytharra Formation and then buried by the marine Moogooloo Sandstone (Figure 4). Though the appearance of the karst could be taken to be tropical in style, the Early Permian climate here is thought to have been cold when not positively glacial. Therefore Brook and Ford (1978) cited this area to support their case that there is no tight relationship between the special kinds of karst often found in the humid tropics and that climate. However the South Australian Permian geological record has pointers to a warmer interval which corresponds in time with the formation of the Western Australian buried and exhumed karst (W.J.R. van de Graaff, pers.comm.; Wopfner & Allchurch 1967). Further investigation is needed here.

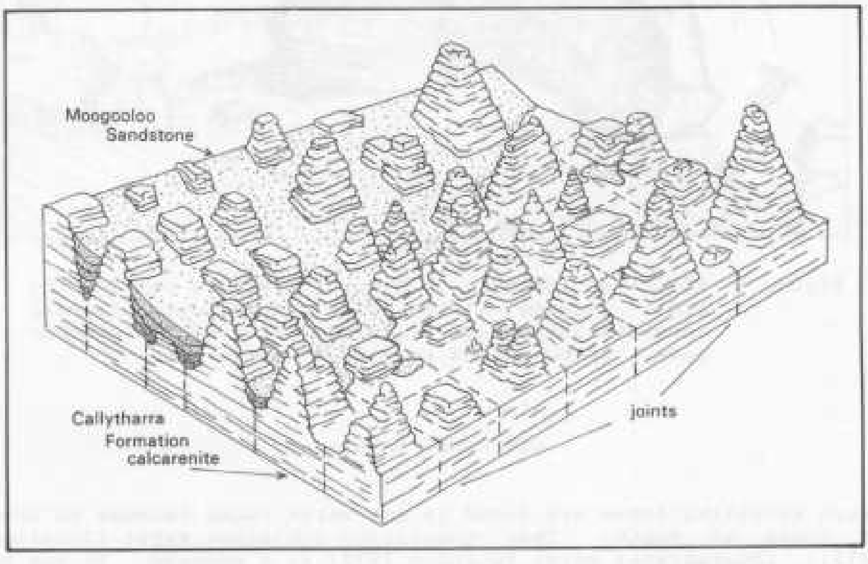

Figure 4 Block diagram of buried and partially exhumed karst in limestone of the Callytharra Formation (Permian). Permian Moogooloo Sandstone formerly covered the whole. The location is east of Gascoyne Junction, Northern Australia. Drawing by R.M. Hocking.

Determining whether caves are exhumed or not is nearly always a difficult matter (cf. Campbell 1977). Sedimentation may take place as part of the process of enlargement of an active cave. A vadose river may shift gravel from bank to bank in transit through a cave and uncemented sand and gravel banks usually represent temporary storage of tools of cave enlargement. So partial fill may be a constituent element of an active cave. Even cemented river gravels may mean no more than a rather longer interval of rest as the river meanders about. When they are of a calibre, usually a larger calibre, or a petrology not found in association with the present cave stream, they are likely to be relict and may be survivals from exhumation.

Some Mole Creek caves such as Baldocks Cave in Tasmania were partially filled with coarse gravel deposits thought to be glaciofluvial in origin. End moraines of outlet glaciers of the Central Plateau Pleistocene icecap lie quite close (Jennings 1967a). Much of this fill has been removed by subsequent erosion so these caves are partially exhumed.

Horse Cave at Walli Walli, New South Wales, (Frank 1974) was also largely filled with allogenic deposits, which were subsequently removed in stages, each halt being marked by flowstone deposition. These were left as false floors as evacuation of the less resistant clastic fill proceeded further. Small remnants adhering to the false floors revealed the history to be one of successive removal of a single fill, rather than one of alternate deposition and removal of different bodies of sediment.

B50 Cave at Bungonia, New South Wales, lies close below the plateau surface. In it, a remnant of an old passage entirely filled with coarse river sediment links the two rooms of the present cave, with the modern link between the two to one side (Figure 5). Whether the old cave apart from this link was completely consumed in later enlargement or some parts of the modern cave are exhumed, ancient cave is hard to determine.

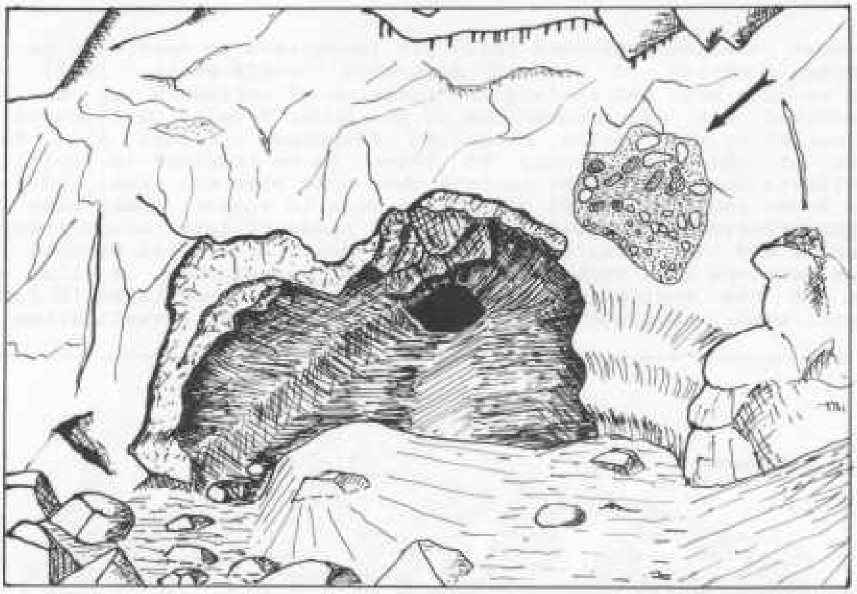

Figure 5 B50 Cave, Bungonia, N.S.W., includes a remnant of older passage filled with consolidated fluvial conglomerate, which links two parts of the present cave. Arrow points to filled tube.

SUBJACENT KARST

Surface karstlike forms are found in non-karst rocks because of the effects of karst rocks at depth. They constitute <u>subjacent karst</u> (Jennings 1965;; Monroe 1972); interstratal karst (Quinlan 1972) is a synonym. It has been well studied in South Wales by Thomas (1974, where he cites earlier valuable papers by him).

The best known instance in Australia is the Big Hole near Braidwood, New South Wales. It is 114 m deep in Devonian siliceous cemented quartz sandstone and conglomerate. No direct evidence of limestone below is yet available but the very tall blind shaft called the Gunbarrel in nearby Wyanbene Cave reaches through Silurian limestone to the base of the Devonian conglomerate above so the circumstantial case for a subjacent origin for the Big Hole is strong (Jennings 1965, 1967b, 1977). The Big Hole has cliffed walls and a high depth/width ratio, which point to sudden collapse into a large cave chamber below.

Such a void is not a necessary component of subjacent karst. North of Mole Creek, Tasmania, an uvula breaches the Tertiary basalt cap of a flat interfluve to expose underlying Gordon Limestone (Ordovician). It is 350 m by 250 m in plan and about 25 m deep, with several lesser depressions within making up the larger whole (Jennings 1967a). Slopes are steep but not precipitous. Most of the basalt cover has disappeared underground and basalt cobbles are common in Mersey Hill Cave, which drains this part of the interfluve. There may never have been a large cave at the site of this uvula.

Where subjacent karst develops into close fields of small dolines, sudden cave collapse is not a likely origin since collapses in cave systems are few and scattered. Removal of overlying rock down widened joints in underlying limestone in a progressive manner is a more likely mechanism in such a context.

Also very large but shallow closed depressions appear to be attributable to progressive subsidence through solution of the limestone surface below without large caves forming at the discontinuity.

Where subjacent karst dolines are completely filled by formerly overlying strata, quarrying may reveal structures in the fill which betray the manner of lowering of the fill into its present position. With instances of this type from the Peak District of England, Walsh et al. (1972) performed simulation experiments with physical models in the laboratory to find whether sudden large scale lowering of the bottom of a hollow or progressive removal of small parts of it at a time would yield structures most like the ones revealed in quarrying. The experiment with the latter mechanism matched the natural pattern better so these particular subjacent karst dolines fitted solution subsidence in the sense of Jennings (1971) rather than large scale cave roof collapse. Compressional rather than tensional structures in the doline fill and the presence of pressure solution effects on the karst rocks are evidence for the slow, progressive process (Bretz 1950). Bretz graphically likened these structures to, 'A water-soaked folded newspaper laid flat across a funnel or flaring basin and then jammed down into it'.

Bretz (1950) also described inverted relief arising from subjacent karst development. Such relief is present in the Mole Creek area according to K.Burns (pers.comm.). Local masses of Jurassic dolerite are now found stratigraphically lower than where they were intruded hypabyssally as sheets or sills. Through solution of the Gordon Limestone below, they were lowered into cavities below their original stratigraphic (and topographic) level. However dolerite proved more resistant to erosion than the limestone, which was subsequently lowered around the dolerite masses so that the latter are now upstanding in the landscape.

Solution subsidence takes place on a much wider scale areally than that of localised doline fills as has been well shown by Thomas (1974). Thus in South Wales an area of Carboniferous Millstone Grit (coarse quartz sandstone and fine quartz conglomerate) about 2 km by 0.5 km and as much as 60 m thick has been lowered up to 240 m in a gradual settlement by solutional removal of Carboniferous Limestone below.

Great care is necessary therefore in the interpretation of outliers of non-karstic rocks in karst terrain. Tertiary basalts of 22 my age flowed over the old Yarrangobilly River valley floor (discussed above) into which the incision of a gorge vitalised underground drainage and led to the formation of many caves. However little of the basalt seems still to be at the level where it solidified. Most remnants are shattered masses lowered varying amounts by solution subsidence (Jennings 1977). This process affects very much estimates of the ages of the caves that may be made.

Questions of a like nature arise in the Chillagoe region of north Queensland but in very different tower karst. Here a Siluro-Devonian sedimentary sequence has been turned on its side by earth movements and heavily faulted. Towers of limestone rise from plains on limestone, siltstone, chert and shale, or from the side of and between hills of siltstone and chert. Robinson (1978) suggested that these towers were very ancient features, which were buried by Triassic (?) shales and sandstones, and later exhumed. This view depends in part on the occurrence of such shales and sandstones between towers near Mungana. However these appear to be faulted down, negating this argument. Robinson also argues his case from similar sandstone found in a depression within another tower, Suicide Bluff, also at Mungana. This sandstone could have been lowered to its present position by solution subsidence, again disfavouring Robinson's proposed history (Jennings, in press).

Related problems arise in the Limestone Ranges of the Kimberleys. Parts of the tops of these ranges appear to be remnants of a formerly widespread planation surface regarded by Wright (1961) as of Upper Tertiary age. On this surface on the Oscar Range are shattered masses of Permian Grant Formation sandstone, which appear to occupy karst depressions (Playford & Lowry 1966), and represent subjacent karst phenomena. Within Kellys Pass in the Lawford Range, not far from the undisturbed Permian outliers sitting higher in the relief (discussed above), there are shattered small bodies of the same sandstone in a valley. These certainly appear to have been lowered by solution subsidence (Figure 6). All of these occurrences are compatible with an Upper Tertiary age for the range-top erosion surface.

West of the northwest tip of the Oscar Range, there are small bodies of sandstone amongst limestone towers rising from a modern planation surface at a lower level than the Tertiary surface and developed at the latter's expense (R.S. Nicoll, pers.comm.). If these sandstones are in their original position of deposition, they imply burial of an older, lower tower karst development of Permian age, followed by later exhumation (cf. the exhumed karst east of Gascoyne Junction, discussed above). Alternatively they could occupy their present position by solutional lowering. The former interpretation would call for a more complex geomorphological history than has been contemplated previously in this Kimberleys region (as do the filled dolines west of Alexander Creek). The latter interpretation is compatible with the history so far accepted. Further study is required.

Features developed in carbonate rocks acting as subjacent karst may be stripped of their covering of insoluble rocks to appear in the landscape for the first time. Nicod (1975) properly points out that it is inexact to call these exhumed and suggests revealed for this category of karst feature. The projecting masses of Jurassic dolerite set in limestone near Mole Creek (discussed above) fall into this category as they are functioning like internal casts of the lost parts of the karst into which they had subsided.

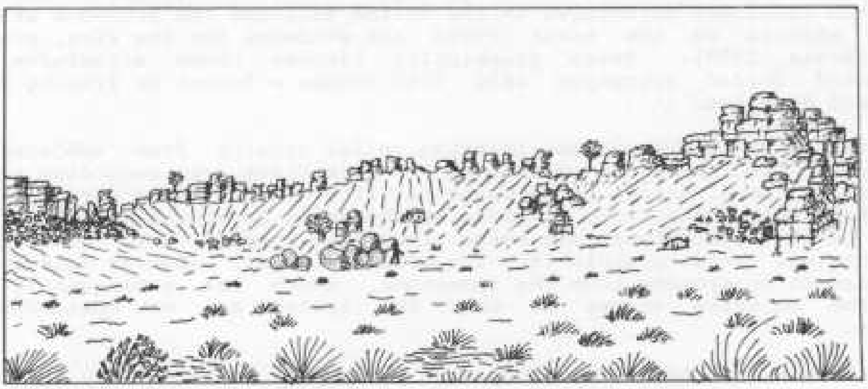

Figure 6 Part of Kellys Pass, Lawford Range, W. Australia. Small bodies of Grant Formation sandstone lowered by solution subsidence to the floor of a valley cut in Bugle Gap limestone.

COMPOUND HISTORY

Several types of elements found in karst geomorphology have been discussed above separately but they are more likely to occur in combination, rendering their decipherment more problematic. Thus burial may be partial or total, affecting the surface or the underground or both. Some examples to illustrate the potential complexity will be given.

The active-relict dichotomy is even more startling at Bungonia, New South Wales, (James et al. 1978), than at Cooleman Plain. Bungonia Creek has cut a gorge over 400 m deep in a subdued plateau at 550 m a.s.l. The gorge in Ordovician to Devonian rocks, including Silurian limestones, is the product of vigorous river erosion such as can be seen going on today and of various slope processes such as rockfall, which not long ago dumped a chaos of boulders at the mouth of the canyon in the limestone. The plateau cuts across rocks of varying resistance to erosion and across vigorous folding and faulting. The latest interpretation of this surface (Young 1977) is that it is a result of protracted continental erosion, followed by marine trimming in Permian time. Burial by Permian marine rocks followed. Then in Late Mesozoic and earliest Tertiary time exhumation took place and Eocene basalts were laid down on the ancient surface. General uplift raised the area to its present altitude; according to Young this was complete about 30 my ago, though others think it continued till much later. Thus in this view the plateau surface is an exhumed Palaeozoic erosion surface. In detail it has been modified. Outcrops of limestone are being dissolved and minor surface solution features are to be seen. Not only is material being washed down into the caves but it is possible that the dolines were not created until the gorge was cut down. The caves for the most part have formed at the same time as the valley cutting, though some of the more or less horizontal passages close to the surface may be earlier. Nevertheless the filled passage remnant in B50 Cave (discussed above) is more likely to be a Tertiary form than a Palaeozoic one.

An erosional interval in the Silurian rocks of Cooleman Plain (Owen & Wyborn 1979) has induced later consequences complicating its own expression in the landscape. In the neighbourhood of Cliff Cave, the Cooleman Limestone has a sinuous, steep margin against which siltstones of the Blue Waterhole Formation abut (Figure 7). It is evident that there was erosion of the limestone prior to the deposition of the siliceous sediments. Whether the erosion was terrestrial or submarine cannot easily be determined because of tilting down to the east in Bowning (Silurian) folding of the whole area and because the surface of exhumation is limited in size, through truncation by the Tertiary planation surface. There has been partial removal of the siltstones in the valley leading to Harris Dam and in the steephead valley of Cliff Cave Spring, which join near the Dam. The siltstones caused the spring to be located here as they had earlier localised the earlier spring which formed Cliff Cave at a higher level. In the interval of valley lowering more siltstones were removed here. Harris Dam despite its name is a natural doline pond in the siltstones but it has been created by removal from below of siltstones into the irregular surface of limestone. Holes appear and disappear in the floor of the pond as the points of withdrawal of siltstone change (Plate 2). Harris Dam overflows in times of favourable water balance to the point of engulfment of the water from Cliff Cave Spring, though overflow of the combined waters down the valley to the North Branch of Cave Creek also occurs. However, as inflow into the pond declines, there is no overflow from it and there is only loss underground through the holes in the floor of the pond. In summary, there are here buried karst landforms partially exhumed, with their pattern controlling the nature and disposition of the active forms of today, and involving a component of subjacent karst.

Buried dolines are likely places for renewal of solution below and consequent subsidence to produce composite features with buried and subjacent components (Panoš 1964). No cases of this are yet known from Australia so by way of illustration a spectacular example from the Marble Canyon of the Colorado River in northern Arizona will be mentioned (Hose & Strong 1981). In the canyon walls, the Redwall Limestone of Mississippian (= Early Carboniferous) age is exposed. Its top is a karst surface with dolines. This was buried with cavities being filled with conglomerate and breccia, followed by a great thickness of Palaeozoic and Mesozoic sedimentary rocks. But subjacent karst action persisted at the doline sites since the shattered fill promoted water movement. As a result breccia pipes stoped upwards to the surface. Later the Colorado River cut its canyon. When the Redwall Limestone was reached, hydraulic circulation was reinvigorated and solution of calcareous matrix in the breccia pipes caused fresh subsidence at the surface high above. This created caves especially at the contact with the pipe walls. One such is Paiute Cave, 161 m deep, with the Redwall Limestone here 450 m below the surface.

Partial burial is a kind of event not well elucidated as yet in Australia. Collapse dolines in the Causses of central France provide a case in point. These had considerable fill of Eocene to Oligocene age which was mined for phosphates. Gèze (1949) argues that the fill was only partial so that the higher parts of the dolines are relict features from those times and may be the oldest of their kind in the world. Main Cave at Isaacs Creek, Timor, New South Wales, combines hilltop location, phreatic excavational forms, and partial sediment fill, itself partially removed (Connolly & Francis 1979). The relict cave is claimed to be Cretaceous in age but this depends on the geomorphological relationship of the ridge containing the cave to neighbouring basalt remnants of Eocene age, about which there is some uncertainty.

Partial burial is even more likely to occur with the fields of residual hills characteristic of several kinds of active tropical humid karst. Thus in Moravia (Czechoslovakia), a tower and pediment karst was partly buried by sediments of an Upper Cretaceous marine transgression with subsequent partial exhumation (Panoš 1964; Bosak 1981). The climate in Late Jurassic - Early Cretaceous time was of a tropical humid nature. Thus in this landscape there are active, relict and exhumed components. The same is true of the Baljanica Mts. in Yugoslavia (Gavrilović 1969) and of the Jura of S. Germany (Büdel 1951). But here the hills are more rounded in character. A problem can arise with interpretation of relief of this kind. Biohermal (e.g. coral reef) masses of limestone are sometimes buried by deeper water shales as they grow upwards. When uplifted and eroded, such a geological structure can yield knobs from which the shales have been stripped and which could be confused with exhumed tropical relief of that kind (Hudson 1933).

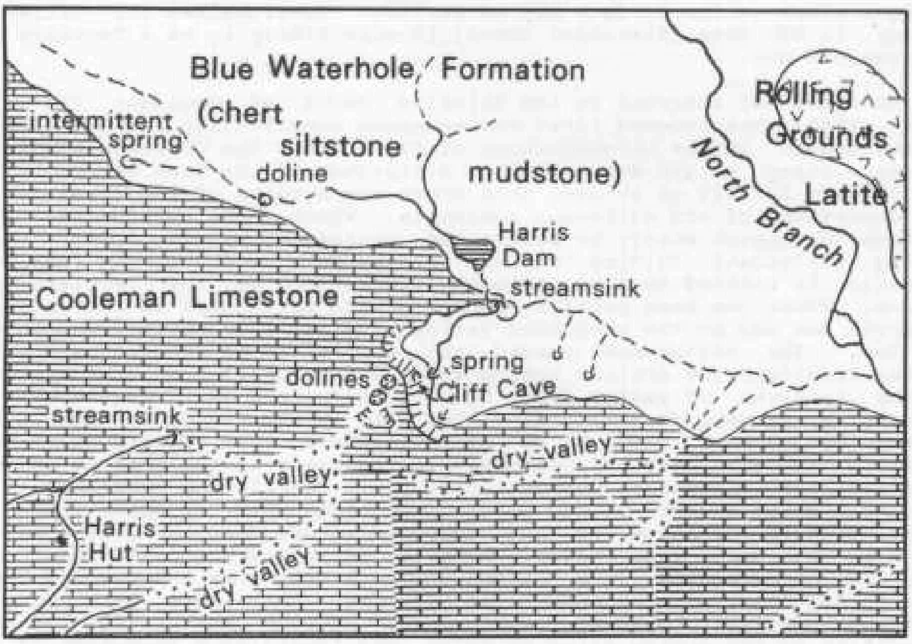

Figure 7 Map of Harris Dam area, Cooleman Plain, N.S.W. From Owen & Wyborn (1979) with some modification. An irregular erosional contact between underlying Cooleman Limestone and overlying Blue Waterhole Formation is partly exhumed. It causes groundwater to emerge in Cliff Cave Spring and locates the subjacent karst doline containing Harris Dam.

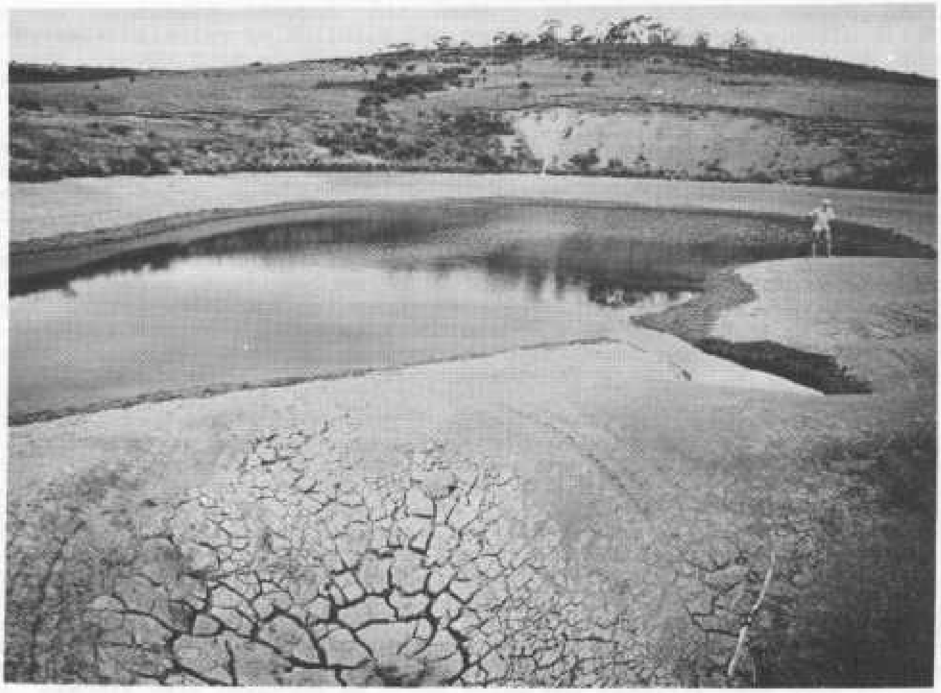

Plate 2 Harris Dam, N.S.W., Cooleman Plain, N.S.W. a subjacent karst doline pond. Three holes where Blue Waterhole Formation siltstone sinks intermittently into Cooleman Limestone below are visible because of low water level. Photo by F.D. Miotke.

TWO PROBLEMATIC TERMS

The terms employed so far have largely been employed in the same sense by investigators; others have not had such consistent usage.

The noun 'fossil' refers to objects which have been buried. Therefore when applied to karst adjectivally, it should be restricted to those features which are buried or exhumed (cf. Birot 1966; Bosak & Horacek 1981; Monroe 1970; Warwick 1976; Commission Francaise des Phénomènes Karstiques 1965). But fossil karst has been used more widely to include relict landforms (e.g. Sweeting 1972; Trimmel 1965; Campbell 1977); this seems undesirable.

Palaeokarst has also been given various meanings (cf. Monroe 1970; Warwick 1976; Ford 1971; Nicod 1975; Trimmel 1965; Commission Francaise des Phénomènes Karstiques 1965). The most useful connotation to attach to it is one that is broad as regards type, allowing it to include relict, buried, exhumed and subjacent features, but restrictive by requiring that considerable subsequent change to the landscape has to have taken place since their creation (Quinlan 1972). The last major orogeny in a region is likely to be a divider in this respect. Thus Campbell (1977) gives a time limit for palaeokarst related to the Laramian orogeny for the northern Rocky mountains, U.S.A., whereas Maire (1980) sets a later limit in relation to the Alpine orogeny in the Mediterranean. In the Crows Nest area in the Canadian Rockies, there are cave remnants punching through the tops of mountain ranges as much as 1200 m above neighbouring valley floors (Ford et al. 1972). These are soundly called palaeokarstic, even though they may be only several million years old. At Yarrangobilly, on the other hand, caves such as Jersey Cave may be 1-2 my old but they do not have topographic relationships varying from those of active caves close to the Yarrangobilly River so that it would be inappropriate to apply the term to them.

On climatic grounds, Tertiary survivals are more commonly regarded as palaeokarstic than Quaternary ones. This may be because climatic oscillations shrank in their time span in the Quaternary. Karst was then subjected to rapidly alternating morphogenetic systems, which are not necessarily cumulative in their effects but may cancel one another out. At Cooleman Plain, probably during the last cold period of the late Pleistocene, the main valleys were aggraded with coarse gravels and a mudflow filled up a blind valley (Jennings 1982). Such happenings should not be thought to warrant applying palaeokarst to them.

CONCLUSION

From the examples set out it is evident that karsts are liable to have complex histories and are compounded of active, relict, buried, exhumed and subjacent elements. Chronology as well as spatial analysis is essential to their understanding and dating caves can be crucial to this. Unravelling such histories is not only important for the systematics of karst geomorphology but can contribute to practical matters such as mineral search, water management and assessment of engineering foundations.

ACKNOWLEDGEMENTS

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GRANITE CAVES IN GIRRAWEEN NATIONAL PARK, SOUTHEAST QUEENSLAND

Brian Finlayson

Abstract

Four caves and two underground streams in granite occur within the Girraween National Park. Only two of these sites have previously been reported. They mainly occur on the margins of major joints in the granite where streams descend into troughs along the joints. The caves are themselves formed in minor joints. In some cases streams have worked their way down from the surface along a joint but at three of the sites streams flow through horizontal joints in the granite which have not been opened from the surface. For these sites it is not clear how the initial passage was opened up underground. The two possible mechanisms suggested here are solution and joint opening following pressure release. The cave morphology clearly indicates that once the flow path is open, abrasion becomes the major process. Flowstone terraces, 'cave coral', and cemented gravels are found in the caves. The speleothems and the cement are amorphous silica (Opal A). Caves in granite may be more common than was previously thought.

INTRODUCTION

Very few caves have been reported in rocks of granitic composition in Australia. Ollier (1965) gave brief mention to a granite cave at Labertouche Creek in Victoria and this cave and a number of other granite caves and related features in Victoria were discussed by Finlayson (1981). Shannon (1975) has mapped and described three caves in granodiorite in Central Queensland. Down Under, newsletter of the University of Queensland Speleological Society, contains some eight separate references to an underground river in granite at Girraween National Park, including a map of the cave published in the December 1975 issue. Willmott et. al. (1981) include this cave in their list of sites of geological significance in Queensland and claim that 'there is no similar feature in southeast Queensland, and caves of this type are uncommon throughout Australia'. This assumption seems to have dissuaded geologists and speleologists familiar with the underground river at Girraween from searching for more caves in the area. During a short visit to the Park in May 1981, the author was shown the location of two more stream passage caves as well as two sites of sinking streams by Mr. W. Goebel, a long-time resident in the area and an employee of the National Parks and Wildlife Service, Queensland.

This paper describes four caves and two sites of sinking streams in Girraween National Park and offers some suggestions as to their origins.

THE REGIONAL ENVIRONMENT

Girraween National Park is situated on the border between Queensland and New South Wales and is part of an area widely known as 'the granite belt' (Figure 1). The Queensland-New South Wales border which forms the eastern boundary of the National Park is located along the watershed of the Great Divide which here separates drainage into the eastward flowing Clarence River system from the westward flowing Severn River which is part of the headwaters of the Darling River. Average elevation is around 1000 metres and Mount Norman, the highest point in the park, rises to 1287 metres.

The nearest station collecting meteorological records is Wallangarra P.O. (877 metres). Median annual rainfall is 787 mm spread throughout the year with a slight summer maximum. The wettest month is December with 94 mm and the driest May with 33 mm. Mean daily maximum temperature ranges from 25.9°C in January to 14°C in both June and July. Mean daily minimum temperatures range from 14.9°C in January to 1.8°C in July. Frosts are common in the winter half-year. Humidity at 9am remains above 60 per cent virtually all year (Bureau of Meteorology, 1975).

Bedrock throughout the area is Lower Triassic Stanthorpe Adamellite (Robertson, 1972; Olgers, 1974) which is part of the New England Batholith. The Stanthorpe Adamellite is coarse grained and occasionally porphyritic. Four varieties have been recognised by Robertson (1972) on both mineralogical and textural grounds. Within Girraween National Park, the major structural feature is a set of master joints trending NNW to NNE which exert a strong control on stream alignments and on the topography generally, though the major drainage direction in Girraween National Park is towards the west (Figure 1).

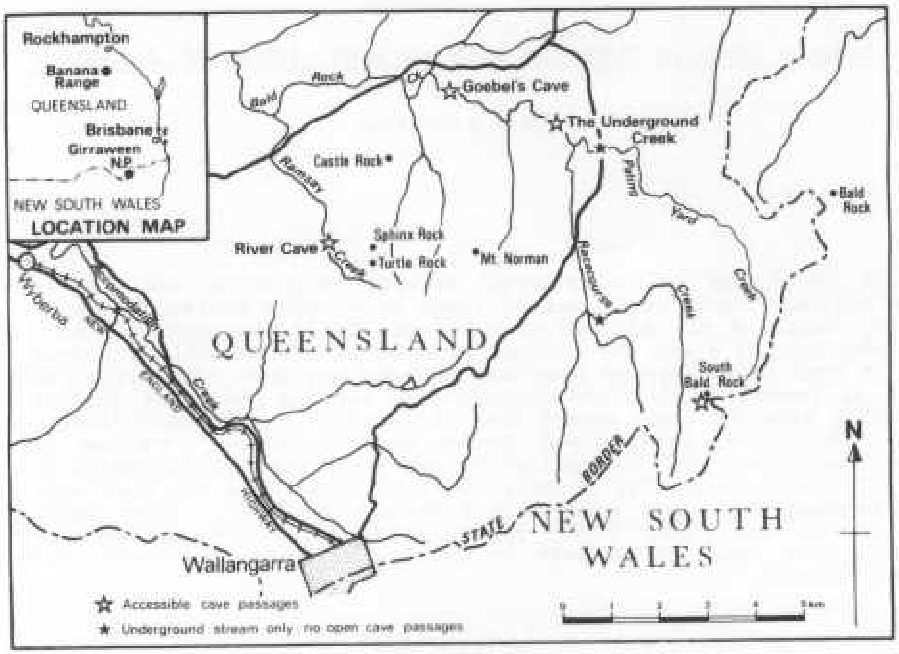

Figure 1. Location map.

Vegetation in the park is open eucalypt woodland and the cypress (Callitris glauca) forms an important part of the tree cover in the sandy soils of the area. Along many of the major joints there are flat swampy areas which support marsh and heath communities. Most of the hills retain their original woodland cover though much of the more gently sloping country has been cleared for grazing or orchards.

SITE DESCRIPTIONS

The locations of the caves and underground streams are shown in Figure 1. There are four caves with accessible cave passage and also two sites where streams go underground but which have no known accessible passages.

River Cave

This is the cave which has been known for some time to the the University of Queensland Speleological Society. Prior to the establishment of the National Park it was referred to as the Wyberba underground river. It has been mapped by Pound et. al. (1975), and their map is reproduced here as Figure 2. The cave is located on Ramsay Creek as shown in Figure 1. The cave is adjacent to a major NNE trending joint where Ramsay Creek makes an abrupt descent into a valley excavated along the major joint. The stream has excavated a minor joint in the granite which dips at approximately 20° and which has a strike roughly at right angles to the major joint direction. The excavated joint can be followed to the surface where the overlying rock has collapsed indicating roughly the position of the original surface stream channel. During periods of low flow water enters the cave through horizontal joints passing through granite in situ. The capacity of these joints (none of which are large enough to be accessible) is exceeded at high flows and part of the original surface channel is used until all flows sink through a boulder pile which is the start of the collapsed upper edge of the joint in which the cave has formed. It appears from surface evidence as if all flow levels are accommodated by the cave system. At the downstream end the stream rises through a boulder pile and there is evidence from deposits and clean boulder surfaces that the rising moves upstream at higher flows.

Inside the cave, the lower surface of the excavated joint still retains its water-worn polish to well above the presently active level. In places the joint is clogged with coarse gravel and boulder accumulations, some of which are cemented together. Parts of the cave roof, particularly in the boulders at the top of the cave, are covered with a deposit identical in morphology with the 'cave coral' of limestone caves.

The cave houses a colony of bats (Miniopteris schreibersii), numerous glow worms, spiders and moths, and bright red freshwater crayfish (Euastacus suttonii) can be found in pools in the cave stream.

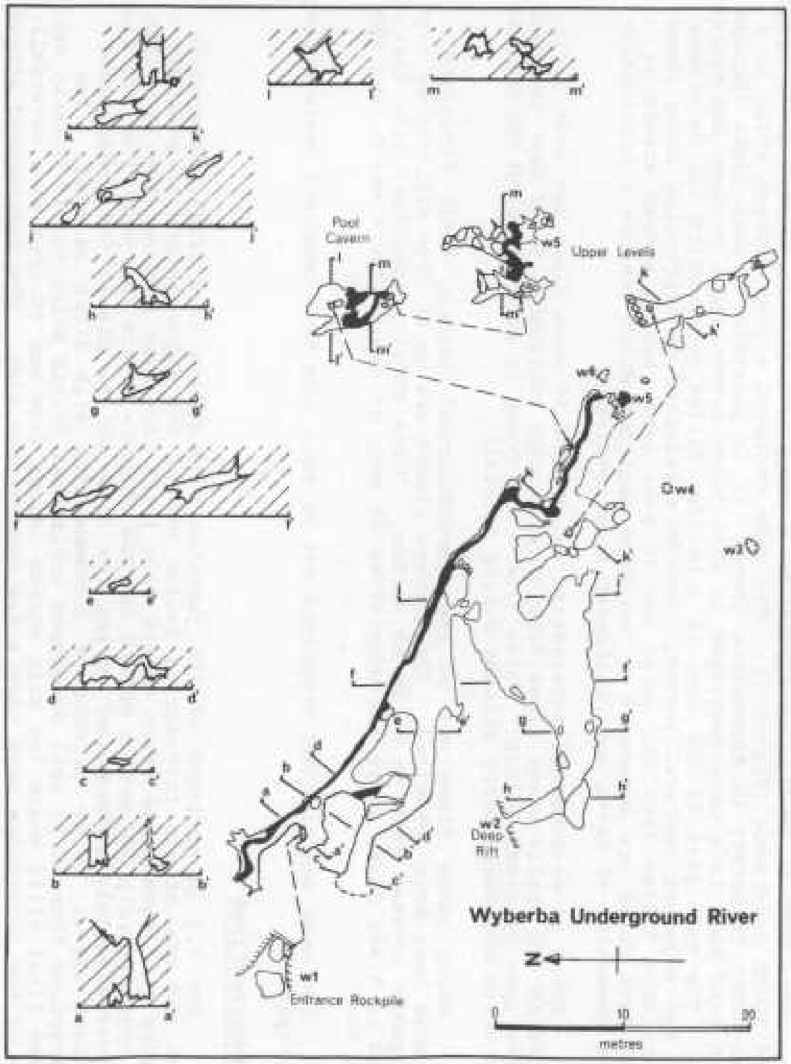

Figure 2. River Cave on Ramsay Creek. (Redrawn by Rob Bartlett from Pound et al, 1975.)

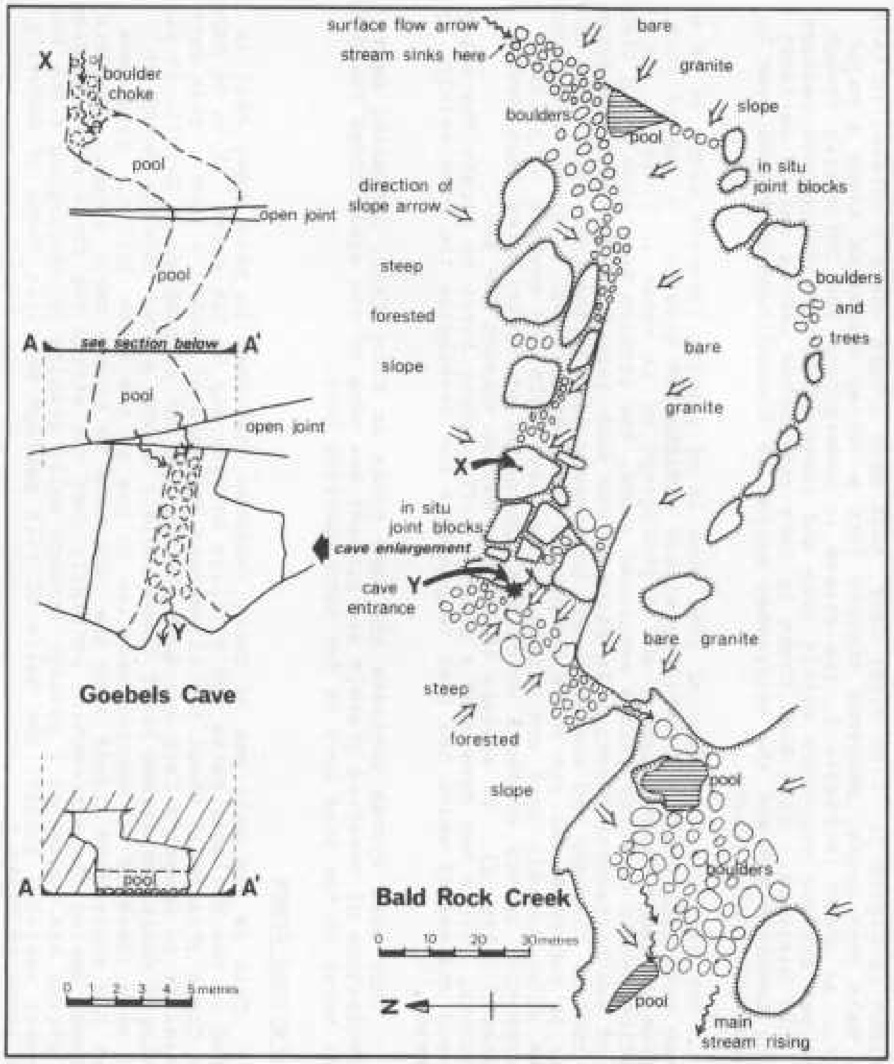

Figure 3. Sketch map of the site of Goebel's Cave on Bald Rock Creek.

Goebel's Cave

The location of this cave is shown in Figure 1 and a sketch map of the site is shown in Figure 3. Like River Cave, this cave occurs where a stream, in this case Bald Rock Creek, descends steeply into a valley excavated along a major joint. As shown in Figure 3, the stream is underground for 200 metres though there are surface stretches within this and there is no continuous cave passage for this distance. Bald Rock Creek is here entrenched into a set of vertical joints trending WNW and the entrenched stream is discontinuously roofed over by boulders and joint blocks.

One particular section of this cave is of special interest since it is a stream cave apparently cut entirely within undisturbed granite. A map of this section is inset into Figure 3 and a photograph of it shown in Plate 1. In addition to the vertical joints mentioned above, the granite here also has a clear set of sub-horizontal joints. In Plate 1, two such joints can be seen, one forms the roof of the cave and the other can be clearly seen in the cave wall. The cave floor is submerged for its whole length and the bedrock floor is pitted with scour holes which contain sand and gravel. The cave walls are covered with large intersecting curved surfaces which are the sides of scour holes that have coalesced (Plate 1). It appears that water moving through the sub-horizontal joints has developed a passage sufficiently large to permit the entry of sand and gravel which has been responsible for developing the cave mainly by abrasion.

This cave system contains the same biota as River Cave, including bats. Accumulations of cemented gravels are present but none of the speleothems found in other caves in the area have so far been observed here.

Underground Creek

This is the only one of these features discussed in this paper that is marked on the National Parks and Wildlife Service map of the park. It is on Bald Rock Creek (Figure 1) about two kilometres upstream of Goebel's Cave. This cave is similar to Goebel's Cave but much shorter and not as complex in detail. It has developed where the stream level drops rapidly across a rock outcrop though in this case there is no obvious relation to one of the major joints. Bald Rock Creek has entrenched itself into the rock band to form a small gorge. Boulders produced during the entrenching partially roof the stream but for a short section the stream has excavated a passage through solid granite by developing along two adjacent vertical joints. The walls of this passage are like those of Goebel's cave shown in Plate 1.

South Bald Rock Cave

This cave is located in a joint in a large bare granite outcrop quite aptly named South Bald Rock (Figure 1). The cave contains a small stream which is a first-order tributary to Racecourse Creek. It is possible to pass right through South Bald Rock in a cave developed in this joint system which is some 400 metres long. The main part of the cave is a boulder filled gorge which has developed from two adjacent vertical joints. Boulders released by weathering along these joints have fallen into the gorge and in some cases became wedged across it. Short dark caves are separated by unroofed sections which contain a distinctive plant community of ferns and rainforest tree species.

There is evidence of substantial water flow at some times but even during prolonged dry spells water flows from an open sub- horizontal joint near the base of the open vertical joints. False floors are found in some parts of the boulder pile which obviously carry streams during rainfall.

Where water flows out of the sub-horizontal joints, small flowstone terraces have been deposited. The terrace risers are up to five millimetres high and pools between them up to 20 mm across. 'Cave coral', identical with that found in River Cave, coats the undersides of many of the boulders which form the cave roof.

The cave contains bat droppings but no bats have been observed there during two visits.

Racecourse Creek

For 5.5 km upstream of its junction with Paling Yard Creek, Racecourse Creek and one of its tributaries follow one of the major joints aligned NNW (Figure 1). Racecourse Creek enters this joint line over a steep drop 30 m high. For approximately 300 metres before the WSW channel enters the joint line the flow is predominantely underground during low flow and in places the underground passages appear to be capable of accommodating high flows as well. The underground flow is in well developed horizontal joints which can be clearly seen in the final cliff where the main stream issues from one of them as a waterfall. None of the joints are more than a few centimetres wide. The underground stream here has not worked its way underground by excavating down from the surface as was the case with River Cave but has developed a passage through granite in situ.

Paling Yard Creek

An underground stream passage, similar to that on Racecourse Creek, has developed on Paling Yard Creek 0.5 km upstream of its junction with Racecourse Creek (Figure 1). Here also the underground stream passage is developed in horizontal joints completely roofed over with solid granite. This site is remarkable for the collapse doline in the stream bed into which the stream sinks. A sketch map of the site is shown in Figure 4 and a photograph of the doline in Plate 2. As shown in the sketch map the underground route of the low flow does not follow the same alignment as the surface high flow channel.

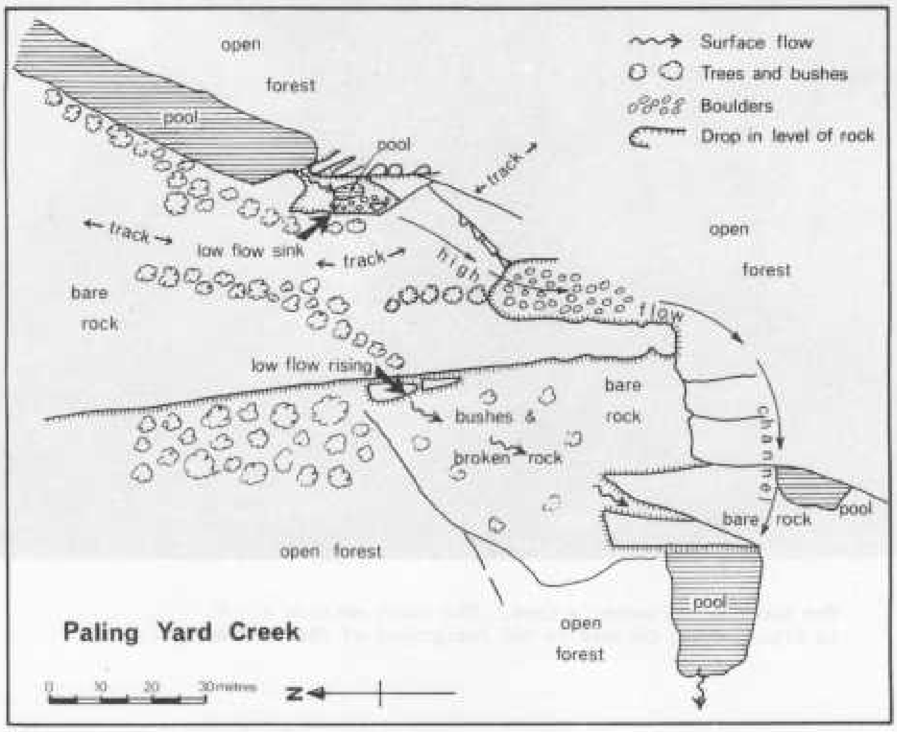

Figure 4. Sketch map of the sinking stream on Paling Yard Creek.

DISCUSSION

Although the granite caves at Girraween are small and apparently insignificant, even by comparison with other granite caves, they include the only caves so far reported which are cut through solid granite. All other granite cave systems of which the author is aware are either developed in boulders or, where the cave is now in bedrock, are roofed over with boulders (see for example, Finlayson, 1981; Arnold, 1980; Shaw, 1980). The underground streams on Racecourse Creek and Paling Yard Creek, while not being caves, are included here since they are interesting features and relevant to the discussion.

All the sites described here are similar in terms of their settings. All are developed adjacent to major well-developed joints in the granite where streams descend steeply across rock outcrops to enter a joint trough. At River Cave, South Bald Rock, Underground Creek and parts of the Goebel's Cave system, most of the cave excavation has been carried out by a stream working its way down from the surface. For part of Goebel's Cave (shown in Plate 1), the low flow entrance to River Cave and the underground sections of Racecourse Creek and Paling Yard Creek, the stream passages have been opened up underground along horizontal or sub-horizontal joints which are most probably unloading joints (Ollier, 1965). It is not clear how the unloading joints were initially opened up. One possibility is that during pressure release, joints are opened wide enough for turbulent flow to develop and to permit the passage of an abrasive sand load. Alternatively, solution may be responsible for that initial opening. Kastning (1977) supports the idea that the passage is opened initially by solution. Clearly solution of the granite occurs and many of the bare rock surfaces at Girraween have solution pans developed on them though it must be remembered that wind and rainsplash can remove insoluble residue from the pans. Since it has always been assumed that an important property of limestone for cave formation is its low proportion of insoluble residue, the opening of joints in granite by solution would seem to be unlikely. It is clear however that once opened sufficiently, abrasion becomes the most important process since forms produced in this way dominate the cave

Plate 1. The interior of Goebel's Cave. The cross section A - A' in Figure 4 was located in the foreground of this photograph.

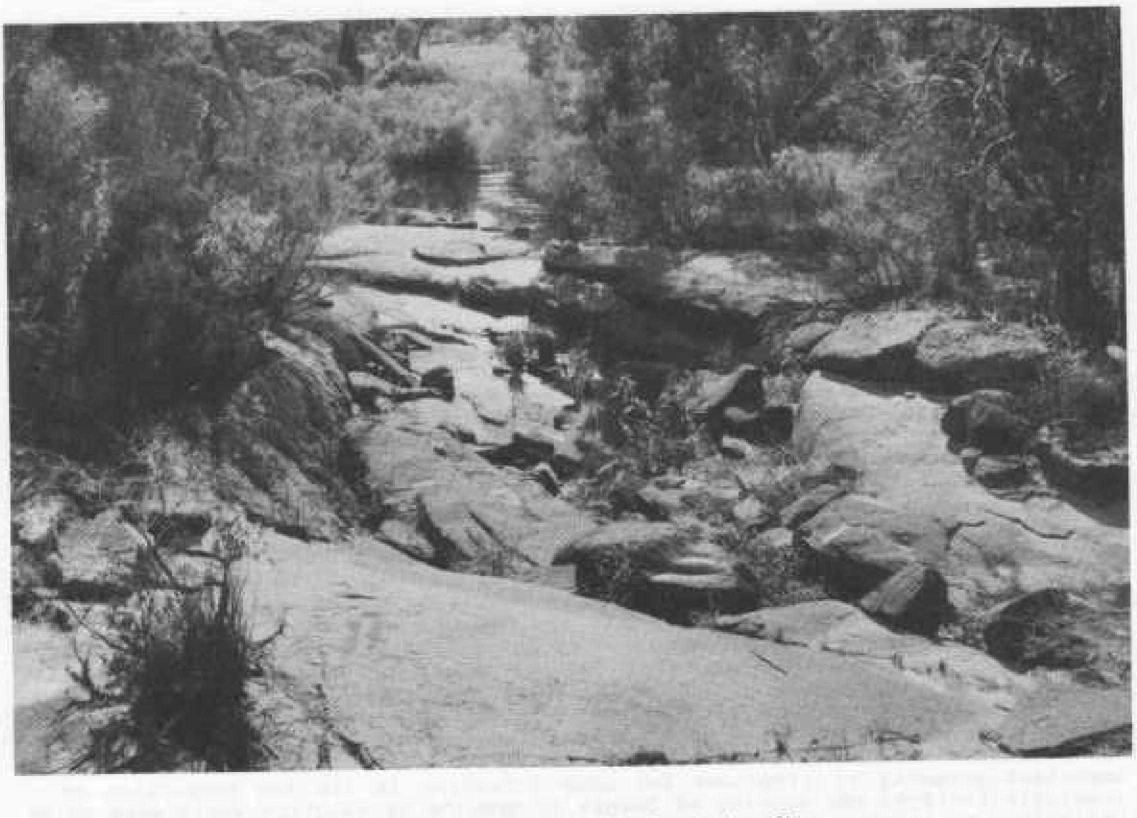

Plate 2. The 'doline' on Paling Yard Creek. This is the low flow sink shown in Figure 5.

morphology (see Plate 1). Granite surfaces that have been subjected to solution as the major process are very rough since the different minerals weather in this way at different rates. The walls of stream passage caves in granite are quite smooth and in many cases highly polished and this indicates abrasion is the dominant process. The underground streams on Paling Yard Creek and Racecourse Creek may be early stages in the development of caves like that shown in Plate 1.

Speleothems, in the form of flowstone terraces and 'cave coral', have not previously been reported from granite caves. Preliminary analyses of speleothem samples from South Bald Rock and River Cave and of the cement from between gravels in River Cave show that they are all amorphous silica deposited as Opal A. Analyses of the minor constituents of this material are continuing.

Since most of the Girraween caves have hitherto escaped the attention of speleologists despite frequent visits to River Cave, there would seem to be a strong possibility that many more granite caves await 'discovery' in this and other areas. The work presented here is based on only two very brief visits to Girraween and it is clear that much more detailed work needs to be done before a full understanding of the modes and rates of development of these cave systems can be presented.

ACKNOWLEDGEMENTS

Sincere thanks are due to Mr. W. Goebel of Girraween for information on the location of caves and underground streams. Fair copy of the map of River Cave in Figure 2 was provided by Dave Gillieson. The author's patient wife held the other end of the tape.

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EVALUATION OF CARBON DIOXIDE AND OXYGEN DATA IN CAVE ATMOSPHERES USING THE GIBBS TRIANGLE AND THE CAVE AIR INDEX

Erik J.M. Halbert

Abstract

Water vapour determines the volume percentage of component gases in cave atmospheres. This is particularly significant in foul air caves where carbon dioxide and oxygen concentrations are measured and used to diagnose foul air types. The variation in atmospheric composition brought about by systematic change in carbon dioxide and oxygen levels is examined and shown on the Gibbs triangle. The current three foul air types are readily identifiable in this visualisation of data, and the boundaries of these types are mapped. Further, these diverse data can be combined into a Cave Air Index by which foul air atmospheres may be assigned to type in a rapid and objective manner. The use of these concepts in evaluation of published data on Wellington and Bungonia Caves and with mine and soil data is shown.

INTRODUCTION

Early work by members of Sydney University Speleological Society (Stillman and Landecker, 1961) showed that relatively simple calculations using gas analysis data could yield information on the origin of foul air in caves. Since that time there has been considerable further work in the field of foul air, particularly in Australia, and the importance of gas analysis in this area of study has been realised by current workers. However, although the importance of gas analysis is acknowledged, and considerable improvement has been made to instrumentation, the analysis in situ of individual gas components with the exception of carbon dioxide is a relatively difficult achievement. Total gas analysis data are still extremely sparse and the role of water vapour in such situations rarely appreciated, especially from a quantitative viewpoint. These difficulties aside, there are increasing numbers of carbon dioxide and oxygen analyses being carried out in caves and reported in the speleological literature.

There are now three major types of foul air recognised in caves and with a large number of possible gas compositions, it is difficult to visualise the analytical data. This is particularly evident now that research is being carried out into type 3 foul air situations where strong enhancement of the residue fraction of the cave atmosphere occurs, through a variety of mechanisms. The residue fraction is a composite figure comprising all components of the atmosphere minus carbon dioxide and oxygen. It thus includes nitrogen, the rare gases, water vapour and, if present, other gases such as methane, hydrogen sulphide etc. In cave literature the residue fraction has often simply been termed nitrogen; however, this is inaccurate and confusing, since there can be foul air situations where the true nitrogen value may be lower than normal but the residue fraction may be higher. These situations are considered in more detail elsewhere (Halbert, in preparation).

THE ATMOSPHERE

Composition and Pressure

The lower part of the Earth's atmosphere is a homogeneous region with circulation such that an essentially constant composition is maintained. The volume percentage of major components remains constant to a height of many thousands of metres although the barometric pressure and consequently the partial pressure of individual components falls rapidly with increasing height (Ehrlich, Ehrlich and Holdren, 1977; Riehl, 1978). The total pressure of a mixture of gases is equal to the sum of their partial pressures. Thus the atmospheric or barometric pressure of dry air is represented by pNitrogen (pN_2) plus pOxygen (pO_2) plus pRare Gases (pRG) plus pCarbon Dioxide (pCO_2).

From the gas laws it follows that the partial pressure of each component of a mixture of gases is determined by the volume percentage which it occupies of the total volume of the mixture. In dry atmospheric air at the standard barometric pressure of 101.325kPa(760mmHg) the partial pressure of nitrogen would be 78.09 percent or 79.12kPa. Other partial pressures are calculated similarly (Table I). Although the volume percentage figures are pressure independent over a very wide range, it is usual to carry out gas volume calculations at the standard barometric pressure and this was used throughout the present work.

The Effect of Humidity

The foregoing comments apply to dry atmospheric air and, under humid conditions, a component for water vapour must be included. Thus in cave atmospheres the barometric pressure includes the water vapour component and the following equation is applicable.

$$\text{Barometric Pressure} = pN_2 + pO_2 + pRG_2 + pCO_2 + pH_2O$$

Since cave atmospheres are usually saturated with water vapour, the partial pressure of each of the component gases is exerted in a total pressure of 101.325kPa minus the saturation water vapour pressure at the temperature of the cave. The saturation water vapour pressure increases with temperature and consequently the volume percentage of gases in the saturated cave atmosphere decreases as the temperature increases. The relationship between these figures at 20°C and 30°C is shown in Table I. Atmospheres with partial saturation have lower water vapour pressure but are calculated in the same manner.

It may be seen that while the effect of humidity is of little significance when carbon dioxide alone is concerned, it cannot be ignored when oxygen and especially nitrogen concentrations are being considered. The effects are commonly taken into account in medical investigations concerned with respiration (Randall, 1962; Altman and Dittmer, 1971) and must also be taken into account where gas temperatures are very high. In such cases, water vapour in gas mixtures such as magmatic gases may comprise 80 to 90 percent by volume (Tiratsoo, 1972).

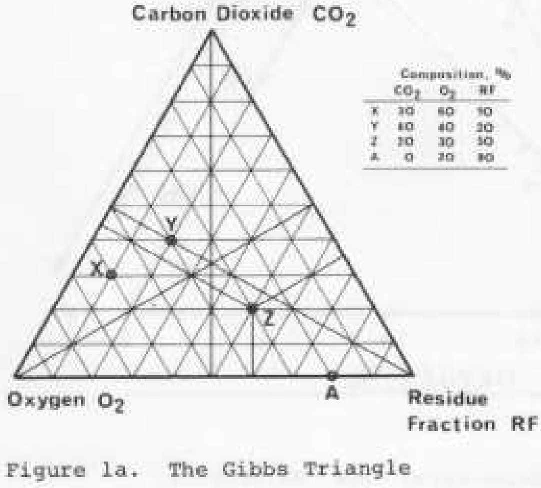
Calculation of New Gas Mixture Compositions

Given the partial pressure distribution of gases within a gas mixture, it is a straightforward procedure to calculate the new percentage volume composition which will result from carrying out any changes on the system. For example to follow the effect of increases in carbon dioxide level by carbon dioxide addition, the partial pressure of carbon dioxide is increased and the resulting levels recalculated to a barometric pressure of 101.325kPa from which the new volumetric percentages are then derived.

In this work a Panasonic 800 computer was used and calculations were made covering the three types of foul air which are thought to occur in caves (James, 1977). In all cases the standard dry atmosphere was taken as starting point before the more realistic saturated conditions were investigated. The inclusion of water vapour in the calculation does not affect the arguments derived from the data but does shift the position of lines in the more detailed figures.

THE GIBBS TRIANGLE

The Gibbs triangle (Figure 1a) is a common method for plotting composition in a ternary system. It was originally developed to interpret ternary alloy phase equilibria (Stokes, 1891) and is still used in such studies (Prince, 1966) although other systems such as rock classifications have been constructed using it as a framework (Turner and Verhoogen, 1960; Jennings, 1971). In this work using gas volumes the corners of the triangle represent the three components, carbon dioxide, oxygen and residue fraction.



	Composition, %		
	CO_2	O_2	RF
X	30	60	10
Y	40	40	20
Z	20	30	50
A	0	20	80

Figure 1a. The Gibbs Triangle

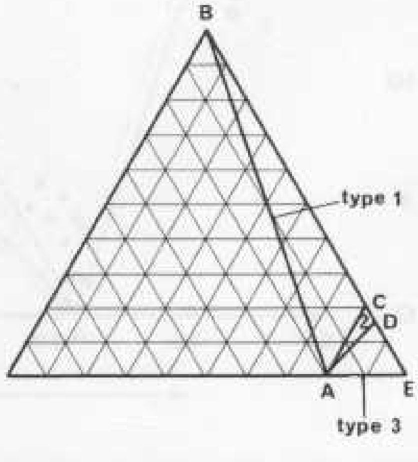


Figure 1b. Theoretical gas compositions for major types of foul air.

The edges of the Gibbs triangle represent the composition of binary gas mixtures and on the scale of Figure 1a, standard air may be represented as such a mixture, at point A. Ternary compositions are plotted as points within the triangle. The characteristics of the triangle are well described by Prince, the most important of which is that the sum of the perpendiculars from any point in the triangle to the sides of the triangle is constant and equal to the height of the triangle and normally this height is set at 100 percent. The perpendicular distances thus may be used to give the composition of any gas mixture in the ternary system as shown in Figure 1a by points X, Y and Z. All points drawn on a line parallel to one edge of the triangle contain a constant amount of the component opposite to the edge. Simimarly, all points on lines drawn from a corner to the opposite edge of the triangle contain a constant ratio of the components along the edge and it is immaterial whether the line meets the edge at right angles or not.

In foul air studies in cave systems there are rarely carbon dioxide concentrations greater than 20 percent, and it is convenient then to consider in more detail the area bounded by the 25 percent oxygen and 25 percent carbon dioxide contours in the Gibbs triangle and this section is used in Figures 2, 3 and 4.

TABLE I Percentage composition and partial pressures of gases in standard dry and saturated cave atmospheres at 20°C and 30°C

Component	Dry Atmosphere		20°C Cave Atmosphere	30°C Cave Atmosphere
	content (vol.%)	p gas (kPa)	content (vol.%)	content (vol.%)
Nitrogen	78.09	79.12	76.30	74.83
Oxygen	20.95	21.23	20.46	20.07
Water Vapour	0	0	2.30	4.18
Rare Gases	0.93	0.94	0.91	0.89
Carbon Dioxide	0.03	0.03	0.03	0.03

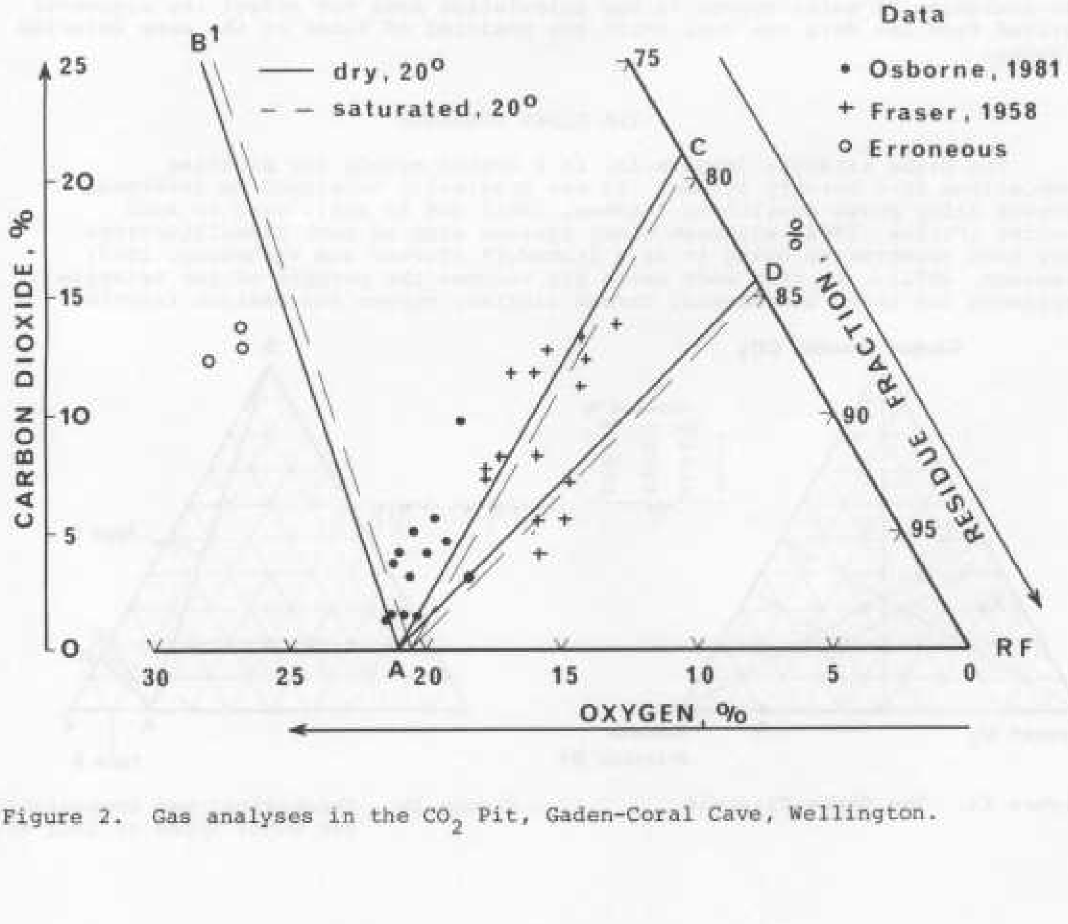


Figure 2. Gas analyses in the CO_2 Pit, Gaden-Coral Cave, Wellington.

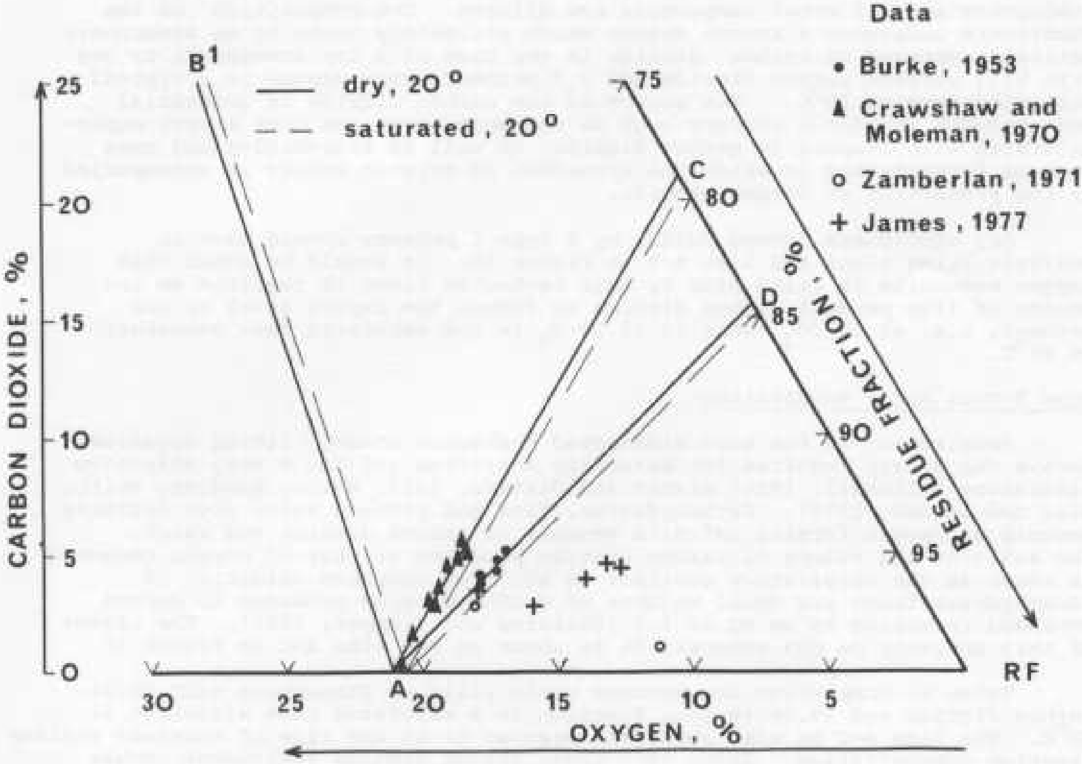


Figure 3. Gas analyses at Bungonia.

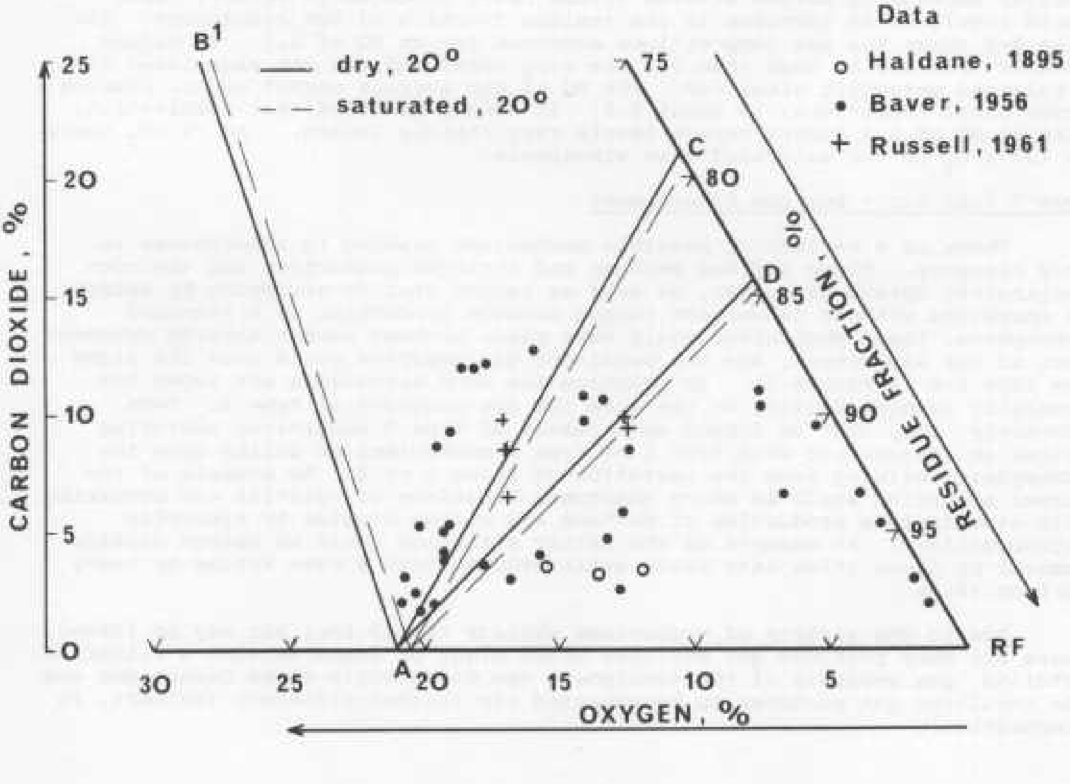


Figure 4. Gas analyses in soils and wells.

Type 1 Foul Air - Carbon Dioxide Addition

This occurs when carbon dioxide alone is introduced into the cave atmosphere and all other components are diluted. The composition of the atmosphere undergoes a smooth change which ultimately leads to an atmosphere entirely composed of carbon dioxide in the case of a dry atmosphere or one with 97.7 percent carbon dioxide and 2.3 percent water vapour in a typical saturated cave at 20°C. The source of the carbon dioxide is immaterial and includes inorganic sources such as volcanic gases and cave waters supersaturated with respect to carbon dioxide, as well as microbiological ones such as fermentation in which the breakdown of organic matter is accompanied by the production of carbon dioxide.

Any atmosphere formed purely by a type 1 process should have an analysis lying along the line A-B in Figure 1b. It should be noted that oxygen reduction is quite slow by this mechanism since it requires an increase of five percent carbon dioxide to reduce the oxygen level by one percent, i.e. at 5% CO_2 there is 19.5% O_2 in the saturated cave atmosphere at 20°C.

Type 2 Foul Air - Respiration

Respiration is the most widespread mechanism whereby living organisms derive the energy required for metabolic activites and has a very extensive literature (Mitchell, 1950; Altman and Dittmer, 1971; White, Handler, Smith, Hill and Lehman, 1978). Carbohydrates, fats and protein react with definite amounts of oxygen forming definite amounts of carbon dioxide and water. The ratio of the volume of carbon dioxide produced to that of oxygen consumed is known as the respiratory quotient or RQ. For complete oxidation of carbohydrate there are equal volumes of carbon dioxide produced to oxygen consumed resulting in an RQ of 1.0 (Cantarow and Trumper, 1962). The effect of this activity on gas composition is shown as the line A-C in Figure 1b.

Taken to completion the process would yield an atmosphere with 20.5% carbon dioxide and 79.5% residue fraction in a saturated cave situation at 20°C. The line A-C is also important because it is the line of constant residue fraction concentration. Above this line, carbon dioxide enrichment occurs with residue fraction dilution while below the line, carbon dioxide enrichment occurs along with residue fraction enrichment.

RQ is not constant for all organic compounds and would be 1.0 only if the organism was utilising carbohydrate exclusively. If utilising protein exclusively it would be 0.8 and if fats exclusively it would be 0.7, both of which situations would result in utilisation of oxygen with relatively smaller amounts of carbon dioxide volume being produced in return. This would result in an increase in the residue fraction of the atmosphere. The line A-D shows the gas compositions expected for an RQ of 0.7. RQ values greater than 1.0 or less than 0.7 are very rare, and are not associated with a balanced metabolic situation. The RQ of the average normal adult, studied under basal conditions, is about 0.8. It should be noted that respiration, with an RQ of 0.7 lowers oxygen levels very rapidly indeed. At 5% CO_2 there is 13.7% O_2 in the saturated cave atmosphere.

Type 3 Foul Air - Residue Enhancement

There is a variety of possible mechanisms leading to atmospheres in this category. These include methane and nitrogen production and the non-respiratory uptake of oxygen, as well as carbon dioxide stripping by water. If operating without concurrent carbon dioxide production on a standard atmosphere, these mechanisms would take place without carbon dioxide enhancement of the atmosphere, and the resultant gas analyses would then lie along the line A-E in Figure 1b. In practice few such situations are known and generally samples falling in the area ADE are regarded as type 3. More correctly they must be formed as a result of type 3 mechanisms operating either in conjunction with type 1 or type 2 mechanisms or acting upon the atmospheres arising from the operation of types 1 or 2. An example of the former situation would be where anaerobic breakdown of material was occurring with simultaneous production of methane and carbon dioxide by symbiotic microorganisms. An example of the latter situation would be carbon dioxide removal by dissolution into fresh water brought into a cave system by heavy surface rains.

Due to the variety of mechanisms whereby type 3 foul air may be formed, there are many possible gas mixtures which might be found in such a situation. Detailed gas analysis of the atmosphere can disentangle these mechanisms and the resultant gas mixtures to be expected are treated elsewhere (Halbert, in preparation).

It is important to realise that type 3 conditions do not need to have low absolute oxygen levels although in practice most of them do. A gas mixture of composition 1% CO_2, 17% O_2 and 82% residue fraction is a type 3 foul air as is one with a composition of 4.5% CO_2, 10.5% O_2 and 85% residue fraction. Also these types of foul air may well have deceptively low carbon dioxide levels, leading to dangerous situations when this is the only gas being monitored.

THE CAVE AIR INDEX

The composition of a ternary mixture is completely characterised by two of the quantities. In the present study, carbon dioxide and oxygen may be specified as the independent variables, and thus the residue fraction becomes a dependent variable which does not have to be evaluated. The gas mixture can therefore be characterised in such a way as to obtain a single numerical value or index which reflects the carbon dioxide and oxygen composition. Such an index ideally is general, simple to calculate and can be used to evaluate real data obtained in a cave system.
The formula proposed is:

$$\text{Cave Air Index} = \frac{CO_2}{21-O_2}$$

where CO_2 and O_2 are the percent volume values on a dry basis. The state in which the data are obtained is dependent upon the analytical method used and in some accurate types of apparatus such as the Orsat and Shepherd, even though the analyses are performed over water, the results obtained are on a dry basis (Himmelblau, 1966; Altieri, 1945). In less accurate instruments such as the Dräger gas detector, the standard deviation of tubes is such that the effects of water vapour are not important. In practice the formula can be used in all normal circumstances.

This formula was tested with theoretical gas compositions obtained in the preparation of the Gibbs triangle and in particular with the compositions forming lines A-B, A-C, A-D and A-E; the defining lines for the various types of foul air. Within the range 1 to 25 volume percent carbon dioxide, the index values for the lines are essentially constant and shown in Table II. Cave air indices lying between these values are indicative of mixtures of foul air types with relative purity being indicated by closeness of the index to the values shown in Table II. When evaluating real situations it should be remembered that the index is sensitive to the accuracy of the oxygen analysis, particularly when the % O_2 is close to 21.

TABLE II Cave air indices and their interpretation

Cave Air Index	Gibbs Triangle Equivalent	Interpretation	
		Foul Air Type	Mixed
4-5	Line A-B	1	
1-4	Area ABC	1+2	1+3
.75-1	Area ACD	2	2+1, 2+3, 1+3
0-.75	Area ADE	2+3	1+3
0	Line A-E	3	

Mixed Situation

The lines, area and indices established in the preceding sections define the gas compositions which would result in any situation where predominantly one type of foul air production was taking place. In practice the possibility of more than one mechanism contributing to a cave atmosphere must always be considered. These cases are not dealt with in detail in this article. However, as a guide, some of the mixed situations possible are shown in Table II.

PUBLISHED DATA AND THE GIBBS TRIANGLE

Given the provisos of the previous section, it was found worthwhile to look at several situations for which carbon dioxide and oxygen analyses were available, to interpret those data using the index and triangle and to see how the results fitted the accepted foul air situations at these places. In plotting the data, the figures as originally provided were used. Wellington data, Bungonia data and data from soil gas studies have been used.

Wellington

The Gaden-Coral Cave at Wellington, New South Wales, has long been known to have high levels of carbon dioxide in some parts of the cave, particularly in and around the CO_2 Pit. Gas analysis of atmospheric composition was early reported by Nurse (1955) and extensive work was carried out by Fraser (1958). In recent times the cave has received attention by Osborne (1981). Carbon dioxide and oxygen analyses from these papers have been plotted on Figure 2, the data from Fraser being derived from his published graphs.

It is interesting to note that Fraser did not claim gas analyses of 12% CO_2 with 22% O_2, 12.5% CO_2 with 20.5% O_2 and 13.5% CO_2 with 20% O_2 in the CO_2 Pit, as has been reported (Lane and Richards, 1963; Osborne, 1981). These erroneous data appear to stem from the way in which Fraser plotted carbon dioxide concentration as the lower line and the sum of the concentrations of carbon dioxide and oxygen as the upper line on his graphs. The peculiarities of these erroneous data are shown immediately when the cave air indices of -12, 25 and 13.5 are calculated and visibly when they are plotted on the Gibbs triangle and found to lie to the left of type 1 line of carbon dioxide addition. Such a situation represents oxygen enhancement and is not known in caves.

The correct data for the gas analyses are 12% CO_2, 10% O_2; 12.5% CO_2, 8% O_2 and 13.5% CO_2, 6.5% O_2 respectively, which compare closely with the 12.4% CO_2, 9.2% O_2 reported by Nurse. These data yield cave air indices of 1.1, 1.0, 0.9 and 1.1 and suggest type 2 foul air.

In Figure 2 no attempt has been made to plot all the published data, especially those data with carbon dioxide levels around one percent. Although these are significant levels of carbon dioxide, it is quite difficult to ascribe such analyses to a particular type of foul air. However, most of the high carbon dioxide values have been plotted where oxygen values were available as well.

It is clear that the bulk of the readings lie close to the type 2 area, particularly those where carbon dioxide levels are above 5%, suggesting that in such cases the major contribution to the cave atmosphere is respiration rather than carbon dioxide addition as has been suggested (Osborne, 1981). Where carbon dioxide levels are less than five percent, a much less clearcut picture emerges and it appears as if both type 1 and type 2 mechanisms may be contributing. With the exception of two analyses from Fraser there is little evidence of type 3 foul air in the CO_2 Pit although the possibility of such an occurrence cannot be ruled out.

Bungonia

The major caves at Bungonia have also long been known to have high concentrations of foul air and have been intensively investigated since 1972 (James, Pavey and Rogers, 1975; James, 1977, 1981). Gas analyses have been made with a variety of equipment types and many of these have been plotted on Figure 3. In comparison with the situation at Wellington it appears as if the major occurrences of foul air are consistent with type 2 and mixed type 2 - type 3 atmospheres. Some series of measurements lie almost exactly along the line of theoretical RQ of 1.0 and others along the line RQ of 0.7. There appear to be very few cases of type 1 foul air in the caves.

Some of the analyses have extremely low cave air indices. For example, a sample from the Grill Cave with 1.4% CO_2, 12.0% O_2, 86.6% residue fraction (Zamberlan, 1971) yields a cave air index of .16, which is consistent with almost pure type 3 behaviour, although the mechanism leading to this atmosphere can only be speculated upon. The somewhat higher cave air index of .43 obtained with the October 1973 sample in Odyssey Cave, Knockers Cavern, with a composition of 2.8% CO_2, 14.5% O_2, 80.3% residue fraction, suggests that this too would be better classified as type 3 foul air rather than type 2 (James, 1977).

Soil Gas and Mine Gas Data

The carbon dioxide-oxygen equilibria existing in soils have been examined by many agricultural scientists and several tabulations of data are available (Baver, 1956; Russell, 1961). Some of these are particularly relevant to the situation occurring in caves since they deal with waterlogged soil in which anaerobic processes contribute to the final gas composition. Some of these data have been plotted on Figure 4 and it may be seen that soil gases may have compositions ranging over most of the diagram, with the exception of the type 1 atmospheres. However, there are sufficient samples to suggest that carbon dioxide addition certainly plays a part in the development of some of the atmospheres even if it does not predominate.

Cave air indices of these samples vary widely, but of particular interest are some of the type 3 analyses. An extreme example of this is the gas sample with 2% CO$_2$, 0.2% O$_2$ and 97.8% residue fraction, yielding a cave air index of 0.1. Such analyses may be compared with the analyses of natural gas samples where the residue fraction may be 100%. Also in the group of very high residue fraction atmospheres are the stinkdamp or blackdamp compositions found by Haldane (1895) where 20% CO$_2$, 80% N$_2$ up to 100% N$_2$ may be found. When these gases invade and mix with more conventional atmospheres, as might occur in a well or mine, then type 3 foul air conditions are also produced.

CONCLUSIONS

The cave air index allows rapid and accurate evaluation of tabular data. It cuts through the complexities of data spanning wide ranges of carbon dioxide and oxygen values and makes assessment of foul air type straight forward. The results obtained with it are consistent with and extend those obtained by the empirical methods of earlier workers and it may be used with published data.

The Gibbs triangle is an effective tool in the detailed examination of foul air compositions at the ternary level. It can be used to clarify relationships between atmospheric analyses within and between caves and also differentiate on a rational basis between the established types of foul air. When used in conjunction with the cave air index it greatly improves interpretation of foul air data.

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APPENDIX

For people wishing to plot their own data and construct their own Gibbs triangles, the composition of Points A, B[1], C, and D have been listed in Table III.

TABLE III Composition of end points in dry and saturated cave atmospheres at 20°C.

Component	Point A (vol.%)	Point B[1] (vol.%)	Point C (vol.%)	Point D (vol.%)
Dry Atmosphere				
Residue Fraction	79.0	59.3	79.0	84.3
Oxygen	21.0	15.7	0	0
Carbon Dioxide	0.03	25.0	21.0	15.7
Saturated Atmosphere				
Residue Fraction	79.5	59.8	79.5	84.7
Oxygen	20.5	15.2	0	0
Carbon Dioxide	0.03	25.0	20.5	15.3

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Contributions from all fields of study related to speleology will be considered for publication. Suitable fields include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be read by referees. Short 'Letters to the Editor', expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

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WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Australia: 32-34. Speleological Research Council, Sydney.

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