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Julia M. James

Helictites, Shawl Cave

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by J.N. Jennings

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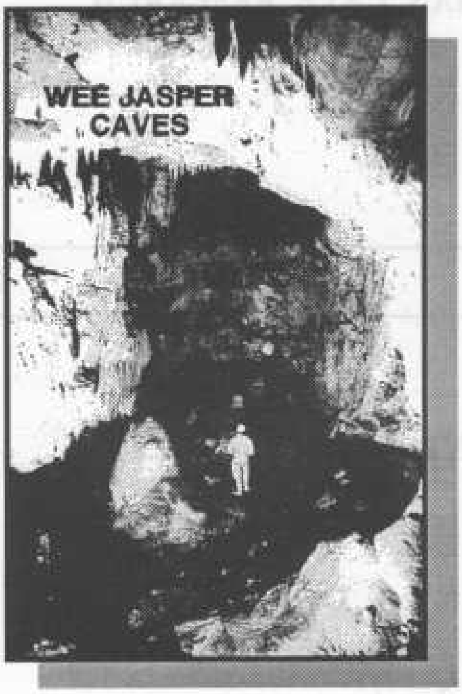

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THE EXIT CAVE QUARRY: TRACING WATERFLOWS AND RESOURCE POLICY EVOLUTION

Kevin Kiernan

Abstract

The principal objective of this paper is to record water tracing experiments undertaken in October 1991, and to review current understanding of the hydrogeology of the karst area. The tracing indicated important underground drainage connections existed between cave systems and a limestone quarry, which has since been closed. In addition, because the research occurred in the context of a major political debate regarding the impact of quarrying on Exit Cave and the future of the quarry, this paper also provides a useful opportunity to place on record part of the scientific input to the subsequent public policy processes, and to consider some implications for researchers when the level of political intervention in the research process is high. Although time constraints and other factors may compromise optimal methodology and create other difficulties for researchers involved in such circumstances, research may be stimulated that would not otherwise occur.

INTRODUCTION

While the Ida Bay Karst System had in recent years been listed on the Register of the World's Natural and Cultural Heritage because of its importance in nature conservation terms, at the time this study commenced operations were continuing at a limestone quarry and indeed an expansion of the quarry had been proposed. At various times temporarily known by the names of its owners (Newlands Quarry; the Australian Commonwealth Carbide Co. Quarry; Benders Quarry) and recently by the more geographical name, Exit Cave Quarry, this was one of a number of limestone quarries operated over past years in the Lune River - Ida Bay area. In August 1992 the Commonwealth government ordered closure of the quarry, but this order was rescinded the following month when further limestone extraction was permitted provided blasting was not employed. In October 1992 the Commonwealth Government again ordered closure of the quarry, and a rehabilitation project has since been established. This government indecision highlights the political pressures under which public policy was evolving. Debate over the future of the quarry essentially revolved around the conflict between the environmental costs of continued quarrying and the social, economic, and local electoral costs entailed in quarry closure.

Within this context a number of studies into various environmental and mining implications of the quarry had been commissioned by involved agencies (Pemberton and Comfort 1990). The karst hydrogeology and geomorphology of the area were obviously fundamental considerations but by mid 1991 the relationship between Exit Cave and the quarry had not been resolved to the satisfaction of government. Hence, a further study (Kiernan 1991) was commissioned by the Tasmanian Department of Parks, Wildlife and Heritage (PW&H). The brief for this study sought not only an investigation of the karst hydrogeology, but also consideration of possible means of reducing the environmental impacts of quarrying to acceptable levels, and necessary environmental monitoring. However, to develop a sensible environmental monitoring program would have been very difficult without an adequate understanding of the underground drainage and caves of the area. This paper covers the hydrogeological component of the study subsequently undertaken, the overall recommendation of which was that the only appropriate course was closure of the quarry. Subsequent events offer useful insight into government decision-making in a case where scientific evidence precluded any comfortable political compromise in a highly charged political environment. In order to facilitate this case study, and for the sake of historical record, the most relevant parts of the hydrogeological section of the original report are published here in close to their original form. Section 1 of this paper reports on the hydrological studies and their implications for understanding of the Ida Bay karst in general and the quarry area in particular. Section 2 describes events subsequent to submission of the report and discusses some relevant aspects of public policy evolution.

SECTION ONE: THE HYDROGEOLOGICAL STUDY

Obvious environmental costs of quarrying at Ida Bay had long been evident. Damage was known to have been caused to Bradley Chesterman Cave through pollution by quarry runoff (Kiernan 1973); water had been diverted to the quarry from Mystery Creek Cave (Kiernan 1972); ASF Pot was largely quarried away and another cave in the quarry was buried beneath rubbish (Clarke 1991); and Exit Cave was considered to be at risk because of the position and orientation of its Eastern Passage (Houshold and Spate 1990). Although the document that nominated the area for World Heritage listing made it clear that it was the total karst system for which protection was sought rather than any specific component such as an individual cave, as the political processes evolved Exit Cave emerged as the focus of concern. Exploration of the Eastern Passage from the Exit Cave end had for some years been stalled at a pile of rockfall blocks, still a linear distance of 1.1 km from the quarry.

Evidence suggesting that the Eastern Passage continued beyond the rockfall pile to the area of the quarry included: (a) the confirmation by dye tracing on two occasions that a small stream which flows underground into National Gallery Cave 250 m from the quarry contributes to the main stream in the Eastern Passage; and (b) the chemistry of the Exit Cave waters, notably the high levels of calcium carbonate evident in the waters of left bank tributaries in this cave that appeared likely to flow from areas to the east and were indicative of considerable rock dissolution having been effected in that area. Other geomorphological considerations suggestive of the Eastern Passage continuing to the area of the quarry included: (a) evidence for a large discharge formerly having flowed through it, and its critical genetic role in evolution of Exit Cave; (b) its location approximately beneath the unconformity on Marble Hill at which point inputs of allogenic water to the limestone have been concentrated; (c) the distribution of known potholes from the surface that continued the same directional trend as the

Eastern Passage beyond its presently accessible limits; (d) the existence of an area of polygonal karst close to the saddle between Marble Hill and Lune Sugarloaf in which the principal waters of the Eastern Passage stream seemed likely to gather; (e) the absence of any other known springs to discharge the water from the polygonal karst; and (f) structural considerations including the orientation of primary joints in the limestone that had dominated cave evolution, the presence in the quarry area of a 30 m thick high grade limestone sequence in which the majority of Exit Cave was formed, and the domal structure of Marble Hill (Goede, 1968, Sharples 1979, Houshold and Spate 1990).

This hydrological, water quality and geomorphological evidence indicated that continued operation of the quarry implied a very high probability of intrusion into the Exit Cave system and the possibility existed that operations on the margin of the quarry may already have done so. The latter suggestion rested on geomorphological evidence and the enigmatic high level of turbidity of one tributary in the Eastern Passage after rain. Likely adverse impacts of extended quarrying included the compounding of these impacts on the karst as a natural system and an increase in impacts on specific components of that system. Proponents of the quarry argued that a drainage link to Exit Cave was improbable, that even if such a link did exist the cave environment could adequately be safeguarded by engineering means, and some even denied that there was evidence of any caves having been encountered during the course of quarrying operations. Although considerable evidence was already available, the limited appreciation of the values of karst and the limited understanding within govern-

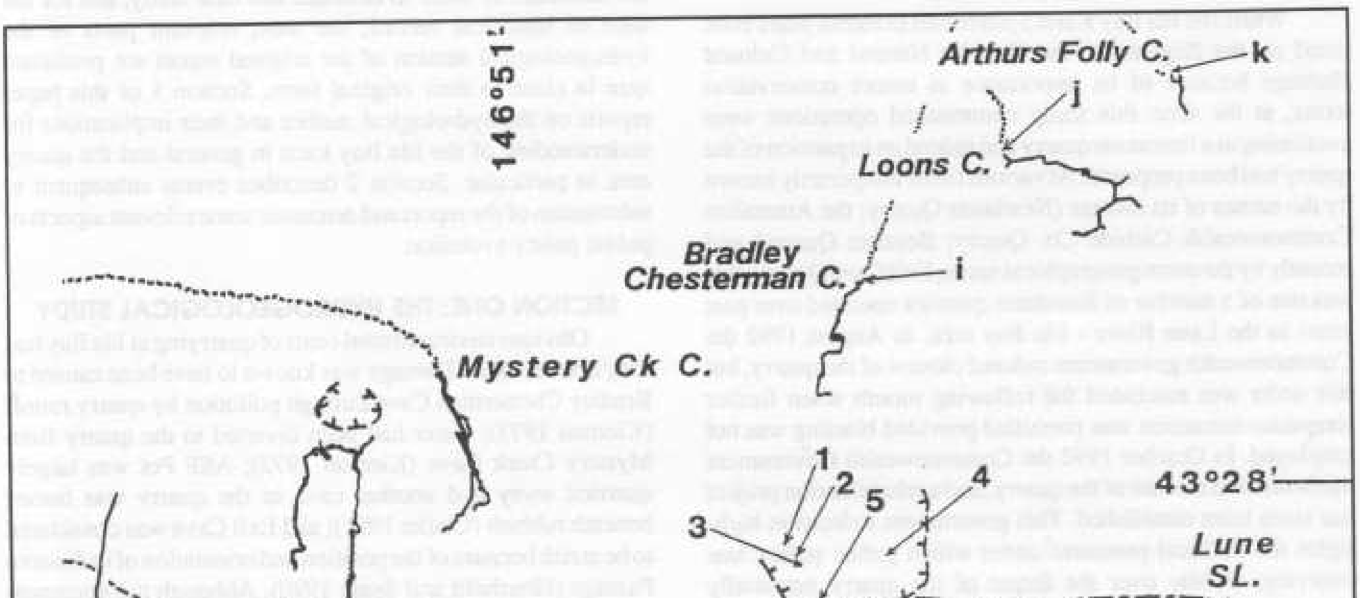

Figure 1. Location of principal caves and the operating limestone quarry at Ida Bay. Potential tracer injection points (PIPs) 1-8 are indicated by number; tracer monitoring stations (TMS) 1-11 are indicated by the letters a-k respectively.

ment agencies of karst as a system, together with inertia and a reluctance to make hard decisions, appeared to favour continued operation and/or extension of the quarry. A clear and unequivocal demonstration of such a connection seemed to be the only mechanism that might force those in government to cease prevaricating, coupled with forceful presentation of such evidence in a form that would not allow deliberate misrepresentation of it by those opposed to protecting Exit Cave in a manner consistent with the terms of its nomination for the World Heritage List. While years of exploratory activity by cavers and previous scientific studies failed to prove a connection between the quarry and Exit Cave, one objective of the present study was to provide that evidence.

PREVIOUS HYDROGEOLOGICAL STUDIES

The earliest known hydrological studies were conducted by Goede (1969). In January 1967 2.7 kg of fluorescein was placed in the sump in Mystery Creek Cave but was not detected at the mouth of Exit Cave despite maintenance of a watch for 56 hours. A second test was conducted in February 1968 utilising the same volume of fluorescein. Several days after introduction of the tracer, and following substantial rain, fluorescein was observed in the Main Exit Cave stream, upstream of the D'Entrecasteaux River anabranch passage and traced upstream to the Mystery Creek stream passage. This demonstrated the underground breach of the main surface drainage divide. An experiment performed in November 1967 involved the introduction of 0.45 kg of fluorescein in a surface stream, Western Creek, at the unconformity just south of the Moonlight Ridge walking track. The tracer reached the accessible part of the cave between two and three hours later, enabling several points of entry to be identified. By this means, Goede (1969) recognised that the surface drainage divide between the Lune River and D'Entrecasteaux River had been breached underground by a southward diversion of Mystery Creek in response to structural controls in the limestone. He reasoned that the deeper incision of the D'Entrecasteaux River relative to the Lune River was of considerable importance in promoting capture of Mystery Creek by the D'Entrecasteaux River. A water tracing experiment performed in the 1970s is believed to have confirmed that a stream which sank into Con Cave emerged in the Conference Concourse section of Exit Cave (Clarke, 1990).

Prior to declaration of the Exit Cave State Reserve, a consultancy undertaken for the Tasmanian government by Richards and Ollier (1976) reviewed the environmental significance of the area. The geomorphic component of that study concluded that some risks were posed by soil erosion associated with potential forestry activities. However, the author does not appear to have recognised that any significant risk might have been posed by the limestone quarry which was excluded from the reserve boundaries supported in that report, and from the reserve subsequently established by the Tasmanian government.

Concern regarding the possible impact of the quarry on the caves of the area had long been held by PW& H officer Greg

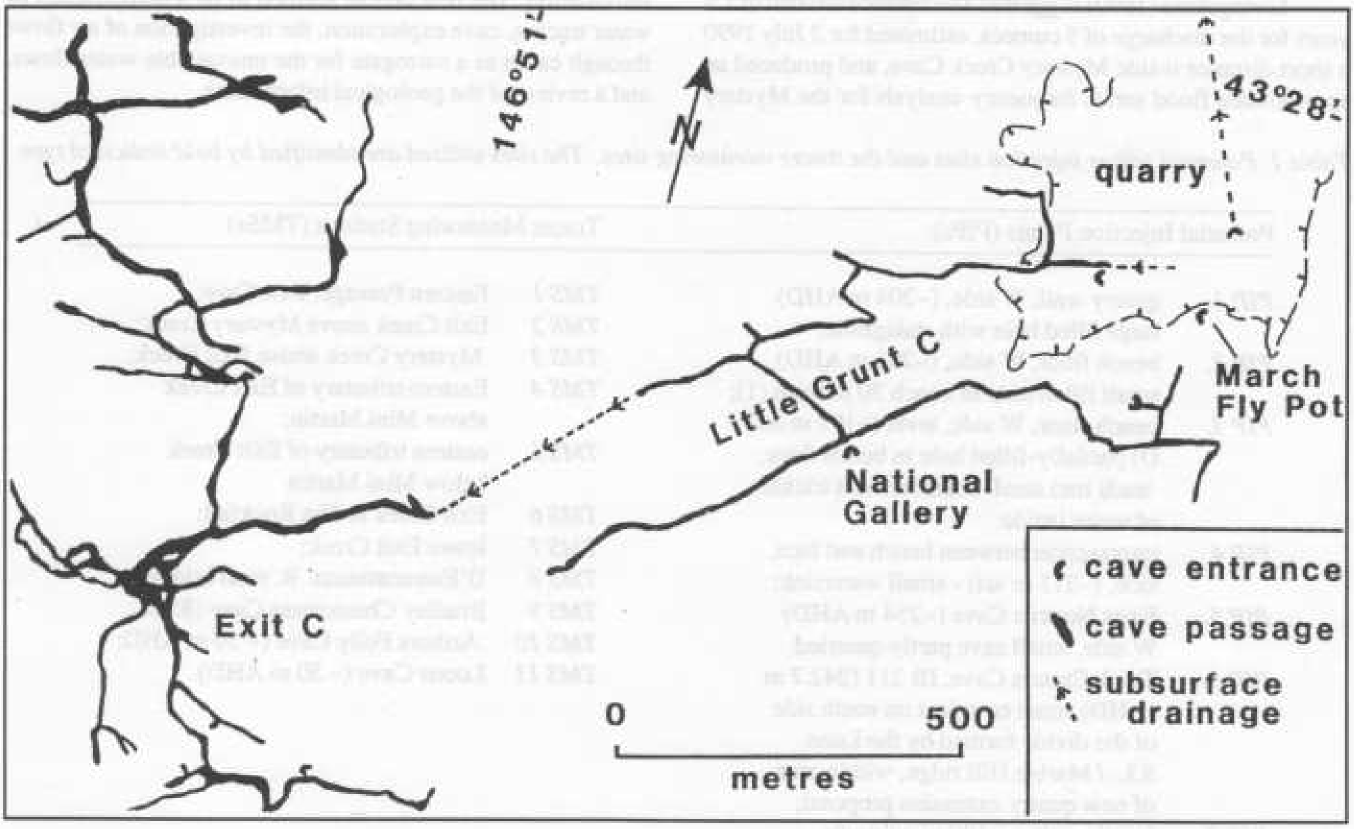

Figure 2. Drainage relationships between the limestone quarry and Exit Cave, and location of extensions discovered in Little Grunt Cave. Mapping of some additional cave passage that could not be fully surveyed in time for submission of the original report has since been completed by Houshold (1992) and is included on this figure, together with his clarification of the drainage relationship between PIP3 and PIP 4.

Middleton and some other cavers. However, it was not until the inclusion of the Ida Bay karst in the Tasmanian World Heritage Area in 1989 that formal legal protection of areas outside the original reserve became possible. Plans to extend the limestone quarry also became more widely known around this time. This situation stimulated research into the Ida Bay karst, and in a consultancy report prepared for the Tasmanian Department of Parks, Wildlife and Heritage, Houshold and Spate (1990) provided an overview of the hydrogeological knowledge of the area up to that time, together with some data on the discharge and chemistry of some cave streams. The authors argued that Grandpa's Sewer, the main north-south axis in Exit Cave, was more recent than either the Eastern Passage - Main Passage area beneath the southern side of Marble Hill, or the Grand Fissure on the northern side of Marble Hill. The role of the unconformity on Marble Hill in conditioning the location at which vertical allogenic water intake shafts have developed has also been recognised to be an important factor in the evolution of the caves (Goede, 1969; Houshold and Spate, 1990). Further water tracing undertaken for Houshold and Spate is reported in appendix 4 of their report (Kiernan, Eberhard and Wilson 1990). In the first of these tests, 1.5 kg of fluorescein was injected into National Gallery on 2 July 1990 with the intake stream at high stage after rain. The fluorescein reached the Eastern Passage in Exit Cave sometime prior to 9 July 1990. A further 1.5 kg of fluorescein was injected into National Gallery on 22 July 1990 with the cave streams at much lower stage, and this reached the Eastern Passage some time prior to 28 July 1990.

Livingstone (1990) suggested a recurrence interval of 1.8 years for the discharge of 5 cumecs, estimated for 2 July 1990 a short distance inside Mystery Creek Cave, and produced an approximate flood series frequency analysis for the Mystery Creek catchment. Flood debris 8-10 m above normal stream level was observed by the present writer shortly after that date in downstream areas of the cave where constriction of the stream channel is likely to impede throughflow. It is possible that this debris may have been related to a flood event in May 1975 that washed away a hydrometric station at Peak Rivulet some kilometres to the north.

INVESTIGATION PROGRAM

Hydrogeological studies

The present study involves the uppermost part of a dry karst ridge where surface water flows are generally non-existent except during winter. Moreover, the political and bureaucratic decision that the study should be undertaken was made late in the year with a limiting date imposed on its completion, and little likelihood that sufficient rainfall would be received during that time to facilitate water tracing using natural runoff. Given the importance of the issue, the possibility of utilising exotic water trucked or pumped to the site was considered but was discounted on environmental grounds. The extent to which cave exploration seemed likely to contribute further information seemed dampened by the fact that recreational cavers had already been very active exploring the area over many years with no discoveries unequivocally demonstrating the directions of subsurface drainage. Sections exposed by quarrying and the information obtained from several drill holes had also been available to earlier workers and this approach seemed to offer only limited scope as a source of new information. The best course seemed to be a combination of water tracing, cave exploration, the investigation of air flows through caves as a surrogate for the unavailable water flows, and a review of the geological information.

Table 1 Potential tracer injection sites and the tracer monitoring sites. The sites utilised are identified by bold italicised type.

Potential Injection Points (PIPs):		Tracer Monitoring Stations (TMSs)	
PIP 1.	quarry wall, W side, (~204 m AHD) large filled hole with stalagmite;	*TMS 1*	Eastern Passage, Exit Cave;
PIP 2.	bench floor, W side, (~201 m AHD) small filled hole in bench 30 m from (1);	*TMS 2*	Exit Creek above Mystery Creek;
PIP 3.	bench floor, W side, level (~197 m AH D) partially-filled hole in bench floor, leads into small chamber with trickle of water inside	*TMS 3*	Mystery Creek above Exit Creek;
PIP 4.	intersection between bench and face, side, (~213 m asl) - small watersink;	*TMS 4*	Eastern tributary of Exit Creek above Mini Martin;
PIP 5.	Exits Nostrils Cave (~254 m AHD) W side, small cave partly quarried	*TMS 5*	eastern tributary of Exit Creek below Mini Martin
PIP 6.	Track Cutters Cave, IB 211 (242.7 m (AHD) small cave just on south side of the divide formed by the Lune S.L. / Marble Hill ridge, within area of new quarry extension proposal;	*TMS 6*	Exit Creek at The Rockfall;
PIP 7	fossil swallet ~ 100 m on south side of divide east of March Fly Pot.	*TMS 7*	lower Exit Creek;
PIP 8.	Little Grunt - (194 m AHD) ~100 m on S side of surface divide SW of Little Grunt	*TMS 8*	D'Entrecasteaux R. road bridge.
		TMS 9	Bradley Chesterman Cave (85 m)
		TMS 10	Arthurs Folly Cave (~ 50 m AHD;
		TMS 11	Loons Cave (~ 50 m AHD).

The very small volumes of water anticipated, despite enhanced runoff from rock surface made bare by quarrying, coupled with the long distances over which tracing was needed, meant that tracer dispersal and retention in fissure storage were likely to make any water tracing very difficult. However, on the basis of structural considerations and the characteristics of other parts of the Ida Bay karst, it was hypothesised that recharge of the aquifer probably involved vertical shafts linked to horizontal trunk stream passages. If this were the case it seemed possible that successful tracing might be achievable if the optimal input points could be located that offered the possibility of direct vertical transit of the tracer down open shafts to any trunk stream at depth. Eight potential injection points (PIPs) for water tracers were located and a network of eleven tracer monitoring stations (TMSs) was established (Table 1 & Figure 1). Tracers available for use were rhodamine WT and fluorescein. This appeared to permit two basic experiments to be undertaken in the time available. PIPs 2, 3 & 5 appeared to be at some risk of leakage to the quarry face, via either natural channels or newly created shatter zones caused by quarrying. While PIP 8 was known to descend rapidly to 130 m, reducing the risk of leakage to the quarry face, its location was not optimal since it lay just outside the planned quarry margin indicated on plans for at least one of the quarry extension options. Hence, despite its obvious systemic relationship, there seemed a risk that a trace from this site would be insufficient to satisfy the level of proof demanded by some parties influential in the decision making process. Activated charcoal detectors suitable for retention of both tracers were installed at the TMSs, and additional cotton detectors for rhodamine WT were installed as a backup. A visual watch was also intended at some sites depending upon the availability of personnel. It was also intended that water samples be collected from some TMSs.

A significant rainfall event during week three of the project enabled some tracing to be undertaken using enhanced runoff from areas disturbed by quarrying and related activities. In view of the likelihood that suitable rainfall conditions were unlikely to arise again during the time available for the study, that insufficient aquifer clearance time was available for more than one test using the same tracing agent, that dilution problems could be severe if minor seepages leaked slowly into a trunk stream of much greater discharge, and that the cost of failure might be the removal by quarrying of the system involved, substantial quantities of tracer were utilised. Given the availability of two suitable injection points on the northern side of the hill, the possibility that one or both could leak through the quarry face, and the limited likelihood a second chance would become available to get information on the directions of drainage from the northern side of the hill, a decision was made to inject two 2.5 kg slugs of fluorescein simultaneously, one into PIP 3 (3:30 pm 4 November 1991) and one into PIP 4 (4:00 pm 4 November 1991). This was an unconventional approach that raised the problem of not being able to differentiate which injection point was involved if the dye was detected at one of the monitoring stations. However, it was considered that by restricting the use of fluorescein to the northern side of the hill, and rhodamine WT to the southern side of the hill if any underground breach of the surface drainage divide existed it would become readily apparent, and such a result would highlight the need for further investigation later. Finally 3 litres of rhodamine WT was injected into a trickle of water running into the entrance of Little Grunt Cave from a nearby landslide from the upper quarry road (4:30 pm 4 November 1991).

Three positive results were obtained from these water traces (Figures 1 & 2). Firstly, a water sample obtained at 2:30 pm on 5 November 1991 from the stream that discharges from Exit Cave proved negative when subjected to fluorometric analysis for rhodamine WT. Samples from TMS 7 (2:30 pm 6 November 1991) and from TMS 8 (3:00 pm 6 November 1991) also gave negative results. However, a water sample collected from TMS 1 (Eastern Passage stream in Exit Cave) at 2:00 pm on 6 November 1991 was strongly positive when subjected to fluorometric analysis for rhodamine WT. A cotton detector collected from TMS 1 at 2:30 pm on 14 November was strongly discoloured by the tracer. No visible discoloration of the Eastern Branch stream was evident on either occasion. Rhodamine WT was subsequently also observed on 20 November 1991 in pools of standing water in a previously unexplored cave stream passage between PIP 8 (Little Grunt) and TMS 1. Secondly, a strong green discoloration of the creek at TMS 9 (Bradley Chesterman Cave) was first observed at 8:00 am on 5 November 1991 and was persisting at 4:00 pm on 6 November 1991. Analysis of a charcoal detector collected from TMS 9 (Bradley Chesterman Cave) at 10:00 am 20 November 1991 indicated the presence of fluorescein. Thirdly, analysis revealed fluorescein in charcoal detectors collected from TMS 1 (Eastern Passage stream) at 2:30 pm on 14 November 1991, from TMS 6 (Exit Creek at The Rockfall) at 3:00 pm 14 November 1991, and from TMS 7 (Exit Creek above the D'Entrecasteaux anabranch passage) at 3:30 pm 14 November 1991)

The implications of these water tracing results were that:

(1) Little Grunt, which lay ~ 50 m from the proposed boundary of the quarry extension, and formed part of the polygonal karst complex, drains rapidly into Exit Cave. Given the presence of visibly discoloured water in a cave stream passage subsequently explored between Little Grunt and the Eastern Passage (described later in this paper) it seemed probable that the sub-visual concentration of rhodamine in the water sample collected from the Eastern Passage on 6 November 1991 arose from the fact that tracer breakthrough was only just commencing. This implied initial breakthrough only 45.5 hours after injection at Little Grunt 1250 m from TMS 1, despite the small discharge, which suggested the existence of a very direct route.

(2) Some, but not all, of the drainage underground into the working area of the quarry, below 213 m altitude, drains northwards and forms part of the Bradley Chesterman subsystem of the Ida Bay Karst System. Given the virtually simultaneous injection of the same tracer in two locations on the north side of the divide it was not certain from the water tracing alone whether the source of the fluorescein was PIP 3 or PIP 4 , or both, and what proportion of the water from this source reached Bradley Chesterman Cave. The breakthrough time of under 16.5 hours to cover the linear distance of ~ 750 m despite the small discharge at the injection points implied a relatively direct route.

(3) Some, but not all, of the drainage underground into the working area of the quarry drained into the Eastern Passage

of Exit Cave. Again, given the virtually simultaneous injection of the same tracer in two locations on the north side of the divide it was not certain from the water tracing alone whether the source of the fluorescein was PIP 3 or PIP 4 , or both, and what proportion of the water from this source reached Exit Cave.

The tracing demonstrated a definite connection between the polygonal karst in the area of Little Grunt and Exit Cave. The underground drainage systems most probably involve the rapid infiltration of water into vertical shaft systems that are linked to streams of modest gradient but reasonable discharge, that flow in caves developed in relatively pure strata, probably the "birds eye" limestone so evident in the genesis of Exit Cave. This appeared the most likely cause of the rapid transmission of the Little Grunt water. In this regard, it was also surmised that had the small stream in Little Grunt followed a relatively torturous route of moderate gradient then transmission is likely to have been much slower; similarly, had the water plunged down one of the steep shaft systems typical of this area to a low gradient "base level" stream passage that still entailed only a small discharge then transmission to Exit Cave is also likely to have been slow. Given the steep descent of the upper part of Little Grunt to -130 m a shaft system was obviously involved for most of the vertical range of the system. In view of these considerations, it was concluded that the only way the Little Grunt water could have reached Exit Cave so rapidly was if it discharged into a larger stream already in existence at the base of the shaft system. Logically this larger water body seemed likely to have arrived from the area generally to the east of Little Grunt, involving infiltration via the rest of the polygonal karst. It may well originate from beneath the slope mantles on the western side of Lune Sugarloaf, depending upon the precise location of the fault and other structural lineaments and their implications for isolating components of the underground drainage networks in the Ida Bay karst.

Cave exploration

Effort was focused on a detailed examination of the upper part of the ridge between Marble Hill and Lune Sugarloaf, including both the areas exposed by quarrying to the north of this ridge and the undisturbed slopes to the south.

Exit's Nostrils Cave (7IB-X12)

This small cave is located at ~ 254 m altitude. Strong air movement is suggestive of connection to a large cave system. Part of the cave has been quarried away and within the 21 m that remains accessible, large blocks have fallen out of the roof and all but its most robust speleothems have been demolished by quarry blasting. The potentially major implications of this for other caves in the area appears to have gone unrecognised. The southwestward orientation of this cave suggests it is developed along the same prominent joint trend as has focused much of the cave development at Ida Bay. About 30 m to the NW of the cave mouth on the same quarry bench two small sinkholes have recently developed, and speleothems are evident beneath blocks displaced by blasting, suggesting a continuation of the same cave. The quarry face still further to the NW is very broken and fragmented speleothems are widespread among the debris. Still further to the NW and parallel to the trend of Exit's Nostrils Cave are major clay bodies and PIP 4. About 100 m southwestwards from the cave lies a shallow sinkhole between two of the quarry roads. These facts suggest that solutional opening of these joints extends right through the topographic divide, while the air movement clearly indicates it is part of a major cave system. No further progress was made within this cave.

Un-named sinkhole

A subjacent karst collapse sinkhole ~ 20 m in diameter and ~ 8 m deep occurs in Permian non-carbonate sediments of the Parmeener Supergroup adjacent to the vehicular track that extends westwards from the presently disturbed area on the northern side of Marble Hill. Although no accessible cave entrance has been found, the presence and size of this sinkhole attests to significant cave development beneath the Permian rocks. Given the predominantly NE-SW trend of cave development, drainage from here is also likely to reach Exit Cave. Human entry could not be gained.

March Fly Pot (IB 23)

A map of March Fly Pot prepared by local cavers and made available to government agencies by Arthur Clarke suggests a generally southwestward trend of development. March Fly Pot lies 35 m south of the 244 m high topographic divide at the head of the present quarry. Its entrance is located at 223 m altitude and the depth of the cave is at least 25-30 m indicating a basal altitude of 195 m. The quarry bench height ~ 15 m north of the divide is 233 m, the bench ~ 30 m distant lies at 218.6 m altitude and the bench 50 m distant lies at 210 m. Major clay-filled fissures occur in the intervening part of the topographic divide, while reports from cavers of the smell of explosives in the cave indicates continuity through the divide of the cave complex of which March Fly Pot forms a part. There is no evidence of water from March Fly Pot emerging in the quarry during times of heavy rain, suggesting that it either descends vertically or that it drains in a more southerly direction. PIP 4 lies only ~ 250 m to the NNE. No new passages were discovered.

Little Grunt (IB 23)

Following the water tracing experiment that proved a connection between Little Grunt and Exit Cave, Rolan Eberhard returned to Little Grunt on 20 November 1991 to investigate a draughting crack from the top of the final pitch which he recalled from an earlier visit. With Stefan Eberhard, Vera Wong and Ian Houshold, the lead was followed via short vertical pitches and a horizontal passage to a major horizontal stream passage. This base level stream was followed upstream for ~ 60 m in an easterly direction to a rockfall, while hundreds of metres of passage was explored in the downstream direction. Pools of standing water still discoloured by rhodamine WT were evident in several areas.

A cave survey party was organised five days later involving assistance from members of the Tasmanian Caverneering Club and Southern Caving Society. The initial part of the downstream section was shown to trend roughly westwards to join a very large rift at least 10 m high that extended southwestwards. Large areas of the cave contained abundant speleothems. After several hundred metres the stream diverts out of this rift into a small passage but the very large rift passage itself continues southwestwards. Several small tributary streams were encountered including one presumed to be the water from

National Gallery. A major horizontal tributary stream passage was shown to originate from the NE and to contain a series of side passages and smaller tributaries. The principal passage was 6-7 m high. Silty sediment apparently metres thick in places appeared to originate from one tributary and to be very similar to material that had been observed on quarry benches around PIP 4. In this part of the cave a series of degraded rimstone pool speleothems are being redissolved by the water. Leaf litter and small mammal bones were observed in one side passage. The cave map indicated the upstream part of this northern tributary passage to lie vertically below the present operating quarry. The exploration of the new cave stream passage confirmed the route between the polygonal karst and Exit Cave to be an open cave passage of large dimensions. Its character was totally consistent with that interpreted from the water tracing results and this lent support to the more general interpretations regarding the structure and function of the underground drainage systems in this area. The downstream extremity of Little Grunt approaches very close to the Eastern Passage of Exit Cave with rockfall blocking further progress in both. Little Grunt is very obviously the upstream continuation of the Eastern Passage.

TOWARDS A HYDROGEOLOGICAL MODEL

Defining the hydrological subsystems

The basal Parmeener sediment on Marble Hill is a diamictite that is probably glacigenic. It does not appear to be a glaciomarine sediment and is probably a tillite. Terrestrial glaciation of the limestone surface is likely to have had significant impacts on its surface relief although whether this is more likely to have involved relief diversification due to the impact of preglacial topography on erosional processes or glaciokarstic effects, or whether vigorous glaciation may have reduced the relief by abrasion, can only be speculated upon. Nevertheless, the possibility must be recognised that this glacial event has left a karstic legacy that may now exist only in fossil form or may have served to focus subsequent solution activity, including the present karst drainage subsystems. Evidence of sub-Parmeener karst includes the large collapse sinkhole formed in Parmeener rocks above the southwestern margin of the quarry, the presence of large avens in Exit Cave that originate beneath the Parmeener cap on Marble Hill, and the presence of caves such as IB 122 which is probably of subjacent karst origin. Whether palaeokarst may have played any role in the later evolution of such features may warrant investigation.

By combining pre-existing knowledge regarding the geology and karst of the Ida Bay area together with the new information now obtained from water tracing experiments, geomorphological investigations, new cave exploration and mapping, and the results of DMMR drilling, four hydrological subsystems can be recognised. For the purposes of this discussion they are termed the Exit subsystem, the Bradley Chesterman subsystem, the Loons subsystem and the Arthurs Folly subsystem. The subsystems are the catchments for major outflows under discharge conditions equivalent to those observed to date. The subsystems include fossil cave passages genetically related to the drainage systems in question. These differentiations may not be valid if hitherto unproven potentially conductive solution cavities exist that would facilitate the sharing or interchange of water if all the solution cavities in the rock mass were water-filled - hence adoption, at this stage, of the term "subsystem" rather than "system". The adoption of the spring discharge points as the termination of the hydrological subsystems poses some hazards also, since the valley floors have been alluviated and the cave floors for the most part have also been buried by sediment. Depending upon constraints imposed by the bedrock topography beneath the alluviated valley floors, the base level to which the streams flow may have been lower than today during episodes of cold glacial climate when the sea level was lower. However, base levels were raised by aggradation that occurred under the environmental conditions that prevailed during the most recent episodes of glacial stage cold climate. Hence, karstification of the limestone beneath the valley floor sediments is to be anticipated and the present-day springs may represent only part of the discharge from the aquifers under discussion.

The *Exit subsystem* comprises all that area that contributes to the water that emerges from Exit Cave and from other potential discharges of water that flow through Exit Cave but which may emerge from springs beneath the valley fills rather than through the present cave mouth. The altitudinal range of the void network in the karst extends over at least 220 m, while the total altitudinal range of the subsystem from the 769 m asl. divide at the head of the catchment to the out flow is ~ 700 m.

The largest point recharge source is Mystery Creek which sinks into Mystery Creek Cave. Topographic maps suggest the entrance to this lies at 125 m altitude but a barometer survey by G. Benn of the Division of Mines and Mineral Resources (DMMR) suggests an altitude of 92 m at the cave dripline. The level of the creek bed at the point of an accident that occurred a short distance inside Mystery Creek Cave in 1990 is 92.20 m according to a survey produced by the HEC for the subsequent coroners inquiry. Available topographic maps suggest an altitude of ~ 65 m at the Exit Cave outflow, while a barometer survey by G. Benn suggests the figure may be nearer 56 m. Irrespective of these uncertainties, these data suggest a vertical difference of ~ 40 between these recharge and discharge points, with perhaps half that decline occurring in the relatively steep first part of Mystery Creek Cave. The westernmost known recharge point is Western Creek Swallet. To judge from topographic maps and the cave map this appears to lie at ~ 220 m but this figure may be too high. This altitude would place this swallet 90 m above the highest upper level passages in Mystery Creek Cave, the entrance to which lies a linear distance of just over 2.5 km to the NE, and 150 m above the Exit Cave outflow. Another western recharge point is Valley Entrance, which to judge from topographic maps lies at 140 m altitude, implying an altitude loss of 65 m to the Exit Cave outflow. Numerous swallets along the unconformity on Marble Hill intercept water at altitudes of up to 340 m, giving the systems a total vertical range of ~ 280 m. The behaviour and chemistry of some of the cave streams has been addressed by Houshold and Spate (1990). These characteristics vary considerably between the streams. The allogenic streams are relatively volatile and highly responsive to rainfall events, notably Mystery Creek which is characterised by an extremely peaky hydrograph.

To the east of the present Exit hydrological subsystem lies the *Bradley Chesterman subsystem*. The altitude of the outflow as determined by DMMR survey is 85 m. The margins of the catchment are poorly known but appear to extend to at least 220 m above PIP 2. Given the reasonably large discharge from Bradley Chesterman Cave and the major influence exerted upon the karst drainage systems at Ida Bay by joints oriented SW-NE, it seems reasonable to assume that drainage from the area immediately west of the quarry may contribute to this system, implying that the upper altitudinal limit of the catchment may reach close to the top of Marble Hill. To the east, water tracing by Houshold and Spate (1990) showed that water sinking into IB 127 reaches Bradley Chesterman Cave. The transit time for the linear distance of less than 200 m was 125 minutes. The potential catchment for this stream extends to the top of Lune Sugarloaf.

None of the recharge points has hitherto been subject to direct exploration to determine its gradient. However, the failure of any of the dyed water to emerge from the quarry face implies that the descent route is very steep. The low gradient of the accessible part of the subsystem, Bradley Chesterman Cave, is common to all the outflow stream caves of the area and does not appear to have been caused by bedding. The stream is highly responsive to rainfall events, presumably due at least in part to the bare and rocky nature of that part of its catchment disturbed by quarrying.

The altitude of the *Loons subsystem* outflow suggested by topographic maps is 65 m. Aspects of this subsystem have again been described briefly by Houshold and Spate (1990). The catchment is not known in detail, but the subsurface hydrological subsystem may be confined east of the fault that trends N-S across the western side of Lune Sugarloaf. Recharge in this case is predominantly by means of vertical shafts and joint controlled rifts that are widespread in the cave. This form is evident both in areas of autogenic recharge, where one such shaft ~ 30 m deep can be followed from the surface, and in areas of allogenic recharge focused around the margin of the non-carbonate slope deposits and presumably at the unconformity between the limestone and the overlying rocks on Lune Sugarloaf. In the inner part of the cave large vertical avens are present, fragments of Parmeener Supergroup rocks and Jurassic dolerite being present on the cave floor beneath them. The form of the cave has ben strongly controlled by jointing. Once again, the vadose stream passages are of very low gradient and appear to have formed independent of bedding controls.

The altitude of the *Arthurs Folly subsystem* outflow, as suggested by topographic maps is 55 m. Again, the limits of the catchment are unclear but the possibility exists that the catchment includes areas on the eastern flanks of Lune Sugarloaf, potentially extending the vertical range of this hydrological subsystem to relatively high levels. Once again, avens developed down joint features are present, and the stream passage is of low gradient and appears to be controlled by local base level rather than by bedding.

Cave evolution

The evolutionary history envisaged for Exit Cave entails a process of progressive incision of cave passages formed along a few major joint trends. Environmental changes in the external environment exerted a major influence, notably oscillations of climate during the late Cainozoic. The probability that Exit Cave evolved through the linking underground of two protocaves was recognised by Houshold and Spate (1990). They considered one of these protocaves to have been focused on the Grand Fissure and the other on the Eastern Passage - Exit Cave outflow area. The similar scale of development evident in both the Grand Fissure and Mystery Creek Cave, and the similar orientations of the passages where these caves approach most closely (notably around the Chamber of Damocles and the entry to Conference Concourse), coupled with the apparent immaturity of the present stream passage that links Mystery Creek Cave to Exit Cave, seem consistent with the Grand Fissure and Mystery Creek Cave being genetically part of the same system, water from which appears to have more recently been pirated southwards.

The altitudinal relationship between the western swallets and Mystery Creek Cave, possibly coupled with speleogens in the upper levels of Mystery Creek Cave that are permissive of their having been formed by an outwards flow, are consistent with this cave system having been formed by a stream that entered at the western end of the Grand Fissure and discharged northwards into the Lune River from the upper levels of the present Mystery Creek Cave. It is envisaged that subsequent incision by the D'Entrecasteaux River led to capture of Mystery Creek in the manner suggested by Goede (1969). The fossil and active stream passages of Conference Concourse have also developed since the capture of Mystery Creek by the D'Entrecasteaux River, and may be related to subsurface drainage changes associated with the filling of Mystery Creek Cave by sediment during a phase or phases of slope instability and alluviation under cold climate conditions. This model implies a long evolutionary history for the Exit hydrological subsystem. Some karst evolution subsequent to initial exposure of the limestone to weathering and erosion is to be expected. The presence of ancient palaeokarst in the area is consistent with this prognosis. These possibilities warrant detailed investigation.

Cainozoic climate change may not only have played a major role in cave filling but may also have been a factor in speleogenesis. The position, form and sediments of the present D'Entrecasteaux River anabranch passage in Exit Cave are consistent with its having been formed by the decanting of glacial meltwater against the margin of the limestone hill (Goede 1969), in a manner similar to that proposed by Jennings and Sweeting (1959) in the Mole Creek area. The configuration and sediments of the Hammer Passage and possibly also the Western Passage are somewhat similar. It is not inconceivable that the injection of meltwater from the margin of the former D'Entrecasteaux Glacier rather than glaciofluvial fans may have ben involved (Kiernan, 1982; Houshold and Spate 1990). Decanting in this manner may also have played a role in promoting development of the recharge point at the western end of the Grand Fissure. Particularly given an abundance of meltwater and lithic tools to accomplish mechanical enlargement of the passages, cave systems could have evolved rapidly under these conditions. The age of various components of Exit Cave is unknown, but Goede and Harmon (1983) have shown that at least one cave fill predates 400 ka BP. Ample time is likely to have been available during which cave passages could have evolved in this manner since it is clear that large scale glaciation of Tasmania has been a recurrent phenomenon since at least the Pliocene (Kiernan 1990), with the earliest known glaciation of Tasmania dating from the latest Eocene-Oligocene (Macphail, Colhoun, Kiernan and Hannan 1993).

As recognised by Goede (1969) and by Houshold and Spate (1990), the Eastern Passage in Exit Cave has developed along the major NE/SW trending joint system that has been a prominent feature in the development of the karst drainage systems. In the case of both the Eastern and Western Passages, and indeed the Grand Fissure, the precise location of the subsurface channel that has developed appears to have been governed by the location of the unconformity on Marble Hill, in which position the infiltration of allogenic water from the Parmeener sediments that cap the hill has been focused (Houshold and Spate 1990). As on the northern side of Marble Hill, deep vertical allogenic recharge shafts with a vertical range of over 220 m have developed close to the unconformity, and autogenic recharge further onto the limestone outcrop also descends by vertical shafts. Some of these shafts originate beneath the Parmeener rocks that cap Marble Hill.

It seems reasonable to assume that the Eastern Passage was formed by water flowing southwestwards. However, the Western Passage was formed by water that flowed north-eastwards towards the central axis of Exit Cave. The Western Passage is of smaller dimensions than the Eastern Passage with which it broadly connects, and appears to be of more recent age. This would seem broadly consistent with a long period of evolution of the main Eastern Passage - Exit Cave outflow system, and a more recent invasion by the Western Branch stream sometime during the late Cainozoic. A hitherto unmapped cave of spacious dimensions discovered by the writer in early 1990 just southwestward of the furthest known extremity of the Western Passage appears to be related to a sinking point of ancestral Western Passage water. This cave is located in a shallow valley that contains considerable allogenic sediment and the cave itself is also largely sediment-filled. Strong air movement is suggestive of a connection between this cave and Exit Cave, as is to be expected given the highly integrated nature of most of the Ida Bay karst system. Discovery of the new cave resulted from a deliberate search that was based on the assumption that a cave should exist in that locality if, as is hypothesised for the present D'Entrecasteaux anabranch passage and the Hammer Passage, the Western Passage had developed in response to the decanting of water from the D'Entrecasteaux Valley against the side of Marble Hill. The location and configuration of the Western Passage is consistent with its having been enlarged by meltwater on the margin of the former D'Entrecasteaux Glacier although it does not demand it.

In summary the evolution of the present drainage subsystem through Exit Cave has involved the integration of at least two separate proto-drainage subsystems: the Grand Fissure/ Mystery Creek subsystem; and the Eastern Passage/Exit outflow subsystem. The location at which these subsystems developed was governed by the presence of the high purity Birds Eye limestone, and by the presence of major SW-NE trending joints susceptible to solutional opening. The precise points at which those joint systems were most effectively opened by solution have been influenced by phenomena that have served to concentrate flows of allogenic meltwater onto the limestone, notably the retreating unconformity on Marble Hill, together with allogenic glaciofluvial sediment and/or glacier ice. A probable initial breach of the drainage divide by northward flowing water that moved through the Grand Fissure/Mystery Creek system was superseded due to the capture of this water in response to the development of a steeper gradient southwards. This would be consistent with the disappearance of the former D'Entrecasteaux Glacier but does not demand it. This capture resulted in a reversal of the direction in which the divide was breached. The development of such invasion routes as the Western Passage, the Hammer Passage and the D'Entrecasteaux anabranch passages has occurred sequentially in more recently.

This long and complex history means that the present Exit drainage subsystem is complicated in detail. Under such conditions it is usual for the directions and patterns of drainage to vary significantly according to stage, with the most recent channels being active under conditions of low flow and other older channels being reactivated at higher stage. The present drainage routes beneath Marble Hill are still only understood in broad outline, with many questions remaining as to precisely where and how some major underground streams fit in, such as the waterfalls of Hobbit Hole. An adequate picture of even the contemporary routes will still be a long time coming, and elucidation of the far more difficult puzzle of where water previously flowed through passages that in many cases are now disguised by waterborne sediments, rockfall accumulations or even palaeokarst fills will be very much more complicated. Hence, management of the Exit subsystem, which is already known to be a highly integrated one, demands a very conservative approach if its nature conservation value is not to be put at risk. As if the hydrological subsystem were not complicated enough, fossil passages that no longer carry any significant water flows have been integrated into the contemporary atmospheric subsystem. This has major management implications.

Synthesis: Towards a hydrogeological model

The evidence from each of these four hydrological subsystems suggests that the hydrogelogy of the Ida Bay Karst System consists predominantly of vertical recharge shafts that descend to near horizontal passages that are occupied by base level streams. A very few streams enter the limestone by means of lower gradient caves, notably the D'Entrecasteaux River anabranch and Mystery Creek. Otherwise, vertical recharge route development is common to all the allogenic and autogenic recharge sources.

Several factors have interacted to condition the location of the foci of karst development at Ida Bay. The first of these is the relative solubility of the limestone strata. Evidence provided by Sharples (1979) indicates that the 30 m thick birds-eye calcsiltite horizon in the middle sequence of the limestone has exerted an important influence. Pseudocheirus Cave has probably developed in the pure limestone above the "Grey Band" (Houshold and Spate, 1990). In addition to evidence obtained during the drilling program conducted by DMMR in 1990, the record of solution cavities evident in cores obtained during earlier drilling at the Exit Cave quarry (Summons, 1981) was re-examined in an attempt to gain further insight into the extent and any zonation of karstic cavities. The original cores DLR 2 and DLR 7 were made available by the DMMR for inspection and laid out for this purpose at the Mornington store. A record was made of all solution cavities, clastic infillings and evidence of apparent speleothem carbonates, all of which are indicative of subsurface karst. This was later checked against the drill logs for these two cores, and suggests that considerably more solution activity is evident in these two cores than had been recorded. Solution features occur predominantly in the most pure limestones, but they are not confined to them.

The second factor of importance is the structure of the limestone. The cave passages have developed along the major joint systems, the most influential of these trending SW-NE. The main NW-SE axis of Exit Cave appears to follow the domal structure of the limestone beneath Marble Hill (Houshold and Spate, 1990). Faulting has played a less prominent role in guiding solution activity. The gentle dip of the limestone has reduced the relative impact on cave evolution of bedding relative to that of joint systems, the dip of the joints being very steep (Summons, 1981). Hence, the development of recharge foci of very steep gradient has been favoured. The absence of any significant outflows of water from the quarry faces compounds the impression of steep infiltration routes. For example, PIP 3 lies within 20 m of the edge of a quarry face 20 m high, while PIP 4 lies 35 m from the edge of a quarry face 40 m high. No water from these sources emerged from the quarry faces during the fluorescein testing.

A third major factor has been the location of the unconformity between the Ordovician limestone and the overlying relatively impermeable rocks of the Parmeener Supergroup. Solution activity by allogenic water that reaches the limestone is focused at this point. This has resulted in the evolution of vertical intake shafts and of horizontal cave passages, that often exhibit a rift form, at greater depth in the limestone. Some avens have also formed beneath the Parmeener rocks, with non-carbonate features such as IB 67 and IB 22 probably having been produced by upward stoping.

A fourth factor of great importance has been the altitude of the local base level to which the various streams drain. The major stream passages exhibit a very low gradient which in the vast majority of cases is not explicable in terms of the bedding.

A further factor of considerable importance to the evolution of the hydrogeology has been the history of climate change during the late Cainozoic and the impact of this upon slope stability and alluviation, together with the direct and indirect consequences of the waxing and waning of glacier systems in the area. The most significant outcomes of these climatic changes include modifications to runoff, the filling of intakes and cave passages with sediment, the diversion by sedimentation of surface water flows and the establishment of new solution foci, and perhaps the superimposition of meltwater from the margin of the former D'Entrecasteaux Glacier onto specific locations on the karst area. Aggradation has changed the local base levels to which the hydrological subsystems drain.

The precise location of any groundwater divide between the Exit subsystem and the Bradley Chesterman hydrological subsystem is unknown, either in a horizontal or vertical plane. It is likely that the position of the divide varies according to the amount of water in the subsystem at any one particular time. Genetically important linkages may exist that may no longer be operative or may be operative only under certain conditions. The presence of solution cavities that have formed along the same joint does not necessarily imply a genetic hydrological link between them since it is to be expected that a susceptible joint may be subject to solutional attack by more than one mass of water. However, given the very close proximity of known recharge points for the Bradley Chesterman subsystem to parts of Exit Cave, the steep intake gradients common in this karst area, and the highly karstified nature of the limestone mass, it is to be anticipated that void space of whatever origin probably extends between the two subsystems , and that flow has the potential to occur through these routes under at least some discharge conditions. On this basis, it seems reasonable to assume that the Bradley Chesterman hydrological subsystem forms parts of the Exit hydrological subsystem for practical management purposes. The hydrological and atmospheric subsystems are not likely to share precisely the same boundaries, and the likelihood of atmospheric interchange between the two cave networks is so high as to make it reasonable to assume that they represent the same cave system.

THE CAVES AND THE QUARRY

The drainage divide

Under the discharge conditions that prevailed at the time the water tracing was performed, the drainage divide between Exit Cave and Bradley Chesterman Cave was shown to lie somewhere between PIP 3 and PIP 4. This narrowed down the location of the underground divide to about 200 m in the horizontal plane. About midway between these two points lay the remains of the deep ASF Pot that had been mostly quarried away. As yet there is no means of determining to which of these two drainage subsystems ASF Pot was genetically connected.

However, the situation may not be so simple as connection of these PIPs merely to one drainage outlet. The close proximity of PIP 3 and PIP 4 emphasises the potential for solution cavities to extend continuously between them and for them to represent the same cave system. At least two issues warrant consideration in this regard. First, where joint systems exist that serve as foci for solution activity, voids initiated independently by seepage water entering at various points along a joint are prone ultimately to become interconnected laterally even if that interconnection is not originally caused by a single stream flowing from a cave at one end of a joint to a cave at the other end. Given the establishment of interconnecting void space in this manner, the potential must exist for water to flow between subsystems during high discharge. Secondly, in the Ida Bay case, the passages leading towards Exit Cave are much larger than those in Bradley Chesterman Cave, raising the possibility that the drainage system encompassing Little Grunt is much older. This in turn raises the possibility that drainage that once reached Exit Cave may have since been captured by Bradley Chesterman Cave. If so, fossil cave stream passages that are susceptible to reactivation under high discharge conditions might exist between PIP 3 and PIP 4.

Given these three considerations, integration of the Exit and Bradley Chesterman hydrological subsystems under at least some discharge conditions would seem very highly probable. The location of the groundwater divide seems likely to be dependent more upon the discharge conditions that prevail at any one time than on the presence or absence of solution cavities. A very large, decorated cave reportedly breached by quarrying and subsequently filled in at PIP 1, and the hole revealed at PIP 4, lay very close to Little Grunt. Again, the close proximity of these caves highlighted the probability that Bradley Chesterman Cave is part of the Exit Cave complex.

Water is only one of the fluids that drains through karst caves. Another is air. Given the importance of cave climates for the functioning of underground processes and the well-being of cave biota, it is probably at least as important to safeguard atmospheric circulation systems underground as it is to safeguard the hydrological systems. Underground airflows will become integrated through any interconnected void systems and will come to represent the same underground atmospheric system even if the hydrological systems were to remain largely independent. In many respects the atmospheric circulation system more adequately defines a cave system than water movements do. The air movement through Exits Nostrils Cave is consistent with its being linked to a substantial cave system underground. Cavers have reported smelling explosives in March Fly Pot also suggesting that air movement from the existing quarry face into March Fly Pot and the unexplored routes for air movement that extend downwards from it. An inwards draught along the main stream passage in Little Grunt was recorded during the day on 21 November 1991, together with a very strong inwards draught along the tributary stream passage that parallels it to the north. Both are consistent with chimney-effect winds. Air movement was also detected in two holes drilled in 1991 by the DMMR. In the first case some H_2S was encountered in a small cavity at 30 m depth in drill hole 2, but circulation in the apparatus was retained. More noteworthy was an updraft detected in drill hole 6 in the lowest part of the quarry. While this draught indicates that the drill hole breached a cave system, the precise physics of what was occurring are not easy to interpret. Given the location of drill hole 6, it seems probable that this was part of the Bradley Chesterman complex. When inspected at 7:00 pm on the 14 November 1991, the updraft was blowing at an estimated 1-2 m/sec despite the considerably warmer condition of the external environment relative to the cave air temperature. Theoretical considerations suggest that a downwards draft would have been anticipated under the prevailing warm weather conditions, as denser cold air drained from the lower end of the system via Bradley Chesterman. It is possible that water-filled passages sometimes preclude air drainage from the system via Bradley Chesterman Cave itself, and that the draught at the drill hole represented leakage from the lower end of that part of the Bradley Chesterman system that extends towards the top of the quarry.

Relationship between the quarry and cave systems

Numerous intrusions into the cave complexes of the Ida Bay Karst System have occurred due to quarrying. For example, Dickinson (1945) recorded a travertine-lined channel over 100 m long that was exposed by quarrying in the now disused Blaneys Quarry, together with the presence of slumped stone and massive water worn boulders. This feature was developed close to the Conference Concourse section of Exit Cave, and along the same joint trend as has been the focus of much major cave development in the Ida Bay karst, including the Grand Fissure and the Eastern Passage in Exit Cave, and the stream passages in Little Grunt. Hence, conspicuous damage to the karst system and its component caves has been occurring in the Ida Bay karst for some time. It is now evident from the tracing of water to Exit Cave from at least one of the injection points in the quarry that the existing quarry has already removed parts of the Exit subsystem. The precise extent to which this has occurred is as yet unclear. It also appears that considerable volumes of sediment and other pollutants have been washed into the Exit Cave system from the quarry. It seems likely that some speleothem degradation may be attributable to water chemistry changes caused by runoff from the quarry.

Personnel involved with the quarry operation who were questioned as to the presence of cavities during the search for potential water injection points indicated their belief that no caves had been breached by quarrying. On the other hand, information from caver Arthur Clarke is that some years ago a collapse occurred beneath one end of a truck adjacent to PIP 1. He suggested this hole to have been 20 m deep and 4 m wide, with about two thirds of its margins encrusted in speleothems, including one dripstone speleothem with a diameter of at least 15 cm. According to Clarke this hole was subsequently backfilled. There is evidence of other holes having been backfilled in various other parts of the quarry. For example, rock also appears to have been dumped into PIP 2, and into the rift in which PIP 3 occurs. PIP 4 originally appeared choked by sediment, but removal of talus blocks that had been pushed up against the foot of the quarry face revealed a hole large enough to admit a human. This enabled fluorescein to be injected. Similarly, excavation through blocks immediately below PIP 5 revealed a cave entrance with strong air movement. These features must have gone unrecognised as being solution cavities, given the fact that the opening of at least some of them by quarrying is likely to have post-dated the "License to Operate" issued by the Department of Environment in August in 1989 which required that the opening of any solution cavities be reported. The date of exposure of the speleothem-covered quarry walls and extensive scatters of smashed speleothem fragments that occur in the upper parts of the quarry has not been determined.

Figure 2 depicts the relationship between the caves and probable recharge networks, and the existing limestone quarry and area into which extension of the quarry had been proposed. It is evident from this figure that the quarry operations had been occurring in situations where the caves have potentially been vulnerable to changes in infiltration regimes, the chemistry of seepage water, and sediment influxes. Caves in the quarry face obviously lie within the 200 m radius of blasting sites within which Baynes and Underwood (1990) suggested caves were "expected to be prone to damage", but so too do other caves in the polygonal karst and the stream passages of Little Grunt at greater depth in the limestone.

The extent to which infiltration water has the potential to reach the caves from the quarry is influenced by the structure of the limestone and the degree to which solution activity has taken place in the joint systems. At the Exit Cave Quarry the dip is, on average, 7 degrees just north of east, increasing to ~ 14 degrees further east (Forsyth and Green, 1976). Hence, the dips are of such a low angle as to be unlikely to greatly influence the gradient of recharge routes. Evidence from throughout the Ida Bay Karst System suggests the dominant mode of recharge is via steep shaft systems developed down joints that reach base level streams. The existence of such streams beneath the southwestern corner of the quarry has been proven by cave exploration. Virtually all joints display evidence of solutional attack. Summons (1981) has identified the principal joint trends in the area and those particularly susceptible to solution. The prominence of the SW-NE trending joint set in cave development at Ida Bay calls into question the strategy proposed some years ago of redeveloping the quarry at a north-south orientation to simplify the situation when clay-filled defects were encountered. The dip of all the joint sets is steep (74-90 degrees) favouring the development of steep recharge routes. A minor normal fault between DLR 2 and DLR 5, and thrust zones that dip at 30-60 degrees E have been inferred from drill hole data (Summons, 1981). If these inferences are correct, the former is likely to favour the development of very steep solution channels, the latter may have the potential to favour some slight eastward deflection but only at a shallow depth. Given that a hole in the quarry had been shown to drain to Exit Cave via Little Grunt, any such deflection has apparently not been sufficient to significantly change the general circumstance of recharge routes being very steep.

The presence of palaeokarst phenomena at the Exit Cave quarry means that it is probable not all of the visible karst features are related to the presently-active parts of the karst or to drainage patterns that operate today. However, the presence of the palaeokarst may equally well mean that the area contains many features potentially subject to inheritance and, hence, likely to be integrated with the present karst irrespective of the context within which they originally evolved. Karst phenomena that have been exposed in the quarry may not necessarily all form part of the contemporary karst assemblage. Recognition and interpretation of the palaeokarst is essential for correct interpretation of the structure of the limestone, and the possibility exists that some previous workers may have interpreted the geological structure incorrectly due to their having confused palaeokarst phenomena with bedrock structures (F. Baynes, pers. comm.).

The presence of palaeokarst sediments might constrain the directions of contemporary karst drainage since the palaeokarst is likely to contain relatively impervious materials. However, the reactivation of long dormant relict karst and even palaeokarst during construction projects (eg Therond, 1972) highlights the extent to which palaeokarst phenomena may also become the foci of subsequent solution activity. Indeed, part of the reason for palaeokarst having received less documentation than it has may rest in the fact that impervious palaeokarst sediments will concentrate water flows and hence the existence of palaeokarst may actually promote subsequent re-karstification that focuses on the margin of the palaeokarst and ultimately often destroys it. Irrespective of the age of any karst or palaeokarst phenomena, similar structural features may orient the direction of karstification during later stages. There is no basis for assuming that palaeokarst features are likely to cut off contemporary karst drainage. On balance, the converse is more likely to be the case.

SECTION TWO: KARST SCIENCE AND PUBLIC POLICY

Government agencies commonly become preoccupied with their own functionally narrow roles and the danger exists that they may lose sight of the fact that their own role comprises only one aspect of the task of governing in the public interest (Davis 1972). Where a commitment to an agency ideology is strong, its goals may be very energetically pursued. As Henning (1970) has observed, professionalism may serve as a line behind which brokerage politics enables agencies to get their own views legitimised. Various tactics are adopted in a bid to secure agency goals that are construed as desirable community goals. But pursuit of the public interest commonly demands trade-offs whereby individual agencies fail to achieve the ends they would most prefer. In the Exit Cave case there was little common ground between the Parks & Wildlife Service (P&WS) and the Division of Mines & Mineral Resources (DMMR). The quarry company, the local community, the conservation movement, and the national government also played prominent roles. This ensured considerable diversity of view as to what constituted the public interest in this case. There seemed little if any room for compromise.

Karst has played a significant role in a number of past environmental and political issues in Tasmania (Kiernan 1984, 1989a). A subsidiary aim of this paper has been to document part of the information base available to government decision-makers wrestling with the future of the Exit Cave Quarry, and to consider how they used it. Most scientists who work for government know only too well how ponderously the information they provide is ever translated into policy, if its existence is acknowledged at all. In the Exit Cave case a political problem existed, and the hydrogeological study had significant implications for the decision-making process. The study demonstrated that not only did drainage from the quarry reach Exit Cave, but that negotiable cave passages that clearly represented part of Exit Cave extended beneath the quarry, where there were cave entrances reburied by rubble. Media coverage had already been given to smashed speleothems exposed on quarry walls. It became impossible for decision-makers in government to continue to ignore or deny the overwhelming evidence, particularly once the report had become public knowledge.

The report on these investigations (Kiernan 1991) described the results and their implications, concluded that the adverse environmental impacts could not adequately be ameliorated within the context of on-going quarrying, and recommended the quarry should close. Such a report and conclusion was not well received by proponents of the quarry, including the Tasmanian state government. Prior to commencement of the study the DMMR contended the suggestion by Houshold and Spate (1990) drainage from the polygonal karst might reach Exit Cave was "too important a generalisation to be based on such limited evidence". However, subsequent to submission of the report an individual associated with the quarry company argued that the effort made to demonstrate the drainage relationships had been inappropriate because such a connection was already assumed: that the question for which an answer was needed was how to minimise the impact of quarrying and how best to monitor it. It might seem questionable whether a sensible karst environmental monitoring program can be developed and responsibly advanced in any case where the underground geography and hydrology is essentially unknown, no baseline data is available over a sufficient time frame to be meaningful, and only seven weeks is available to complete the entire exercise. Nevertheless, consultants for the quarry owners prepared a draft Environmental Management Plan (EMP) to guide continued operation of the limestone quarry and in it condemned the hydrogeology report as inadequate and unprofessional, and in essence ignored it. Considerable effort continued to be focused on discrediting both the hydrogeology report and particularly its author, who was excluded from any further significant official role in the decision process, and from continuing with his research into the hydrogeology of the quarry area.

In January 1992 Jeff Butt and other cavers examined a further hole at 235 m altitude on one of the quarry benches. This new cave, EMP Pot, was explored to a depth of 80 m and comprised a shaft 20 m wide. Its lower levels contained many broken speleothems, presumably shattered by blasting, and also quantities of mud presumed to have been washed in from the quarry. The cave lay almost directly above the extremities of Little Grunt. Exploration and mapping of Little Grunt itself has now revealed 3 km of passage, extending to within 150 m of the rockfall choke in the Eastern Passage of Exit Cave (Houshold 1992). Conservationists occupied caves in a bid to halt quarrying

The political processes that led to the latest closure of the quarry dragged on for another 12 months after completion of the study reported here, during and since which time other studies ensued. They included a further water tracing experiment undertaken by Parks Service personnel in February 1992, using water trucked to the site, that finally clarified the uncertainties left by the simultaneous fluorescein injection and showed that it had been PIP 3 that drained to Exit Cave while PIP 4 drained to Bradley Chesterman Cave (Houshold 1992). The Exit Cave quarry was closed only when political negotiations between the Tasmanian and Commonwealth governments broke down and the Commonwealth government acted unilaterally. Rehabilitation work undertaken at the Exit Cave Quarry is currently being monitored by the P&WS. Some of the company's equipment remains on site and the electricity supply remains connected .

Just as each generation of cavers and scientists builds upon the foundations laid by those who preceded them, so too with environmental policy. Commonwealth government intervention on Exit Cave did not demand as long a cabinet or caucus room debate as the multi-day arguments in connection with the original World Heritage listing of the Southern Forests that included Exit Cave. Some of the broad issues regarding the responsibilities of the Commonwealth in connection with World Heritage sites, and the question of "states rights", had already been addressed in that debate and perhaps more significantly in earlier deliberations and determinations regarding the Franklin River. On the other hand, the economy and unemployment had since emerged as the predominant political issues in Australia and Commonwealth government priorities had changed, as had the government's perception of the mood of the electorate. The survival of the Commonwealth government seemed likely to hinge on marginal seats, including some of those which it could be argued it had gained on the basis of its earlier conservation policies. But in contrast to earlier Tasmanian conservation issues, Exit Cave was little known to voters in key mainland electorates, while in Tasmania it had become a politically volatile issue, particularly in the marginal local electorate that encompassed Exit Cave where the pro-quarrying lobby was powerful. Such things led to Commonwealth indecision and loss of face, but the reality that Exit Cave was progressively being destroyed could no longer be denied, nor legal precedents derived from the Franklin River case, nor the possibility of an embarrassing public conservation campaign in mainland electorates.

Sponsorship of research into the conservation values of karst by apparently unlikely parties has been necessitated by political circumstances in Tasmania on a number of occasions. In the Franklin River case the Hydro-Electric Commission sponsored its own reconnaissance of karst caves in a bid to counter public advocacy by independent scientists regarding Kutikina and other archaeologically important caves which they argued provided additional reasons for not proceeding with a hydro-electric dam. In the Southern Forests case a forestry company engaged scientific expertise only to find the information it unearthed in various karsts provided a stronger argument for preservation than for forestry development. In the Exit Cave case the political situation demanded government funding for research that would have been unlikely to occur otherwise, at least in the short term, but it also imposed near crippling constraints on the time frame in order to meet political needs rather than the niceties of research methodology. Under such circumstances progress has to be made quickly, but often a far better result could be obtained with only a little extra time.

In such a situation the costs are not just to good science but often also to the researcher, either through a sense of having not been able to complete a task to their personal satisfaction, or because one vociferous party or another ultimately is likely to be put offside. In the Lake Pedder case one academic was threatened with legal action by the Hydro-Electric Commission after producing a report related to public policy which did not reflect favourably on the HEC's actions. The HEC once also threatened to sue an author if there was any repetition of critical comments he had made in the professional journal *Engineers Australia*, and to sue the publishers, while on another occasion it even threatened to sue the Tasmanian Department of the Environment if it released a report containing passages critical of the HEC for allegedly impeding environmental studies in the Franklin River area. Claims of bias or incompetence are common. The extent to which any researchers will risk such charges, and how they will react to them, depends upon the relative importance to them, at any one time, of a range of considerations. These include personal factors such as their financial circumstances, perceived family responsibilities, temperament and stress tolerance, and also include various professional issues including their level of concern about job security and alternative opportunities, the allegations against them, their image among particular peer groups, support networks, professional competition, and attitude to the matter under study. In the Lake Pedder case the researcher responded by further publication (McKenry 1972), in other cases where pressure has been brought to bear this has not been the case. Researchers have no legal recourse where attacks on their professional reputation are unwritten and are made behind closed doors, while great professional damage can be inflicted by transmission of non-specific and hence non-contestable imputations through informal networks.

In many cases, clashes of this kind stem not from the facts of an issue but from the values of those involved. McKenry's study of the HEC presupposed a set of standards quite different to those that had become traditional and accepted in the Commission and indeed Tasmania generally. The Exit Quarry hydrogeology report was also based on a different set of values and expectations to those of the quarry proponents and of government officials dedicated more to resolving a political problem than to dealing with nature conservation values. The report argued that a very high standard of protection and environmental monitoring was appropriate for a World Heritage site that had been explicitly stated to have been set aside to protect its natural processes. Most, even in the Parks & Wildlife

Service (PW&S), had sought to underplay the latter point in an effort to find some acceptable compromise that would make the political problem go away.

Consultants in particular are often heavily reliant on maintaining good will in their potential client catchment. Costs may often reasonably be expected by any researcher who fails to provide a report that either says what a sponsor wants it to say, or who fails to at least present any contrary findings in a format that will allow a gradual and face-saving escape from any difficult situation. Problems may also be encountered by government employees whose livelihood may be at risk if they indulge in any form of whistle blowing. In the present case the impacts upon Exit Cave were accruing daily, extension of the quarry into even more highly sensitive areas close to the unconformity were proposed, no legal impediment existed to a resumption of blasting and existing stockpiles were all but exhausted. Hence, in addition to simply presenting the hydrological data, the report also sought to break an impasse by drawing definite conclusions, firmly advocating a course of action, going to pains to minimise escape clauses, and adopting a very direct approach in an effort to thwart further evasion. This included adopting the name "Exit Cave Quarry" once that connection was proven.

This study has once again demonstrated the benefits of an integrated karst research program. In this case initial cave exploration efforts (Clarke 1990, 1991, Eberhard 1990) provided a basis for subsequent geomorphic study, which in turn provided a basis for water tracing experiments that enabled a focus on further targets for cave exploration. The high level of co-operation between researchers and recreational cavers was fundamental to the successful outcome in this case. However, in times of environmental controversy the degree to which liaison between conservationists and the relevant nature conservation agency is considered legitimate often differs from the level of acceptance accorded a close liaison between a mining company and the government agency responsible for mineral resources. There is often a tension between what is a useful liaison and what is perceived as being appropriate agency behaviour, and in part this is likely to relate to the position of the agency in the bureaucratic pecking order. In this case complaints were made about cavers "finding out" about water tracing experiments, as if oblivious to the fact they were involved in their conduct. Yet close and no doubt useful liaison between the company and DMMR is equally suggested by the admission by an officer of the DMMR that his agency's input to the draft terms of reference for the study had actually been written by a person associated with the quarry company, a point noted in the hydrogeology report in recording the range of viewpoints taken into account. The DMMR reacted strongly to incidental mention of this point in the hydrogeology report, perhaps because the phraseology of its final input might permit an interpretation that an attempt was being made to constrain investigation of the possible linkage between the quarry and Exit Cave, which might be taken to imply the DMMR was adopting the role of an advocate for the mining company rather than protector of the public interest with respect to the state's mineral resources. Such facts highlight how opposing agencies may become involved in liaisons that are considered inappropriate by one another. Similarly, informal protocols exist regarding what should or should not be placed on the public record, irrespective of what may actually be happening and considered acceptable at an operational level. In controversial times transgression of such protocols, or a deliberate challenge to them, are unlikely to leave much scope for calm seas. Many factors will impinge on a researcher faced with a decision of this kind.

Responses to any report will reflect the values, expectations, aspirations and expertise of the recipient, and in this case the opposing parties shared little common ground. One senior official asserted of the report that "Opinion is repeatedly presented as fact and the whole document has been used as a platform to espouse the writer's views on the subject - without the benefit of the requisite hard data... the entire report falls short of the standard expected and required". On the other hand, a professional karst academic suggested the report was "a very solid piece of reasoned scientific research...[the author] should be commended on his production of a balanced assessment....His report is of such a quality that it might be used as a model for such investigations elsewhere. I commend it to you without reservation".

It is unlikely that the validity of a process of medical enquiry and the worth of significant results obtained would be discounted if it were to be revealed that the doctor responsible was personally seized by a passion to rid the world of disease. Genuinely significant scientific advances made by an engineer committed to resolving a technical problem in a difficult project, and seeking to justify his conviction that it could be achieved, would be no less real as scientific advances if some in society considered that project to be socially undesirable. Similarly, if the evidence obtained is strong enough, a significant advance in scientific knowledge concerning an environmental issue is no less real simply because those responsible might have a personal belief regarding the actions that should flow from the information they provide. In a highly charged political environment however, questions of personal motivation become more prominent. In this case, given a personal history of involvement in nature conservation, I was an easy target for claims of bias, even to the extent of imputations that I had fabricated the evidence now published in this paper. The risk of such a situation arising potentially weakened the position of the PW&S in subsequent bureaucratic negotiations, and possibly raises questions as to their wisdom in nominating me to undertake the study. The situation potentially enhanced the opportunity for their opponents in the bureaucracy to brush aside the result of any study I might undertake. Indeed, the quarry company was still asserting in a press release dated as recently as 9 March 1993 that "[federal minister] Mrs Kelly commissioned a biased report from a former Director of the Wilderness Society".

Where any consultants report is controversial there may well arise a diversionary side-show in which personal integrity or professional competence are challenged and the author is excluded from any effective continuing role in the ongoing decision-making process. But if the scientific facts are strong enough any such attacks or exclusion may not matter because it is difficult for the real issue to be ignored forever. When a controversial matter is being dealt with by an agency that is low in the bureaucratic pecking order but which contains genuinely committed people, maintaining workable personal relationships with antagonistic individuals in more senior agencies can be difficult. But it is essential. A side-show can often be exploited to achieve this, and anecdotal reports from involved officials suggest this to have occurred in the present case. The more junior PW&S has not seen fit to publish the hydrogeology report so badly received by its more powerful sibling the DMMR. Indeed, to this date the PW&S has still not formally accepted the hydrogeology report, responded to correspondence on the issue or even acknowledged its receipt. On the other hand, both the PW&S and the Commonwealth government have relied heavily on the report to help carry the issue forward to a conclusion. While one may approve or disapprove of such an approach, it is nevertheless in the nature of political processes and the manner in which public policy frequently evolves. In many government decisions informal inputs and interactions can be influential, perhaps serve as the straw that breaks the camel's back, or even become the predominant factor. Seldom are government decisions simply a transformation of facts to actions solely by means of intellectually rational processes.

One-sided resource assessments are commonly involved when issues such as the Exit Cave Quarry arise. Prior to this controversy the limestone resources in the quarry area had received considerable attention from government, but the environmental values had been virtually ignored. Two years prior to the quarry being closed, there had been general informal concurrence among various senior officials when I proposed at a ministerial office meeting that in order to prevent a similar problem arising again, any investigations of other potential quarry sites should include not only the limestone resource but also the karst. Around 4% of Tasmania comprises poorly documented carbonate rocks. There was agreement that the significance of what might be lost to quarrying, not just at Ida Bay but also at other possible alternative quarry sites, needed to be determined in the context of a statewide assessment of Tasmania's karst (Kiernan 1989b). However, in the months that followed the DMMR continued to insist that the Exit Cave Quarry was the only viable source of limestone to meet the needs of the company's customers. The period over which environmental investigations might have been undertaken at any alternative site was thereby reduced. Then as closure of the Exit Cave Quarry came to seem more likely, the DMMR finally admitted a viable alternative limestone deposit existed at Risbys Basin in the Junee-Florentine karst, where sufficiently high grade limestone had been demonstrated in a DMMR report by Calver (1990), and then sought in turn to present Risbys Basin as being the only possible alternative to the Exit Cave Quarry. Even after admission of this alternative, and despite the investment of considerable DMMR resources to prove up the limestone at Risbys Basin for the company, environmental investigations there remained relatively neglected. Less than one hour after initiation of informal exploration of the area by Rolan Eberhard, Kevin Kiernan and Ian Houshold in April 1992 a new cave had been discovered. That this cave had not previously been recorded during the months of limestone investigation, despite it being the conspicuous sink of a major stream, highlights how low a priority environmental values remained at a state government level. Once again, any rational process of resource assessment would seem to have been overwhelmed by other factors. The quarry company has not taken up the Risbys Basin option and some of its plant and equipment remains on site at the Exit Cave Quarry, where the electricity supply remains connected.

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For assistance with the water tracing experiments reported here I wish to express my thanks to Stefan Eberhard. Michael Pemberton from the Tasmanian Department of Parks, Wildlife & Heritage established the project. Rolan Eberhard's persistence regarding the possibilities for further exploration in Little Grunt were fundamental to discovery of the new extension. The subsequent survey of the Little Grunt streamway was undertaken with Rolan and Stefan Eberhard, Vera Wong, Ian Houshold, Jeff Butt, Arthur Clarke and Bob Reid while Stuart Nicholas processed the survey data. A map of the Ida Bay karst area produced within the Tasmanian government from data provided by Arthur Clarke considerably aided both this study and virtually all the other studies undertaken into the future of the quarry, over a period of some years. For help in other ways I am grateful to Jo Bauer, Grant Dixon and Peter Bosworth.

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PROCEEDINGS OF THE WOMBEYAN KARST WORKSHOP

November 19-22, 1993, Wombeyan Caves NSW, Australia

Convenor: Ernst Holland
Karst Resources Manager, Jenolan Caves Trust
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THE GEOLOGY OF THE WOMBEYAN KARST

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The Wombeyan Karst is developed in the Wombeyan Limestone which is presumed to be of Late Silurian age. The Limestone was folded and exposed in the Early Devonian when caves formed. The Limestone was then buried under the caves filled by the silicic volcanics of the Lower-Middle Devonian Bindook Porphyry Complex. The Limestone was intruded by the Columba Granite and small basic intrusions which were probably responsible for its metamorphism.

Limestone breccias and open crystal-lined cavities in the limestone represent a post-metamorphic phase of karstification which predates and is intersected by the present caves.

The limestone was buried under sandstone and conglomerates which could be Permo-Triassic or Lates Cretaceous to Tertiary in age. These are found filling a cavity intersected by Creek Cave.

The "modern" phase of landscape development and karstification has removed much of the sandstone and conglomerates and produced caves and limestone gorges.

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INTRODUCTION TO THE WOMBEYAN KARST HYDROLOGY

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Water has been the most important agent in shaping the past and present karst landscape at Wombeyan. It has formed the caves and subsequently filled them with decoration. Water fits into the theme of the Wombeyan karst workshop as it essential for the support of life forms associated with the karst. This introduction to the hydrology will discuss the present drainage and the role of thermal waters in the evolution of the Wombeyan karst will be discussed as part of the geology.

The Wombeyan karst is a fluviokarst and thus its landscape features include deranged drainage, blind valleys, stream sinks, large and small springs, closed depressions and caves. Wombeyan Creek and Mares Forest Creek and their tributaries supply most of the allogenic input into the karst and at times flow completely across it. The hydrologic systems associated with the major creeks will be described in detail and the role that they have had in forming caves outlined. Hydrological studies at Wombeyan commenced during the preparation of the book "Wombeyan Caves". Results from that study and subsequent water tracing and chemical studies will be presented.

Major changes to the Wombeyan drainage have occurred in the last 20 years as a result of enormous volumes of sediment being deposited along the drainage routes by floods. The implications of these changes on the water routes through the caves and the potential for backflooding will be discussed.

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COLD CLIMATE PROCESSES AT WOMBEYAN CAVES

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In many of the upland valleys of the Southern Tablelands there are extensive colluvial fans which are presently stabilised under vegetation. Several of these fans have been related to cold climate conditions, though it must be recognised that the imprint of more then one cold climate phase in the Pleistocene or even earlier may be implicated. Even today there is cold air drainage and widespread frost shattering which affects slope deposits. Many of the deposits are formed in thinly bedded or foliated rocks which tend to produce a platy gravel regolith under todays weathering conditions. The precise processes leading to their formation must remain unclear due to the development of convergent landform types under a wide range of mass movement processes. For soliflucation or cold-climate slope deposits, the criteria are as follows:

1. The deposits from shallow mantlles, usually <1 m thick on upper slopes, but thicken to several metres or even tens of metres on lower slopes.
2. Slope profiles on these deposits are generally smooth but may have steps and lobes.
3. The deposits are derived from local parent material upslope, and are composed of angular, often platy, gravels. There may be included organic materials.
4. There is crude bedding within openwork layers, and strong downslope orientation of the long axes of the gravels.

At Wombeyan two slope deposits have been dated by radiocarbon: the slope deposit at Hockey Gully has an uncalibrated age of 19,7000 +- 1500 BP (ANU2252; Jennings et al., 1982:62). The Basin cave deposit is dated at 27850 +- 1100 BP (ANU 3606; Gilleson et al. 1985). Thus both are associated with a period of increasing or maximum cold during the Last Glacial. In both cases the dates were gained from charcoal intimately associated with the open work gravels. Evidence from other nearby sites suggests widespread hillslope instability broadly contemporaneous with that at Wombeyan.

The precise mechanisms for hillslope instability and increased sediment supply may relate to both climatic change and bushfire events. Cold climate conditions may have promoted soliflucation processes, but other factors may have been operating. It is now clear from faunal evidence that during the Last Glacial the southern Blue Mountains supported tussock grasslands (Morris et al. in press). Forest communities would have been restricted to lower elevations and northerly aspects. Under a grass cover low intensity fires are more frequent and thus more open conditions may promote slope destabilisation. Thus it may be impossible to disentangle the effects of low temperatures and fire in valley side erosion.

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ALLUVIAL STRATIGAPHY AT WOMBEYAN CAVES

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Wombeyan Creek is a minor tributary of the Wollondilly River, and its broad infilled blind valley above the Victoria Arch at Wombeyan Caves Reserve is at 580 m above sea level. Three terraces and a small floodplain are visible within the valley. Through time Wombeyan Creek has meandered freely within the bedrock confines of this limestone valley and oversteepened slopes due to meander incision are visible at several places. This meander incision, together with hillslope instability due to cold climate conditions, has promoted the development of valley side fans of colluvium which interfinger with the alluvium. From earlier research it is clear that a major phase of hillslope instability occurred immediately prior to and during the Last Glacial from c. 28,000 years before present. This produced extensive colluvial fans of coarse frost shattered gravels and cobbles in many places.

Closer examination of the terraces immediately upstream of the Victoria Arch suggest that their long gradients coincided with a series of solutional wall incuts (Walker & Middleton, 1970). The terrace stratigraphy is laterally continuous, suggesting plugging and unplugging rather than meander migration. It appears that the lower areas of the blind valley are the result of periodic aggradation and subsequent incision of the valley fill, and the terraces are most likely erosional in nature. The nature of geomorphic processes in this small upland valley is such that major changes in the fluvial morphology may occur on timescales ranging from hours to centuries. The geomorphic system is dominated by high magnitude, low frequency events rather than steady-state processes. A single flood event of a few hours duration may deposit more alluvium and sculpt valley sides more effectively than a century of base flow. Rainfall analysis (Spate & Gillieson, 1992) suggests the following return periods for 24 hr intensities: 75 mm, 2 yr; 100 mm, 5 yr; 150 mm, 25 yr. Planning should avoid placing infrastructure within range of floods caused by such rainfall.

The second terrace of Wombeyan Creek extends either side of the channel and forms the main alluvial surface at 585 m altitude. Beneath an overburden of angular gravel is a thick silty sand topsoil which conformably overlies a thick and extensive flood sand deposit. It is a strong massive sand and is probably the result of rapid deposition during one major flood event. Charcoal in this deposit has been sampled for radiocarbon dating and a sample was taken for thermoluminescence dating (TL) from the sand body itself. Below this flood deposit is a buried topsoil (with charcoal) which is a silty clay loam. At the base are coarse alluvial deposits of unknown depth which may relate to a very early phase of increases sediment supply. These deposits are noticeably coarser than the contemporary gravel to boulder fractions. They are strongly weathered and may have equivalents in the roof of the Fig Tree Cave and other caves associated with the Victoria Arch. All suggest increased fluvial vigour in the past. This plugging and unplugging of the Victoria Arch complex is reflected in cave sediment accumulations and some paragenetic cave development on top of the fill.

References

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EASTERN AUSTRALIAN QUATERNARY MAMMAL CAVE FAUNAS: THEIR PALAEOCLIMATIC AND FAUNISTIC SETTING - AND THEIR POTENTIAL

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Fossil mammal faunas found in early years of Australian cave exploration were primarily regarded as a source of information on the diversity and anatomy of the extinct megafauna, although at the beginning Thomas Mitchell attempted to correlate those he found in Wellington with an arid period, with sea levels, with lunette formation and with the development of surface topology at the time, to extend these speculations further.

With the rise of evolutionary biology there was some interest in cave faunas as a source of evolutionary information but it was generally agreed that, as "Ice Age" equivalents, they only illustrated the demise of megafauna as did cave faunas in Europe.

Now, because of extensive palaeoclimatic information derived from a wide range of disciplines, and realization that the caves of eastern Australia contain deposits extending back into the Tertiary, and the recognition that virtually the whole of the characteristic Australian marsupial fauna (and many of the murids) are arid adapted, it seems likely that the caves have the potential to illustrate the whole of the spectacular and rapid Australian radiation after the loss of the rainforests.

The topographic and ecological diversity of eastern Australia also highlights the sensitivity of the cave faunas as indicators of faunistic and climatic change.

Currently, very few reliably dated deposits are known and, except for the last 30 Ka, nothing can be said with any certainty of faunistic change or turnover. Deposits formed from the end of the last interstadial illustrate progressive faunal depauperization with a loss of megafauna before climatic amelioration following the glacial maximum. The reason is not apparent but is not likely to be solely climatic.

Reliably dated fossil faunas reveal unexpected associations that indicate that Bioclim analysis based on modern data alone may not be as useful as is currently believed for developing predictions of the consequences of global warming to modern faunas.

THE INVERTEBRATE CAVE FAUNA OF WOMBEYAN

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Fifty seven species of cave dwelling invertebrates are recorded from the Wombeyan karst. The fauna includes one species of oligochaete, two mollusc species, four crustacean species, five myriapod species, twenty two arachnid species and twenty three insect species. The Wombeyan karst has the highest recorded diversity of troglobitic species in New South Wales (consisting of at least eight species, plus a further five species which may be troglobitic). The maintenance of water quality within the karst system is considered important for conserving the integrity of the aquatic cave communities. Water quality is threatened by an increase in sedimentation, organic pollutants and toxins which may derive from quarrying and roading activities, farming practices and tourism development.

THE GREGORY KARST AND CAVES, NORTHERN TERRITORY

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The Gregory Karst is located in Gregory National Park in the west of the Northern Territory of Australia, between Katherine and Kununurra at approximately lat. 16 03'S, long. 130 22'E. The area has been investigated by speleologists only since 1990 and this is a preliminary report drawing attention to a significant new tropical karst.

The Gregory Karst has developed in almost horizontal 10-15 m thick beds of the Supplejack Dolomite Member outcropping at the valley margins of rugged tropical karst develops when the overlying beds are stripped. A highly seasonal hydrologic regime and rapid infiltration over a wide front promotes a dense network of joint-controlled grikes and a maze of underground passages with strong lithological control. Although research has only just commenced, preliminary evidence indicates that some caves may be very old.

DISTRIBUTION OF BRYOPHYTES ON LIMESTONES IN EASTERN AUSTRALIA

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A comparison was made of bryophytes on limestone and nonlimestone substrates at three locations in southeastern Australia: Jenolan Caves, London Bridge, and Attunga. Bryophyte abundance at each location was recorded in terms of number of species present and percent ground cover. At each location bryophytes collected from limestone substrates were more abundant, in number of species and percent ground cover, than those collected from nonlimestone substrates. Some species were exclusively collected from limestone sites. Many bryophyte species present on limestone are more usually associated with arid and semiarid areas of Australia. Distribution of bryophytes on limestone and nonlimestone sites at Attunga appeared to have been affected by grazing stock.

SPELEOGENESIS IN AEOLIAN CALCARENITE: A CASE STUDY IN WESTERN VICTORIA

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Most studies of karst landscapes and their processes have been concerned with consolidated, often well jointed limestones. There are particular problems involved in the study of karst processes in softer less compact limestones such as chalk, coral reefs and aeolian calcarenite. Previous studies in aeolian calcarenite indicated these problems and Jennings (1968) developed a scheme of speleogenesis in aeolian calcarenite. A study of karst processes in aeolian calcarenite at Bats Ridge in western Victoria has developed this scheme further.

The karst features and processes at Bats Ridge are an integral part of the landscape of the mid Pleistocene calcarenite dune system. The resolution of the problems of the rapid subaerial speleogenesis in the area is achieved by the synthesis of the known karst features of the ridge and the geology and geomorphology of the area.

Karst development on this aeolianite ridge depends on lithological conditions as well as the availability of aggressive water capable of solution. The diagenesis of the calcarenite is occurring now and must have been occurring by the mid Pleistocene. This simultaneous lithification of the carbonate dunes into aeolian calcarenite rock and the development of solutional karst features in the dunes is the characteristic feature of the speleogenesis in this area. It is the formation of a hardened kankar layer (cap rock) in the dunes of sufficient compressive and tensile strength to support cavities, which is the result of these interrelated factors that has strongly determined the formation of the karst features.

HYDROGEOLOGY OF THE ELLIS BASIN KARST, NEW ZEALAND

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A thick sequence of marble extensively outcrops along the Arthur Range in the South Island of New Zealand. South of the Arthur Fault is the Ellis Basin karstfield.

Dye tracing of a major sink, Grange Slocker, shows that most of the underground drainage of the Ellis Basin flows to the Pearse Resurgence, 6.4 km to the ENE. Minor local underground drainage resurges at the periphery of the Ellis Basin karstfield.

Cave exploration has mapped underground streams that flow E-SE in the caves Tomo, Thyme, Blackbird, Falcon, Incognito and Gorgoroth. These streams are tributaries of the major underground stream, Thunderchild in the cave Exhaleair, which flows SSW-WSW, before swinging to the east downstream. The flow direction of the Thunderchild stream away from the resurgence is unusual.

Geological surface and underground mapping has delineated a south-plunging asymmetric syncline controlling the Ellis Basin karst drainage. The Thunderchild stream flows down the synclinal hinge zone, and the streams of Tomo, Thyme, Blackbird, Falcon, Incognito and Gorgoroth flow obliquely down dip towards the synclinal hinge. Stream flow from downstream Thunderchild to the Pearse Resurgence may be controlled by the strike around the nose of the adjacent anticline.

Intrusive insoluble dolerite dykes and sills and partly soluble thick carbonaceous calcareous siltstone unit(s) interbedded in the marble also influence underground stream development.

VEGETATION CHANGE ON THE NULLARBOR PLAIN

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Twenty eight shrubland and woodland vegetation types are found on the Nullarbor Plain, and these are broadly organised in zones parallel to the coastline. There is a clear relationship to rainfall gradient and substrate type. Rainfall intensity and frequency controls patterns of recruitment in myall and saltbush, while the depth of closed depressions affects plant species distributions at a local level. Grazing drastically reduces chenopod regeneration and favours unpalatable halophilic species with annual herbs and grasses. These annuals are relatively flammable, and chenopod shrubland will thus only carry fire with a heavy grass cover after prolonged rain. The combination of fire, rabbits and variable climate has eliminated chenopods over large areas of the plain. Pastoralism has been present since 1875 with carrying capacities ranging from 10-16 ha/sheep and maximum numbers around 10-14,000 sheep per property. Changes in land cover since 1972 have been assessed using difference images of satellite data at five year intervals. In the last decade vegetation recovery has been evident on Mundrabilla and Koonalda stataions, with bare waterpoints recovering in about five years. GIS modelling has demonstrated that the locus of wind erosion is in these bare zones where vegetation cover drops below 15%. Contemporary issues in land management include the spread of invasive plants and the maintenance of disturbance by rabbits. There is a lack of management resources for control of exotic species in existing reserves while large areas have recently been added to the conservation reserve network. Ecotourism has grown and there are clear visitor impacts at cave and coastal sites. There is a need for the integration of conservation management and pastoralism rather than separate and often opposed development.

INSECT LARVAE AND TUFA FORMATION AT LOUIE CREEK, NORTHWEST QUEENSLAND, AUSTRALIA

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Louie Creek is a karst spring-fed stream situated in the northeastern portion of the Barkly Karst, northwest Queensland, Australia. The stream deposits tufa along a 1.5 kilometre reach, mainly as a series of cascades. As with virtually all tufas elsewhere in the world, algae and cyanobacteria are intimately associated with the deposits. The precise nature of the plant biological role is unclear. In addition to microphyta, the tufas are hosts to a range of insect larvae. The three most abundant larval families identified to date are Simuliidae (order: Diptera), Hydropsychidae (order: Trichoptera) and Pyralidae (order: Lepidoptera). The larval types prevailing on or within a particular tufa are to some extent influenced by the hydrological regime.

Hydropsychidae are the larvae exerting the greatest influence on tufa formation. They construct retreats and cases composed of vegetable matter and small tufa chunks reworked from the tufa substrate. They also build nets which not only trap food but also act as sites for calcite nucleation. In some instances, tufa-cemented Hydropsychid cases and nets can form layers up to a centimetre thick and can give rise to distinct tufa micromorphologies. Pyralid larvae spin cocoons which also become nucleation sites for calcite crystals. In addition, Pyralidae appear to bore through the softer varieties of tufa, forming slightly meandering tunnels similar to those produced by terrestrial Lepidoptera. These 'burrows' are extremely well preserved in some ancient tufas.

Although insect larvae have been previously recorded in tufas, no studies have been carried out which examine their role in tufa formation. It is clear from preliminary results obtained from Louie Creek that these organisms are in some cases very important in tufa growth and development.

INFORMATION FOR CONTRIBUTORS

SCOPE

Contributors from all fields of study related to speleology will be considered for publication. Suitable field 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.

MANUSCRIPTS

Submitted manuscripts should be in final form ready for publication. As proofs are not normally sent to authors particular care should be taken to check for typing errors. Manuscripts should be typed, double spaced, on one side of the paper. The title should be upper case bold and the author's names should follow. A brief and explicit summary of the notable aspects of the paper, headed abstract, should precede the main text.

Throughout the main text headings should be in upper case, centred and bold, while subheadings should use lower case bold aligned with the left margin. Acknowledgements should be placed at the end of the text before the references, and the author's addresses for correspondence should follow the references.

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REFERENCES

References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication (e.g. "(Grey, 1988)"). Where there is more than one reference to the same author in one year the letters a, b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by "et al." should be used in subsequent citations. References should be checked particularly carefully for accuracy. Journal titles should be abbreviated following the "World List of Scientific Periodicals", which is available in most large libraries.

The following examples illustrate the style:

GREY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. *J. Aust. ent. Soc. 12:* 207-221.

VANDEL, A., 1965 *Biospeleology. The Biology of the Cavernicolous Animals.* Pergamon, London. Pp. xxiv, 524.

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 Austalia:* 32-34. Speleological Research Council, Sydney.

ILLUSTRATIONS

Figures and photographs should not duplicate information in tables or other material. Photographs should be clear black and white prints with sharp focus. The number of pages with photographs will be kept to a minimum. Where several photographs are to form one plate they should be mounted together on white card. Any lettering required on photographs should be applies with "Letraset". Figures should be drawn in Indian ink on white card, heavy paper or tracing material and lettered using stencils or "Letraset" or supplied as Laser prints. Most computer drawn documents can also be handled if they are in Macintosh format.

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