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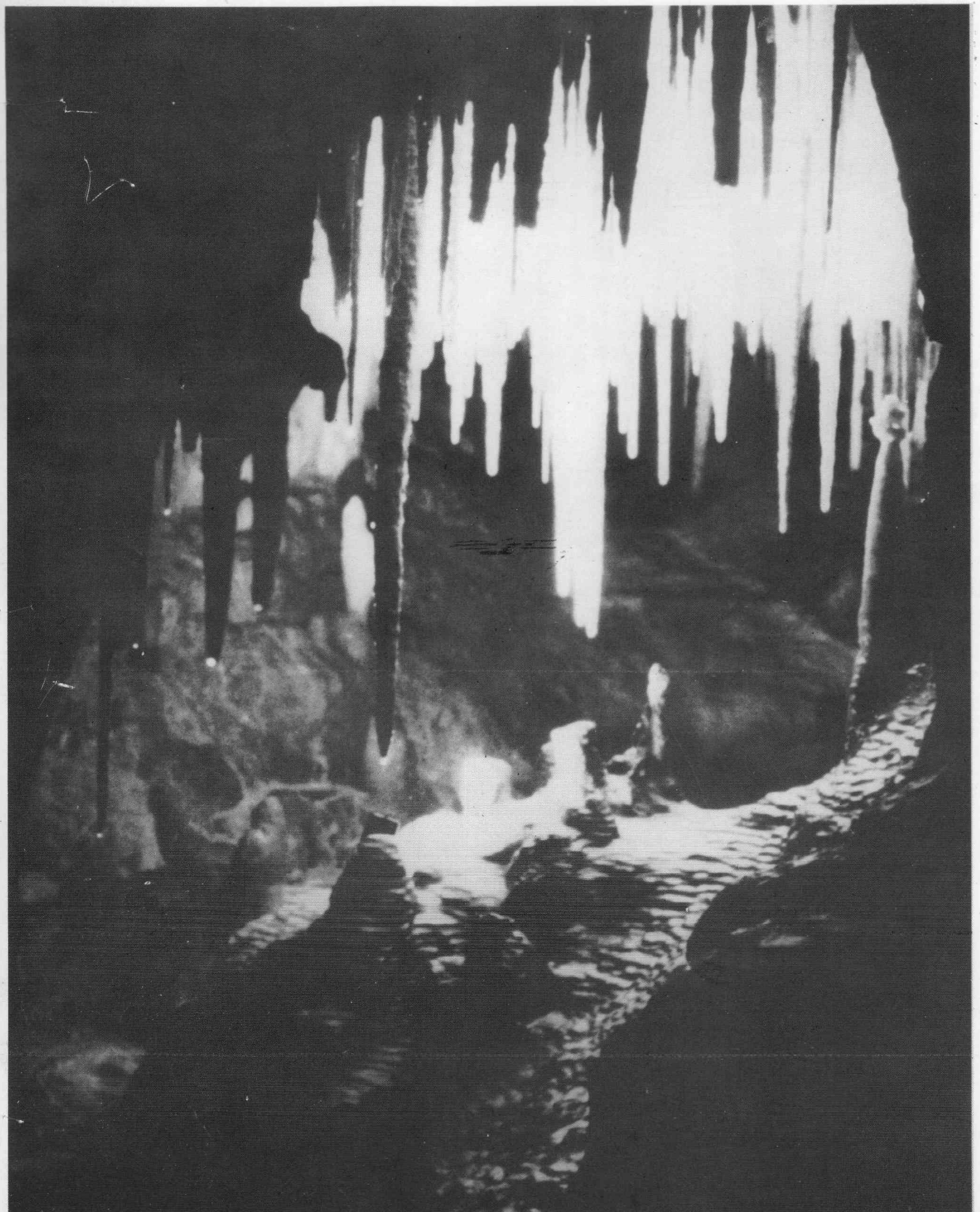
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Kellys Hill Cave, Kangaroo Island
Photograph by Keir Vaughan-Taylor

HELICTITE

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

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

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

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To explore and chart and organize and promote the exploration and charting of caves and cave systems.

To promote, support and assist in the scientific evaluation and investigation of caves and to foster speleology as a science and a sport.

To promote and to assist in the promotion of speleology and speleological Societies and to assist such Societies with grants of money and otherwise.

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OBITUARY - JOE JENNINGS

Joseph Newell Jennings, doyen of Australian karst geomorphologists and one of Helictite's greatest supporters and most regular contributors, died suddenly on Saturday 25th August 1984. He leaves behind his wife Betty, daughters Sarah and Judy and son Guy, to all of whom we extend our sympathy. A full obituary will appear in the next issue of Helictite.

REVIEW

CAVE IN A COLD CLIMATE

CASTLEGUARD CAVE AND KARST, COLUMBIA ICEFIELDS AREA, ALBERTA, ROCKY MOUNTAINS OF CANADA : A SYMPOSIUM, by D.C. Ford (ed) 1983 Arctic and Alpine Research 15: 425-554. Price of issue US$14 for institutions, $8.50 for individuals, $5 for students.

To devote a whole issue of 130 large pages to a dozen papers on Castleguard Cave and its setting shows sound judgement on the part of the editors of this journal; no other cave in a cold climate has received such a diverse and modern scientific attack as this has at the hands of Derek Ford, his colleagues, both long-term and visiting, and his research students at McMaster University. Nearly all the papers were presented at the 8th International Congress of Speleology, Bowling Green, Kentucky, 1981, in a symposium which was its scientific acme.

First, Ford repaints succinctly the context of Castleguard Meadows, Castleguard Mountain, with its own small glaciers, and Columbia Icefield, much of which also is directly underlain by the extremely massive Middle Cambrian limestone that gives rise to this karst (Figure 1). The Meadows were entirely overrun by ice during the Last Glacial Maximum; it disappeared by about 10,000 BP. The glaciers recovered a little in recent centuries to build Neoglacial moraines but in the present century have retreated from the latter about 500 m, exposing freshly ice-scoured pavements, which exhibit the best developed subglacial calcite crusts yet described. This calcite deposition is formed by pressure melting and solution of the rock where the ice bears heavily on it, followed by regelation where the pressure is less and precipitation occurs. I would only criticise this contribution on some minor terminological points, e.g. 'sinkhole' is used so broadly to encompass many forms from open shafts (pots) through a range of dolines to complex forms, including a uvala and an incipient polje, that it confirms my long-held view that it has ceased to be a useful term.

The next paper by Ford, Peter Smart and Ralph Ewers is a description and interpretation of the evolution in plan and profile of Castleguard Cave with its 18 km of passages and its 350 m of depth. Parts of the headward complex beneath the Columbia Icefield are thought to belong to an older cave directed SW. Glacier ice still blocks one passage here and injections of glacial ice and debris are thought to have disrupted this cave and directed fresh development SE down the dip of massive Cathedral Mountain Formation limestone. This took the form of a multiple-loop, dynamic phreatic cave, with dip tubes in 4 bedding planes connected by 3 lifting sites in joints and faults. Vadose entrenchment of the upper parts of the inner 3 dip tubes has produced keyhole passages on the grand scale. Apart from the final lift and tube, which opens high up the Castleguard R. valley wall, the cave is mainly inactive. Because of summer floods in the forward part, exploration has to be done in late spring before much snow melts. Overlying shales, dolomites and dolomitised limestones have become more pervious with time and also have been stripped away in parts glacially. This has allowed local invasion by vadose waters down shafts and these waters quickly descend below the known cave to a postulated lower cave that feeds lower springs in the valley wall and its floor. Glacial action and karst development have progressed together. The interpretation is most convincingly presented, apart from a perhaps inevitable vagueness about the original, SW-directed cave. Getting to and working in that headward complex is most arduous.

There follows a study of clastic sediments in the cave by Jacques Schroeder and Ford. Perhaps most interesting is the ramp of highly rounded limestone pebbles at the foot of the most forward phreatic lift, still active in summer. Winter frost wedging in the shaft loosens fragments which floods lift up, sometimes to the top. The more rounded a pebble becomes the harder it is for it to be lifted up and out. In this way a lag gravel accumulates at the bottom of the shaft. In the central part of the cave there are eroded remnants of 3 varved silt fills, deposited in full glacial conditions and all older than 140 Ky (thousand years). In the headward complex are breakdown deposits, in part of frost wedging origin when the Icefield was not present, and gravels of glacio-fluvial nature. Given the difficult character of the cave, the careful field observation behind this contribution is most praiseworthy, beside which criticism of the extension of the coastal geomorphological term, 'shingle beach', to the phreatic lift lag gravel is but a quibble.

Next comes the chronology of the cave through its speleothems by Mal Gascoigne, Alf Latham, Russell Harmon and Derek Ford, mainly relying on the uranium/thorium method, but also employing palaeomagnetic age determination of speleothems for the first time. Combined, these methods show that two specimens are between 0.72 and 1.25 My (million years) old; this implies that much of the cave had ceased to be phreatic by 0.72 My. The varved silts have all to be of Penultimate Glacial age or earlier. This contribution is further evidence of the leading role the McMaster group has played in speleothem dating.

With the aid of quantitative dye tracing and comparison of hydrograph records from two summers, Chris Smart examines the hydrology of this alpine karst with its great relief and partial burial by ice. The upper Cathedral Mountain Formation limestones form the main aquifer. There are various water intake areas. The many streamsinks in the northern Meadows and in benchlands near the Castleguard Mt. glaciers account for only a small part of the underground drainage. Most is from the Columbia Icefield and Saskatchewan Glacier through surface meltwater descending shafts and caves in the ice to enter buried limestone. The main output area includes about 100 springs in and near to the floor of the Castleguard R. valley, some from bedrock like the Big Springs - summer overflow springs, and others rise through valley floor deposits, e.g. Artesian Spring - perennial baseflow springs. These highlying springs appear to be fed not only from the northern Meadows but also from the Saskatchewan Glacier. Castleguard Cave is a simple conduit system but the lower springs imply a network of fissures forward of a large conduit in the postulated lower cave.

The hydrological system developed under ice and the wide spread of the springs both in plan and altitudinally is attributed to glacier action, blocking outlets with both ice and till, and interfering by erosion also. Where glacier soles lose water to the limestone, geothermal heat flux is reduced so there is less basal sliding and erosion by the ice. Conversely where springs rise beneath the ice, pressure is reduced and there is warming, with consequent reduction of sliding and erosion.

The cave atmosphere is dealt with by Tim Atkinson, Peter Smart and Tom Wigley, the lone Australian in the team of authors. The cave has a dynamic, 'chimney' system, the higher entrance inferred to be connections with crevasses under the Icefield. Wind blows downhill and out through the cave mouth in winter, uphill and into the cave in summer. In spring and summer, reversals occur at intervals of the order of a day. The gas, radon-222, in the cave air was measured at many points; its concentration was lowest where there are tributary fissure passages and roof water inlets. These introduce air with less radon than that which has had long contact with cave rock surfaces. This effect is a significant one and is taken to point to a large volume of small voids in the bedrock around the cave.

There is a central warmer section in the cave where the air temperature is 2.5 to 3.8°C. This is not only warmer than air in the forward and headward parts but also exceeds the mean external air temperatures. This is ascribed to geothermal heat flux suffering less loss beneath Castleguard Mountain than on either side. Asymmetry in this heat profile is attributed to cooling of the headward parts by entry of meltwater from the Icefield.

In winter there is an increase in relative humidity inwards for 1200 m from the cave mouth from 80% to a few % less than saturation; consequently there is much evaporation here, causing sublimation of ice. Between 1200 and 4500 m much of the air is still below saturation and walls are dry, with evaporites precipitated on them. The inner part of the cave has 100% humidity and the walls are damp from condensation. Nevertheless some parts here also have evaporites, attributed to summer evaporation with the reversed pattern of air flow, etc.

The cave mineral distribution, closely related to the climate, is the concern of Russell Harmon, Tim Atkinson and J.L. Atkinson. The first 450 m of the cave has dripstone ice and floor ice in winter, hoar frost in early summer before the floods. Small calcite speleothems occur throughout the cave but the warm, central core is characterised by large clacite speleothems and in the drier areas by other carbonate minerals and evaporites. Pasty 'moonmilk' is of calcite and huntite; dry 'moonmilk' crusts of hydromagnesite and monohydrocalcite. There are aragonite, mirabilite and epsomite needles. Gypsum occurs in a range of forms and is often found wedging bedrock fragments loose. Water analyses show that calcite speleothems are not due to CO_2 degassing - there is a dearth of biogenic CO_2. From stable isotope analyses, aragonite, hydrated carbonates and sulphate minerals appear to be due to evaporation, whereas the large calcite deposits are thought to be due to preferential deposition from large seepages which have dissolved dolomite and/or sulphates just prior to entering the cave. One stalagmite yielded a palaeotemperature curve for 155 Ky to 95 Ky; it shows short warmer periods within the latter part of the Penyltimate Glacial and also the warm period of the Last Integracial around 105 Ky.

Jean Roberge and Daniel Caron discuss a rare speleothem, cubic cave pearls, in many nests in the central part of the cave, totalling many thousand individuals. They lie in layers, sometimes with a second above, forming neatly rectangular patterns. One individual cube was examined by SEM and XRD. Entirely of calcite, it had grown round a calcite fragment at the centre, surrounded by spherical layers to 1.3 cm diameter but thereafter with cubic layers till it reached 6 mm diameter. The transformation is explained by thickening at corners where the grains were not in contact with one another and the bottom; renewal of supersaturated water near those contacts is restricted. Absence of rotation is implied. The regularity is explained by sudden freezing of the pool surface with the formation of needle ice orthogonal to it. These grow down to irregular groups of spherical pearls, displacing them into their own regular pattern. The explanation fails to consider why the top surface of the pearls also flattens where there is a single layer and in the case of the upper layer where there are two.

Tim Atkinson enlarges on the problem of accounting for active calcite speleothems beneath glaciers and rock desert where biogenic CO_2 is lacking. Amongst several possible hypotheses, he plumps for the common or paired ion effect. Solution of dolomite and oxidation of pyrites to sulphuric acid, which dissolves more limestone, lead to supersaturation and calcite is precipitated because it is the least soluble of the species. Thus old speleothems can no longer be taken to the indicative of vegetated soils above, only absence of permafrost.

Another problem is the discrepancy between radiocarbon and uranium/thorium dates for 6 straw stalactites, the former being 8-10,000y older. Mal Gascoigne and D.E. Nelson show this is too great to be accounted for by incorporation of dead carbon from the bedrock. Oxidation of carbonaceous components in the overlying rocks is proposed as the source of further dead CO_2, though the authors admit that it doesn't satisfy all their chemical and stable isotope data.

The only biospeleological paper in the sumposium by John Holsinger, John Mort and Anneliese Recklies centres on two blind, unpigmented aquatic crustacean species found in many sediment-rich pools through the cave, included the subglacial parts. This fauna is regarded as a remnant of an ancient preglacial population. The cave remained ice-free during glacial stages and acted as a subglacial refuge. Their food supply would consist of organic matter washed through the glacier and into the cave, including red algae often seen on glacier surfaces. Alternatively these allocthonous accessions could feed bacteria and fungi which act as food for the crustaceans.

A 'Concluding Discussion' highlights the points of greatest general interest from the whole symposium.

Even this lengthy analysis fails to reveal the range and wealth of findings and ideas, which Ford and his team have so admirably drawn from a cave difficult of both access and exploration. They have made their presentation more generally useful by starting each paper with a brief survey of the systematic background to their specific studies. There are many informative diagrams and apposite photos. Speleologists who buy the issue will certainly get their money's worth; if they can't afford it, they should persuade their club or a convenient library to get it.

J.N. Jennings

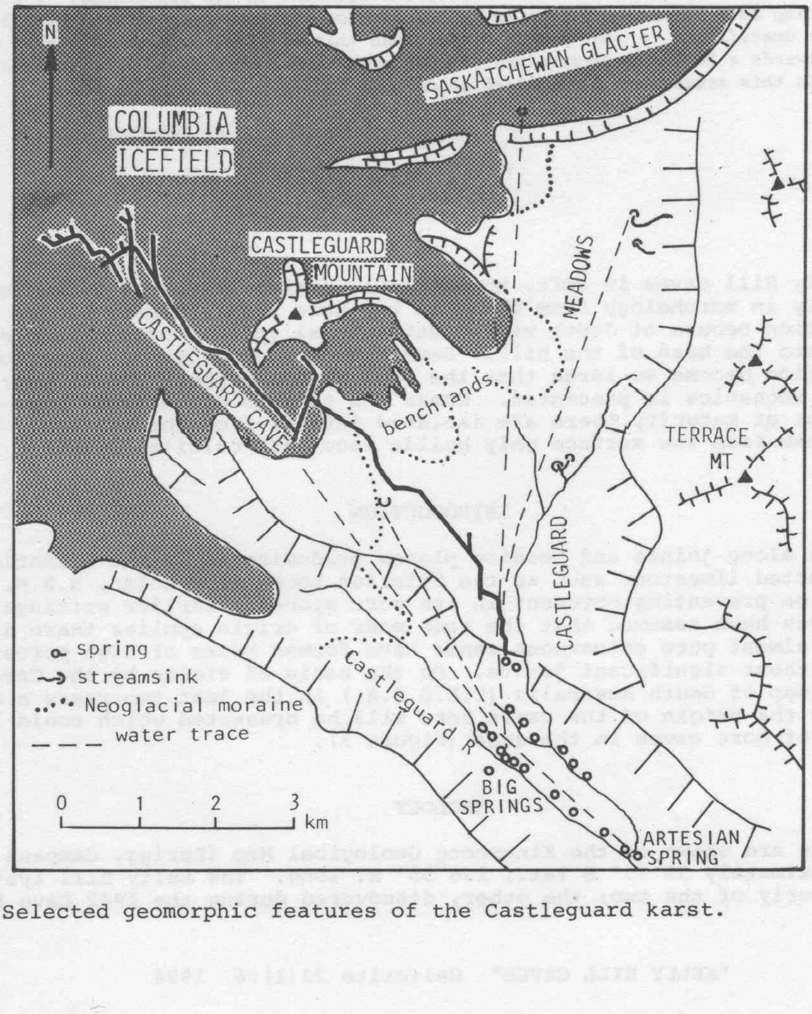

Figure 1. Selected geomorphic features of the Castleguard karst.

THE ORIGIN OF THE KELLY HILL CAVES, KANGAROO ISLAND, S.A.

A.L. Hill

A paper read at a C.E.G.S.A. meeting on 9th April 1957 in the South Australian Museum.

Explanatory Note

Those who got to know A.L. Hill ("Hilly") of Adelaide soon recognised that he not only enjoyed his caving but that he liked to exercise his engineer-trained intelligence on scientific aspects of caves. Amongst the products of that latter facet of his speleology was a paper on the geomorphology of the Kelly Hill caves on Kangaroo Island which he presented to C.E.G.S.A. in 1957. It interested his audience greatly and he sought critical opinions from Drs. P.S. Hossfeld and A.W. Kleeman of the Geology Department of the University of Adelaide. They considered that with some stylistic revision it would be worthy of publication in a scientific journal. Later he asked my opinion and I concurred in this. Unfortunately, amongst his manifold caving and cave science activities, he did not find time to pursue this before his untimely death.

My estimate of his paper was such that I made use of it in a general paper on karst in aeolian calcarenite in Australia and I included a figure from it in my book on karst. I would probably have made more reference to his ideas if the article had been published. More than once I contemplated seeking its publication posthumously. Recently Sue White found it helpful when investigating the aeolian calcarenite karst of Bats Ridges, Victoria, and she urged this step also.

I have therefore edited the paper along the lines I think a journal would have required if it had been submitted in the late fifties or early sixties. Nevertheless I have neither abridged his ideas nor revised the writing in the light of advances in knowledge since that time. To a degree this latter course will render it an historical document on its appearance. I believe it is worth publishing as a significant item in the history of Australian speleology, which would otherwise remain unavailable to most people. More than that it is my opinion that even now it can still help us towards a better understanding of cave origins and evolution. The Editors of Helictite join in this assessment and publish it on both counts.

J.N. Jennings

Abstract

The Kelly Hill caves in soft, homogeneous, extremely porous dune limestone differ markedly in morphology from those in the more usual, dense, bedded limestones. Solution occurs at depth with great lateral spread through swamps overflowing into the base of the hill. Development occurs by roof breakdown as areas of solution become so large that the roof cannot support the weight; a theory of the mechanics is presented. Domes and tunnels of collapse rise above the watertable; at maturity there are isolated infalls from the surface. Water percolating down from the surface only builds secondary calcite deposits.

INTRODUCTION

Solution along joints and bedding planes predominates in the formation of caves in compacted limestone such as the Silurian rocks at Jenolan, N.S.W., capillary action preventing movement in its pore spaces. Earlier writings on the Kelly Hill caves have assumed that the same mode of origin applies there also. However, here almost pure calcareous sands have formed rocks of high porosity (about 30%) without significant joints. On the basis of visits by the Cave Exploration Group of South Australia (C.E.G.S.A.) in the last two years a different hypothesis for the origin of the caves here will be presented which could lead to the discovery of more caves in the area (Figure 1).

GEOLOGY

Two caves are shown on the Kingscote Geological Map (Sprigg, Campana & King, 1954) at approximately 35°59' S lat., 136°55' E. long. The Kelly Hill system is the more northerly of the two; the other, discovered during the 1942 Cave Reserve

Survey was relocated and named K-11. On the map, the caves are shown as occurring in Pleistocene 'Consolidated dune limestone (aeolianite)'. These deposits are found extensively in the coastal areas of southern Kangaroo Island, Yorke Peninsula, and the Southeast of the State. (Tindale, 1933; Hossfeld, 1950; Sprigg, 1952)

In the Kelly Hill area these wind-blown, calcareous sands form minor ranges with a dense vegetation and with occasional limestone outcrops. They rise to a height of about 25 m above the low plain of Recent sand and clay to the north.

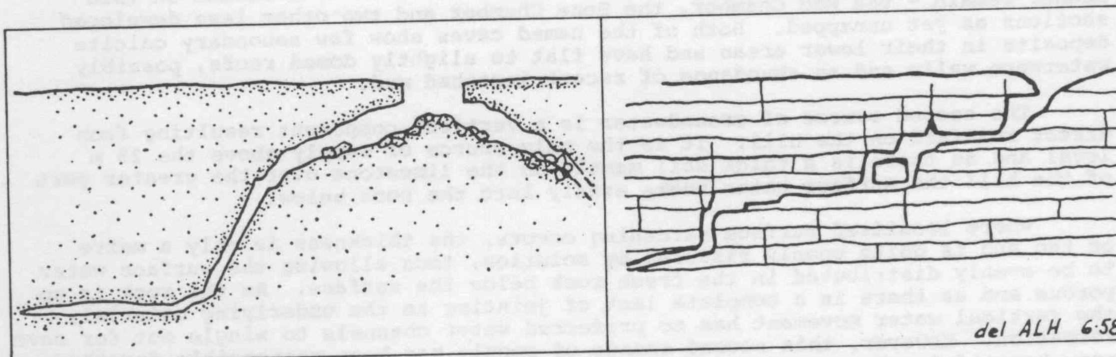

Figure 1. Comparison between Kelly Hill Caves and generalised solution cave.
Left: Kelly Hill Caves, generalised cross section.
Right: Solution cave, generalised long section.

The main group of caves is located in a hill 150 m south of the boundary of the Pleistocene aeolianite. Of major importance is the drainage to the north of this boundary. The drainage across these relatively impervious Recent beds is northwards to South West River, except along their southern margin where there are occasional low-lying areas. There are no signs of surface runoff channels on the aeolianite ridge and consequently no sedimentation results in these marginal areas. The climate of southern Kangaroo Island is strongly seasonal (Figure 2). Swamps develop in these low-lying areas and water is known to rise regularly to a level where it drains southwards visibly into inflow points on the aeolianite ridge. Never has it been observed draining out of these points.

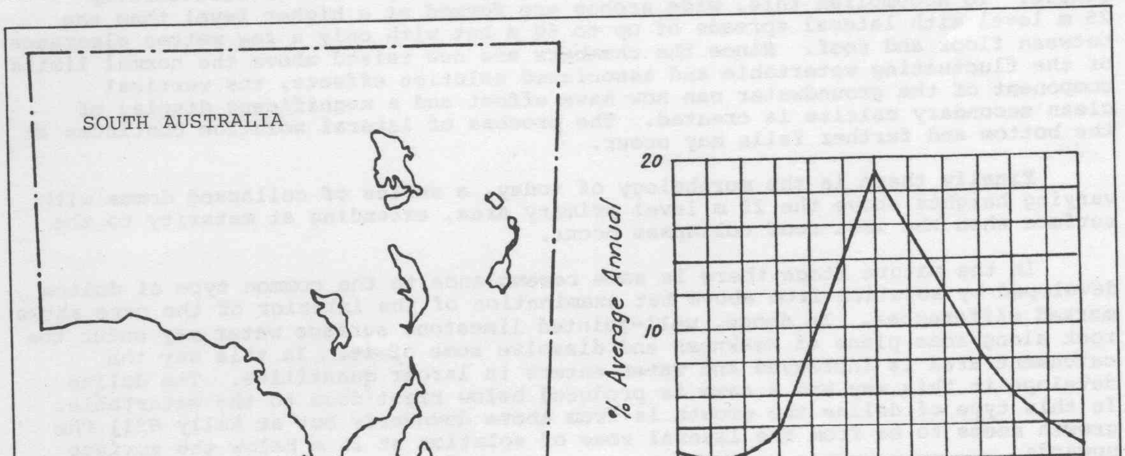

Figure 2. Location map and mean monthly distribution of rainfall at Kelly Hill Caves.

GROUNDWATER MOVEMENTS

There are two groundwater sources for the hill that are of importance. First the seasonal rise in water level gives long periods of exposed surface water in the adjacent low-lying area. A major lateral movement towards the hill causes a corresponding rise in the water table under it. Being mainly surface water, this has a negligible amount of carbonate in solution and the southward movement through the base of the hill is accompanied by a considerable rise in calcium carbonate content in the winter months, but only at a level of 25 m below the top of the hill and below. By the usual process of solution this has led to the evacuation of large areas rather than channels as the very porous nature of the dune limestone would permit easy entry of this water in all directions.

Only four chambers, all more than 25 m down, which have formed in this manner remain - the Mud Chamber, the Bone Chamber and two other less developed sections as yet unmapped. Both of the named caves show few secondary calcite deposits in their lower areas and have flat to slightly domed roofs, possibly waterworn walls and an abundance of recent inwashed mud.

The second source of groundwater is a vertical component resulting from direct rainfall on the hill. It is the only source of supply above the 25 m level and as there is a thick soil mantle on the limestone over the greater part of the hill the surface water soaks evenly into the rock below.

Where localised surface hardening occurs, the thickness is only a metre or two and is quite openly fissured by solution, thus allowing the surface water to be evenly distributed in the fresh rock below the surface. As the rock is so porous and as there is a complete lack of jointing in the underlying material, the vertical water movement has no preferred water channels to single out for cave formation. However, this second source of supply has been responsible for the many beautiful and varied secondary deposits for which the Kelly Hill caves are mainly known.

INFLUENCE OF LITHOLOGY ON THE CAVES

Given the two distinct groundwater movements and the extremely porous nature of the rock, the lateral water movement can dissolve out areas of considerable lateral spread below a particular level and this leads to large, unsupported, flat roofs (Figure 3).

Had the bedrock been more dense and jointed, then, no doubt, self-supporting tunnels would have been created. The aeolianite is unable to support itself after a certain stage of cave development is reached and roof collapses occur. These will continue until the resulting caves take up a shape that is structurally stable. To accomplish this, wide arches are formed at a higher level than the 25 m level with lateral spreads of up to 60 m but with only a few metres clearance between floor and roof. Since the chambers are now raised above the normal limits of the fluctuating watertable and associated solution effects, the vertical component of the groundwater can now have effect and a magnificent display of clean secondary calcite is created. The process of lateral solution continues at the bottom and further falls may occur.

Finally there is the morphology of today, a series of collapsed domes with varying heights above the 25 m level primary area, extending at maturity to the surface when the last roof collapses occur.

In the mature stage there is some resemblance to the common type of doline developed by solution from above but examination of the interior of the cave shows marked differences. In dense, well-jointed limestone surface water may enter the rock along some plane of weakness and dissolve some of it. In this way the catchment area is increased and water enters in larger quantities. The doline develops in this way and a cave is produced below right down to the watertable. In this type of doline the growth is from above downwards but at Kelly Hill the growth seems to be from the lateral zone of solution at 25 m below the surface upwards.

Again, with the doline due to solution from above, the material on the floor of the caverns developed from them will often be mainly material washed in from the surface, with occasional loose rocks fallen from inside. In the dune limestone caves, the floor material is entirely rubble fallen from inside the cave.

At Kelly Hill, domes have been entered from below, which have not been opened to the surface as yet. As there is here no evidence of disturbance of the covering rock at all, this disproves formation by solution from above.

MECHANICS OF ROOF COLLAPSE

In the Kelly Hill caves, the cross-sections through any of the main passages are remarkably similar, beginning with a cleanly broken, presumably shared fissure at the side, varying in slope from 45° to 60° from the horizontal (Figure 4). In places where they give access, they have been traced from the 25 m level of solution chambers but more generally the clearance between the hanging and the footwall is very small and choked with fallen rubble. At the top of the fissure the cave arches across a distance between 10 and 20 m, averaging about 15 m in a roughly fractured roof, occasionally with loose, hanging blocks of rock.

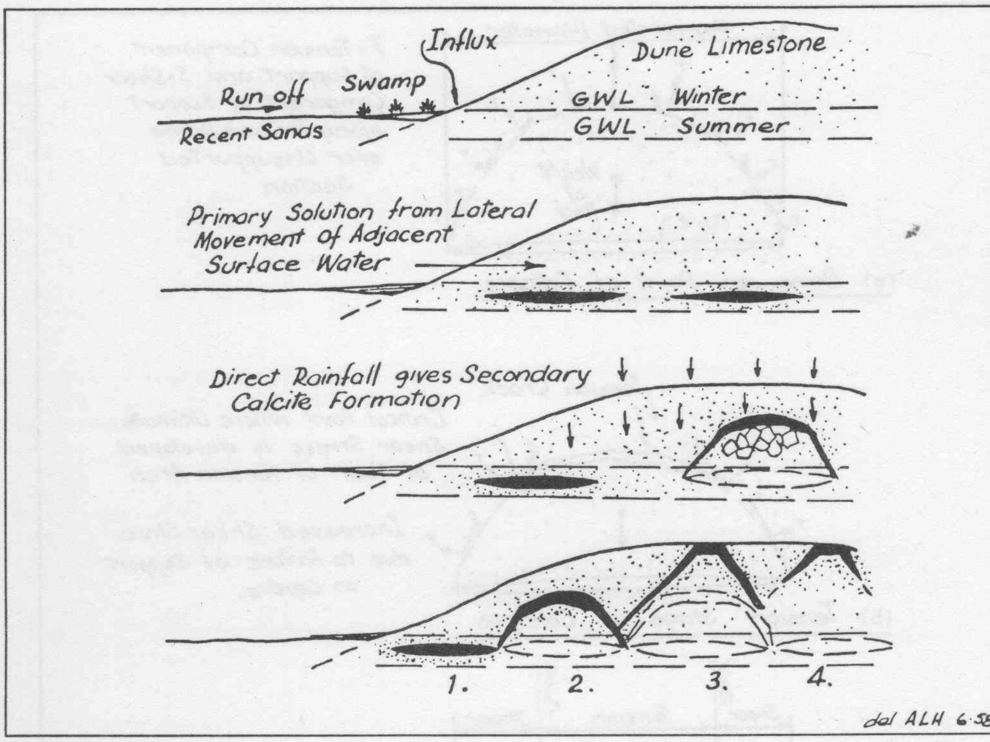

Figure 3. Relationship between groundwater and cave development (N-S section).

This part appears to have fallen out purely as a tension rupture. The floor is mostly covered in this section with broken material from the roof. Symmetrically disposed on the opposite side is another sheared fissure.

The known areas of the cave chambers were projected down to the 25 m level on the assumption that the visible part of the cross-section was continued. The resulting projections showed that the system consisted of seven circular areas of complete breakdown, ranging in diameter from 40 to 60 m at the 25 m solution level, and having a mean base of 52 m. At no point did the projected collapse areas overlap the known solution areas, and in some places where these circles approached one another collapse tunnels have occurred, connecting the circles. There are two major tunnels about 35 m across at the base.

The ratio of the diameters of the circular areas to the width of the tunnels, 52:35, is consistent with mechanical principles as the undisturbed walls in the circular base areas are arches self-supporting across all diameters, whereas the tunnel arches are supported across the width only, there being no support along the axis of the tunnel.

This arch hypothesis needs substantiating by relating these spans to the laboratory test strength of the Kelly Hill dune limestone, though this is a complex task.

A simplified example of cavern breakdown and roof collapse has been treated by Davies (1951). In this case, however, the collapse is thought to be a two stage process of tension and shear. Davies refers to a 'tension dome' in bedded rocks of ellipsoidal shape over an unsupported area. If such a dome on the point of collapse is considered, the main stress pattern will be as shown in Figure 4 (a). The roof section forms a complex beam supported around the tension dome by a combination of tension and shear.

The first stage of collapse probably occurs with tension cracks appearing towards the top of the tension dome (Figure 4 b). Once this occurs, the cracked section gives no support and the load is transferred around the arch where the shear stress is increased. This continues to a critical point when the increasing shear stresses equal the ultimate shear stress of the rock and a shear on both sides of the arch takes place as the second stage of collapse (Figure 4 c).

Whether an interval of time is possible between the two stages or whether the collapse is continuous once it has begun is uncertain. The true stress pattern has been generalised for the purpose of this preliminary explanation. However, it appears that an uncracked flat roof is safe up to about 30 m on width at Kelly Hill and that the presently arched areas are safe from further collapse except for minor roof falls and where weaknesses are introduced by the presence of adjacent domes.

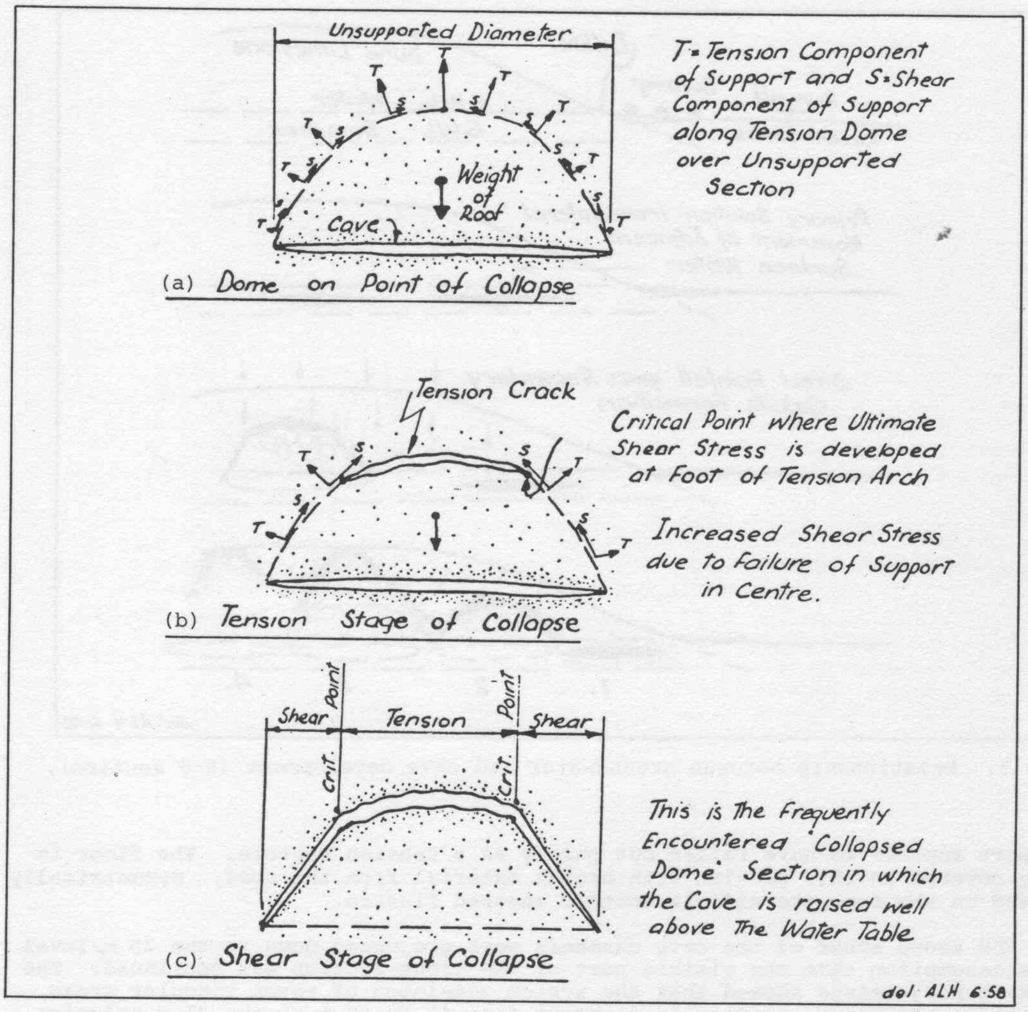

Figure 4. Mechanics of roof collapse.

CONCLUSION

This hypothesis was originated in 1956 after the second expedition of C.E.G.S.A. and the third expedition has shown that every cave in the area so far investigated can be assigned to one of the four stages shown in Figure 3. Several of these water inflows occur along the edge of the ridge and could be indicators of new caving areas in the Kelly Hill Reserve.

It is even more important to test this hypothesis in other porous, soft, limestones in Australia which house caves from western Victoria to Naracoorte in South Australia, Eyre Peninsula, possibly in some cases in the Nullarbor, and in the Southwest of Western Australia.

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A PRELIMINARY SURVEY OF WATER CHEMISTRY IN THE LIMESTONES OF THE BUCHAN AREA UNDER LOW FLOW CONDITIONS.

Mark Ellaway and Brian Finlayson

Abstract

Water samples from selected sites in the Buchan area were collected on two different occasions (survey 1 and survey 2) in an preliminary attempt to characterize the samples taken in terms of chemical composition. Chemical constituents such as Ca^{++}, Mg^{++} and titration alkalinity (as mg/l $CaCO_3$) varied considerably and ranged from 9.0 - 187.0 mg/l, 2.5 - 43.3 mg/l and 27 - 417 mg/l (survey 1) and 3.5 - 188.7 mg/l, 3.5 - 40.0 mg/l and 44 - 424 mg/l (survey 2) respectively. This range in values is attributed to the differing lithology of the sample sites chosen and reflects the geological control on water chemistry of karst landscapes. A computer program for determining equilibrium speciation of aqueous solutions was used to calculate partial pressure of carbon dioxide and saturation indices with respect to calcite and dolomite.

INTRODUCTION

At any particular site of water discharge, be it surface stream, spring or groundwater flow, variations in water chemistry are known to have seasonal and discharge related components. Discharge related components in quality variations arise from the mixing of waters which have taken a variety of pathways through the catchment (see for example, Pinder and Jones, 1969). In karst areas particularly, seasonal components are due to seasonal variations in soil carbon dioxide and soil organic production in addition to seasonally influenced variations in discharge. These various components in water chemistry variations are difficult to isolate and this paper reports an attempt made to sample water representing only the baseflow component of flow emanating from the limestones of the Buchan Area in East Gippsland, Victoria. Samples were taken during drought conditions in 1982-83 and so represent only baseflow. As such it was expected that water quality would be essentially controlled by lithology.

THE AREA AND STUDY METHODS

Geology

The limestone area at Buchan is some 350 km east of Melbourne in East Gippsland and is an example of "karst barré" (Sweeting, 1960). Predominantly calcareous sediments of Early Devonian age (the Buchan Group) occupy a basin-like depression in the Lower Devonian Snowy River Volcanics (Vanderberg, 1976). The Buchan Group is composed of three main subunits: i) the Buchan Caves Limestones; ii) the Taravale Formation and iii) the Murrindal Limestone. These units extend over an area some 20 km long (N-S) and 2 - 10 km wide (E-W) as shown in Figure 1 (Teichert and Talent, 1958).

The oldest of the three main subunits, the Buchan Caves Limestone disconformably overlies the Snowy River Volcanics (Husain, 1981) and reaches a thickness of 370 m at Buchan. It begins with the lenticular Spring Creek Member which consists of terrigenous clastic sediments derived from the erosion of the Snowy River Volcanics (Husain, 1981). At Buchan the Spring Creek Member is followed by 30 - 40 m of poorly fossiliferous dolomite and dolomitic limestone and grades into fairly pure limestone. Conformably overlying this unit is the Taravale Formation a thick sequence of interbedded mudstones and calcareous mudstone (550 m at Buchan) which occupies most of the southern part of the Buchan Basin (Teichert and Talent, 1958).

Towards the north, a tongue of Taravale Formation (the Pyramids Member) separates the Murrindal and Buchan Caves Limestone. The Murrindal Limestone is a lenticular limestone which grades laterally with, and partly overlies the Taravale Formation. This formation is composed of two members; the lower McLarty Member comprises 60 - 190 m of well-bedded fissile limestone and minor mudstone, and the upper Rocky Camp Member, consisting of 60 - 100 m of coarse calcarenite with coraline boulders (Teichert and Talent, 1958; O'Shea, 1980; Vanderberg and O'Shea, 1981).

Small outliers of Buchan Caves Limestone occur and are widely distributed over the Snowy River Volcanics e.g. New Guinea, Jacksons Crossing and The Basin. Non-marine gravels to the south-west and north of Buchan are associated with Tertiary uplift and earth movement in the highlands, and subsequent deposition is limited to stream alluvium and colluvial deposits (Douglas, 1977).

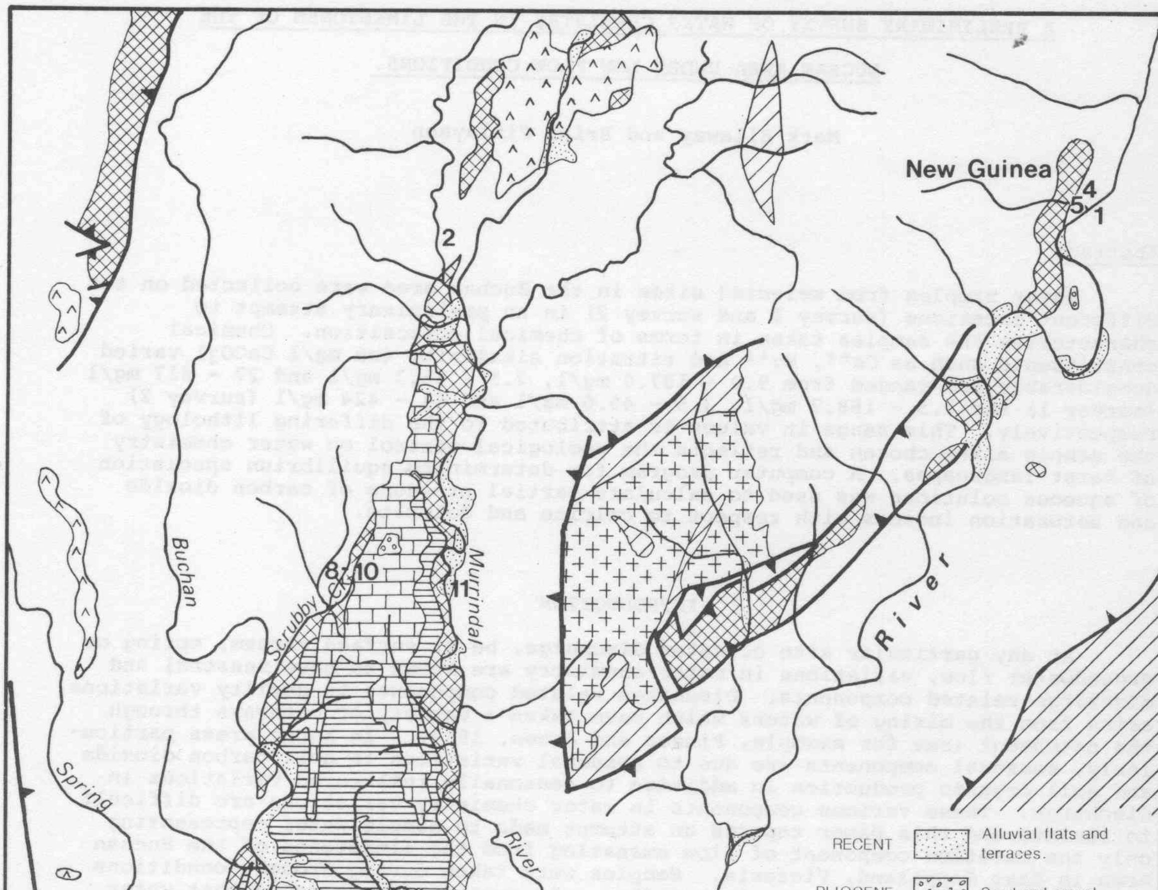

Figure 1. Geology of the Buchan area and sample sites.

TABLE I: SITE DESCRIPTION.

Site No.		Flow state Survey 1 (22nd - 24th) Oct. 1982	Flow state Survey 2 (22nd - 24th) Feb. 1983
A. Major through Streams:			
1	Snowy River at New Guinea (above limestone outcrop)	Flowing	Low Flow
2	Murrindal River (near Murrindal Homestead)	Flowing	Pools only
3	Buchan River (at main road bridge in town)	Flowing	Pools only
B. Resurgences and exsurgences without tufa deposits:			
4	Resurgence at New Guinea 2 (NG-2)	Flowing	Pool only
5	Resurgence at New Guinea 5 (NG-5)	Flowing	Pool only
6	Exsurgence at Moons Cave (B-54E) (Buchan Caves Reserve)	Flowing	Low Flow
7	Duke's resurgence (B-4) (Buchan Caves Reserve)	Flowing	Low Flow
C. Resurgences and exsurgences with tufa deposits:			
8	Scrubby Creek 1 (M-49) (Pool inside cave near spring; "calcite rafts")	Flowing	Low Flow
9	Scrubby Creek 2 (Spring at top of tufa terraces)	Flowing	Low Flow
10	Scrubby Creek 3 (stream as it leaves tufa terraces)	Flowing	Low Flow
11	M-4 exsurgence	Flowing	No Flow
12	Bitch of a Ditch resurgence (EB-49)	Flowing	Low Flow
D. Other sites:			
13	B-67 Cave stream	Flowing	Low Flow
14	Spring at sink (Where stream flow from the Snowy River Volcanics sinks in the Buchan Caves Reserve)	Flowing	Pools only
15	Farm dam (On Buchan Caves Limestone near B-67)	No sample	Standing water

Flow - visual comparison.

The Early Devonian limestone area of the Buchan District represents one of the largest outcrops of cave and karst forming limestone in South-Eastern Australia and approximately 300 caverns, sinks and karst features have been recognized by the Australian Speleological Federation (Matthews, 1979).

Drainage of the area is provided by the southerly flowing Buchan and Murrindal Rivers, both of which have their headwaters in the Snowy River Volcanics. The Murrindal River flows approximately along the eastern boundary of the Buchan Caves Limestone and the Snowy River Volcanics. The Buchan River follows a similar contact on the west, but cuts across the Buchan Group towards the east and meets with the Murrindal where the former emerges from the Buchan Group. The Buchan River continues eastwards through Snowy River Volcanics until its confluence with the Snowy River. A number of intermittent streams such as Wilson Creek, Tara Creek and Spring Creek flow into the Buchan River (Figure 1).

In this study water samples were taken from exsurgences and resurgences, cave pools and from the main streams. A brief description of each sample site is given in Table I and shown in Figure 1.

Climate

The Buchan District has a warm temperate climate (Koppen-Geiger classification Cfb). Rainfall varies considerably with topography, ranging from around 1500 mm per annum in the highlands (New Guinea) to 815 mm at Buchan (L.C.C., 1982).

TABLE II: RAINFALL DATA FOR BUCHAN FOR THE PERIOD 1883-1983.

Month	J	F	M	A	M	J	J	A	S	O	N	D	Total
Rainfall (av.)	67	59	60	65	67	80	64	60	69	79	71	74	815
Wettest Year (1974)	72	49	16	193	190	187	188	99	98	124	129	49	1394
Driest Year (1979)	17	6	89	37	64	14	14	62	31	51	47	7	443
1982	83	4	119	18	31	48	85	10	55	50	10	52	565
1983	39	15											

All values in mm.

Maximum air temperatures for sampling days -:

October	22nd	19°C	23rd	16°C	24th	19°C
February	22nd	33°C	23rd	25°C	24th	27°C

Rainfall is fairly evenly distributed throughout the year, for instance at Buchan, the maximum and minimum monthly rainfall averages are 80 mm and 59 mm respectively. Table II contains average monthly rainfall data for Buchan and rainfall data for the period Feb. 1982 to Feb. 1983. Using rainfall deciles as drought indicators (Gibbs and Maher, 1967), 1982 was the 9th driest year on record for the period 1883-1983 and as such falls in decile range 1 i.e. the lowest 10%, and using the classification of Gibbs and Maher (1967) rainfall for 1982 is "very much below average". Therefore water samples taken should represent the extreme low flow end of the range.

Field and Laboratory Methods

Water temperature, conductivity, dissolved oxygen, pH and Eh values were measured in situ at each site (Figure 1) and are given in Table III. Dissolved oxygen was not measured on survey 2. Temperature, conductivity and dissolved oxygen content were measured using a Yellow Springs Instrument model 33 M SCT and a model 57 oxygen meter respectively. Water temperatures were also measured in the field using a calibrated mercury bulb thermometer (0 - 100°C) as a check against temperatures measured by both the Y.S.I. instruments.

pH and Eh measurements in situ were obtained using a Radiometer PHM 80 digital portable pH meter with the appropriate electrodes. Calibration was carried out in the field after the buffers (pH 4.0 and 7.0) and Zobells solution (Carver, 1971; for Eh measurement) were bought to groundwater temperature.

Water samples were collected in acid-washed (6M HNO_3) polyethylene bottles after rinsing 3 times at each site and placed on ice. Depending upon which particular chemical analysis was required sample preservation techniques were used in accordance with methods available (Parker, 1972; Stainton et al, 1977; U.S.E.P.A., 1979).

Methods used for the chemical analyses of the water samples collected were also chosen from the above methods manuals. Calcium and magnesium were determined by atomic absorption spectroscopy and sodium and potassium by flame photometry. Alkalinity was determined within 6 hours of sampling by titration against standard 0.02 M HCl to pH 4.5. Nitrate was determined using an Orion nitrate electrode (survey 1 only). Chloride was determined using a Corning model 901 chloride meter and sulphate was determined gravimetrically (survey 1 only).

RESULTS AND DISCUSSION

The results obtained from the chemical analyses and by computation are shown in Tables IV and V respectively. The data in Table V was obtained using the computer program WATSPEC (Wigley, 1977). WATSPEC calculates speciation within the aqueous phase and derives data such as the mineral saturation index and the logarithm of the partial pressure of carbon dioxide with which the solution is in equilibrium (-log(PCO_2) in atmospheres).

The mineral saturation index of calcite (SIc), for example, is defined as

$$SIc = \frac{\{IAP\}}{Kc}$$

where, IAP is the ion activity product of the dissociation products (i.e. Ca^{++} and $CO_3^{=}$) and Kc is the dissociation constant for calcite. For SIc <0, the solution is undersaturated or aggressive with respect to calcite and for SIc >0 supersaturation occurs. In this paper log(PCO_2) values are used instead of -log(PCO_2). For a solution in equilibrium with the atmosphere log(PCO_2) = -3.5.

During survey 2, a number of sites which were sampled in survey 1 were not flowing and pools of water were sampled. It is these sites which show the greatest amount of variability in terms of chemical composition. This is most noticeable in the results, especially for Buchan River where concentrations of Ca^{++}, Mg^{++}, Na^{+}, Cl^{-} and titration alkalinity increased approximately 5 - 8 times. Other sites such as Spring Creek, New Guinea 2 (NG-2), New Guinea 5 (NG-5) and Murrindal River showed quite significant increases in the concentrations of certain ions. These increases could in part be attributed to a concentrating effect due to reduced flow rates, but it cannot fully explain sites such as NG-2 and NG-5 where only Ca^{++}, Mg^{++} and titration alkalinity increased significantly.

The other sites sampled during survey 2 all showed reduced discharge compared with survey 1 (visual comparison). The chemical composition of water from these sites, particularly those from either exsurgences, resurgences or cave pools were quite similar on both surveys, e.g. with Mg/Ca ratios (e.p.m.) being B-67 0.38 - 0.32, Dukes 0.34 - 0.33, Scrubby Creek 1, 2 and 3 0.19 - 0.16, 0.21 - 0.17, 0.24 - 0.17 and Bitch of a Ditch 0.53 - 0.50 for survey 1 and 2 respectively.

TABLE III: Physical parameters measured <u>in situ</u>; Survey 1(22nd - 24th Oct. 1982) and Survey 2 (22nd - 24th Feb. 1983).

Site	Temperature (°C) 1)	2)	pH 1)	2)	Conductivity (µmhos) 1)	2)	Eh (mV) 1)	2)	Dissolved (mg/s) Survey 1 only	Oxygen (% Sat.) Survey 1 only
A. Major through streams.										
Snowy River	16.0	24.0	7.80	8.15	135	216	401	386	8.7	88.3
Buchan River	14.5	21.5	7.73	8.11	92	600	504	412	9.5	93.1
Murrindal River	14.0	31.0	7.50	8.18	271	522	430	361	9.8	95.2
B. Resurgences and Exsurgences.										
New Guinea 2	13.5	16.8	7.80	7.67	275	514	411	422	9.9	95.2
New Guinea 5	14.0	15.0	8.00	7.45	245	517	414	426	10.2	99.0
Moons	13.8	16.0	7.71	7.49	619	652	463	443	9.6	93.2
Scrubby Creek 1	16.0	17.0	7.91	7.68	603	600	419	413	10.1	102.5
Scrubby Creek 2	16.5	17.0	7.75	7.66	557	600	418	422	9.8	100.5
Scrubby Creek 3	18.0	19.5	8.15	7.90	513	570	406	414	11.4	120.6
Dukes	17.0	18.0	6.93	6.78	1500	1616	437	483	7.3	75.7
B-67	17.0	19.0	6.85	7.09	1824	1771	412	369	5.2	53.9
Bitch of a Ditch	18.0	17.2	7.00	7.19	1003	700*	418*	412	8.8	93.1
M-4	13.2	-	7.90	-	534	-	414	-	9.6	91.4
Other sites.										
Spring Creek	12.0	19.0	7.05	7.10	338	851	457	381	9.6	89.7
Farm dam	-	23.0	-	7.96	-	247	-	317	-	-

1) Survey 1. 2) Survey 2. - No sample. * Error in reading

Conductivity at 25°C.

<u>Survey 1</u>

Water temperatures ranged from 12.0°C at Spring Creek to 18.0°C at both Bitch of a Ditch and Scrubby Creek 3. pH, Eh, conductivity and dissolved oxygen content (D.O.) ranged from 6.85 (B 67) to 8.15 (Scrubby Creek 3), 406 mV (Scrubby Creek 3) to 504 mV (Buchan River), 72 µmhos (Buchan River) to 1520 µmhos (B 67) and 5.2 ppm (B 67) to 11.4 ppm (Scrubby Creek 3).

Saturation indices for calcite (SIc) and dolomite (SId) varied from -1.28 and -2.95 in unsaturated water, such as Buchan River to 0.80 and 0.98 respectively in saturated water at Scrubby Creek 3. Log(PCO_2) values ranged from -3.25 at Buchan River to -1.25 at B 67. Of the 14 water samples analysed, 8 were saturated with respect to calcite and 6 of these were similarly saturated with respect to dolomite. Visible signs of carbonate saturation such as tufa terraces and "calcite rafts" were noticeable at 6 out of the 8 sites, B 67 and Moons being the exceptions. Calcite rafts were noticed at Dukes but no tufa terraces exist.

At Scrubby Creek (see site description, Table I), calcium levels dropped from 85.2 mg/l (Scrubby Creek 1) to 69.1 mg/l (Scrubby Creek 3) while magnesium levels remained reasonably constant over the distance of approximately 150 m. Values for SIc, SId, D.O. and pH all showed an initial decrease from the cave water first emerging and then an increase to the site at the end of the tufa terraces, e.g. SIc 0.68 to 0.51 to 0.80, SId 0.62 to 0.32 to 0.98, D.O. 10.1 to 9.8 to 11.4 ppm and pH 7.91 to 7.75 to 8.15. Log(PCO_2) showed the opposite trend, increasing from -2.54 to -2.38 and then decreasing to -2.84. Dissolved carbon dioxide calculated from the formula given in Skougstad et al (1979) gave values of 5.5 to 7.8 to 2.7 mg/l respectively. Temperature increased slightly from 16.0 to 16.5 to 18.0°C at the respective sites.

In their studies of tufa depositing streams Brook and Ford (1982) and Dunkerley (1981) noted similar observations. Brook and Ford (1982) in their study at Tufa Creek (subarctic Nahanni karst, N.W.T.), observed an air temperature rise from 2.0°C at spring outlet to 13.0°C where the creek disappeared 600 m away, pH rose from 7.1 to 8.4, SIc and SId showed increases of -0.34 to 1.04 and -1.35 to 1.60 respectively. Magnesium content remained fairly constant, but calcium levels dropped from 277 to 229 mg/l and log(PCO_2) fell from -1.63 to -3.08. Dunkerley (1981) in his study of a tufa depositing stream (near Mt. Etna, Queensland) noted changes over a distance of 430 m such as calcium and magnesium levels decreasing (calcium 4.63 to 3.39 mM and magnesium 2.74 to 2.28 mM); log(PCO_2) values fell from -1.08 to -1.99; SIc and SId increased from 0.73 to 1.23 and -1.08 to 2.38 respectively.

TABLE IV: RESULTS OF CHEMICAL ANALYSES.

(All values are in mg/l except alkalinity which is expressed as mg/l $CaCO_3$).

Site		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	Alkalin.	$SO_4^{=}$	NO_3^{-}
Snow River	1)	11.0	5.7	9.1	0.7	14.0	36.1	1.2	<0.1
	2)	11.5	9.1	14.2	2.1	23.0	67.8	-	-
Buchan River	1)	9.0	2.5	5.5	0.7	8.0	27.3	3.7	<0.1
	2)	70.1	14.7	26.5	1.9	60.0	207.2	-	-
Murrindal River	1)	18.9	11.3	16.9	1.8	36.0	65.1	6.6	<0.1
	2)	54.7	16.5	23.8	2.3	43.0	194.7	-	-
New Guinea 2	1)	24.5	8.1	15.2	2.2	21.0	90.0	8.6	0.2
	2)	70.1	12.6	14.5	2.2	24.0	225.1	-	-
New Guinea 5	1)	27.3	5.5	11.8	1.6	16.0	86.7	7.8	0.2
	2)	73.6	13.1	11.8	1.4	17.0	226.9	-	-
Moons	1)	74.7	18.4	21.8	1.5	45.0	236.8	9.9	0.3
	2)	90.7	15.7	21.0	3.1	43.0	264.7	-	-
Scrubby Creek 1	1)	85.2	9.9	15.8	1.0	30.0	228.9	6.6	0.5
	2)	89.0	8.7	16.2	1.3	35.0	234.9	-	-
Scrubby Creek 2	1)	81.0	10.4	15.7	1.0	31.0	225.0	7.0	0.5
	2)	96.8	10.0	16.2	1.2	36.0	250.4	-	-
Scrubby Creek 3	1)	69.1	10.3	15.8	1.0	31.0	196.3	10.3	0.5
	2)	85.6	9.0	16.2	1.2	36.0	228.2	-	-
Dukes	1)	163.8	34.3	90.0	2.7	220.0	366.3	24.3	0.4
	2)	178.3	36.2	83.9	3.9	256.0	390.5	-	-
B-67	1)	187.0	43.2	102.5	2.9	306.0	405.9	33.3	0.3
	2)	188.6	39.9	110.0	2.9	305.0	408.8	-	-
Bitch of a Ditch	1)	122.4	39.3	31.5	1.2	65.0	416.7	12.1	0.3
	2)	126.6	38.3	33.0	1.2	68.0	424.2	-	-
M-4	1)	62.5	14.1	16.9	1.8	34.0	193.7	10.3	0.5
Spring Creek	1)	17.7	14.9	27.3	2.7	50.0	78.6	9.1	0.1
	2)	91.2	29.9	41.7	10.3	82.0	337.7	-	-
Farm dam	2)	4.1	6.7	23.2	12.7	38.0	43.9	-	-

\- Sample not analysed. 1) Survey 1 2) Survey 2.

TABLE V: COMPUTED DATA.

Site	SIc 1)	SIc 2)	SId 1)	SId 2)	log(PCO_2) 1)	log(PCO_2) 2)	Mg/Ca (e.p.m.) 1)	Mg/Ca (e.p.m.) 2)
Snowy River	-1.0	-0.27	-2.10	-0.37	-3.20	-3.24	0.85	1.32
Buchan River	-1.28	0.83	-2.95	1.23	-3.25	-2.76	0.47	0.35
Murrindal River	-0.87	0.90	-1.80	1.61	-2.66	-2.80	0.98	0.50
New Guinea 2	-0.34	0.38	-1.00	0.21	-2.83	-2.29	0.54	0.30
New Guinea 5	-0.10	0.15	-0.72	-0.27	-3.04	-2.08	0.34	0.29
Moons	0.40	0.34	0.37	0.11	-2.33	-2.05	0.42	0.17
Scrubby Creek 1	0.68	0.50	0.62	0.19	-2.54	-2.29	0.19	0.16
Scrubby Creek 2	0.51	0.53	0.32	0.28	-2.38	-2.24	0.21	0.17
Scrubby Creek 3	0.80	0.72	0.98	0.70	-2.84	-2.51	0.24	0.17
Dukes	0.11	0.03	-0.24	-0.41	-1.36	-1.18	0.34	0.33
B-67	0.11	0.39	-0.20	0.33	-1.25	-1.47	0.38	0.32
Bitch of a Ditch	0.16	0.35	0.04	0.39	-1.37	-1.55	0.53	0.50
M-4	0.44	-	0.38	-	-2.61	-	0.37	-
Spring Creek	-1.32	0.07	-2.58	-0.11	-2.14	-1.55	1.37	0.54
Farm dam	-	-1.10	-	-1.72	-	-3.24	-	2.68

1) Survey 1 2) Survey 2 - No sample taken.

Brook and Ford (1982) attributed the chemical changes noted in their study to a rapid loss of CO_2, brought about by an increase in water temperature (therefore reduced solubility) and by disequilibrium between water PCO_2, and atmospheric PCO_2 (log PCO_2 fell from -1.63 to -3.08). They concluded that supersaturated conditions were due to the fact that CO_2 degassing occurs more rapidly than the precipitation of calcite, and to the inability of dolomite to precipitate even in supersaturated conditions. Dunkerley (1981) concluded that rapid degassing (temperature remained constant), especially at places of good aeration was the main cause of carbonate precipitation, but that the loss of CO_2 to the air proceeded more rapidly than the deposition of carbonates i.e. SIc and SId both increased downstream.

The results obtained in this survey follow similar trends to those observed by the above mentioned researchers in that the loss of CO_2 to the air occurs more rapidly than the deposition of carbonates. The distance over which Scrubby Creek can be studied is shorter than the distances mentioned above (Brook and Ford, 1982; Dunkerley, 1981) due to mixing with water draining the Snowy River Volcanics just below Scrubby Creek 3.

B-67 has been shown to be linked to the resurgence at Dukes by tracing with fluorescent dye (L. Mill, pers. comm.) a straight line distance of approx. 2 km. The lower levels of chemical constituents at Dukes when compared to levels obtained at B-67 indicate either a loss from solution (precipitation) or dilution with groundwater with lower concentrations. The presence of "calcite rafts" at Dukes could in part explain the loss of some Ca^{++} and Mg^{++} but the loss in Na^+ and Cl^- is harder to explain, particularly Cl^-, a loss of 86 mg/l and tends to indicate mixing with other waters, possibly derived from the overlying Taravale Formation or from the neighbouring Snowy River Volcanics (which would be expected to have concentrations similar to those in Spring Creek).

NG-2 and NG-5 are reasonably similar in chemical composition, but considerably lower in concentration than the water samples taken from other sites in the Buchan Caves Limestone. This could be due to water draining the Snowy River Volcanics and then passing through the limestone. Other sites such as Moons, M-4 and Bitch of a Ditch were saturated with respect to calcite and dolomite. Extensive tufa terraces occur at Bitch of a Ditch and to a lesser extent at M-4 but are not noticeable at Moons or Dukes.

The other sites sampled (Snowy River, Buchan River, Murrindal River and Spring Creek) all drain from Snowy River Volcanics before passing into limestone areas and are undersaturated with respect to calcite and dolomite.

TABLE VI: Comparison of chemical composition of Snowy and Buchan Rivers with S.R. and W.S.C. data.

Site	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	Alk.	E.C.	$SO4^{=}$
Snowy River	4.6-15.0	3.2-11.0	3.6-17.0	0.5-1.9	8.4-24.0	24-72	81-225	<2-6
mean (n=15)	9.3 (3.0)	6.4 (2.1)	11.0 (3.7)	1.3 (0.4)	17.0 (5.0)	48 (15)	150 (39)	-
Survey 1	11.0	5.7	9.1	0.7	14.0	36.1	135	1.2
Survey 2	11.5	9.1	14.2	2.1	23.0	67.8	216	-
Buchan River	3.3-20.0	1.5-6.0	3.7-12.0	0.7-1.9	3.4-25.0	18-67	35-210	<1-4
mean (n=15)	7.7 (4.2)	3.1 (1.1)	6.7 (2.2)	1.3 (0.4)	8.8 (5.2)	33 (13)	94 (43)	-
Survey 1	9.0	2.5	5.5	0.7	8.0	27.3	92	3.7
Survey 2	70.1	14.7	26.5	1.9	60.0	207.2	600	-

All results are in mg/l (except alkalinity, mg/l $CaCO_3$ and E.C. umhos).

n = number of samples ( ) standard deviation.

Survey 2

Temperatures of the surface waters sampled in this survey were 7 - 17°C higher than those of survey 1 which is consistent with the differences in air temperature between the two surveys (Table II). Of the other sites, Bitch of a Ditch showed a decrease of 0.8°C and increases of 1°C or less were recorded at NG-5, Scrubby Creek 1, Scrubby Creek 2 and Dukes, while NG-2, Scrubby Creek 3, Moons and B-67 recorded increases of 3.3°C, 1.5°C, 2.2°C and 2.0°C respectively. The small decrease at Bitch of a Ditch may not be significant and the ~ 1°C increase probably represents seasonal temperature fluctuations in the groundwater system. Sites with larger increases may be more closely linked with surface and near-surface storage areas and Scrubby Creek 3 obviously reflects exposure to higher air temperatures during flow across the tufa terraces.

Sites where flow had ceased at the time of the second survey (see Table I) will not be discussed further here since it is impossible to separate out changes caused by evaporation from other changes, though, as mentioned earlier, the results show that these sites do not show simple evaporative concentration for all constituents.

Samples from Scrubby Creek showed an increase in SIc and SId going from sites 1 to 2 to 3 (SIc 0.50 to 0.53 to 0.72, SId 0.19 to 0.25 to 0.70) although CO_2 (dissolved) increased from 9.6 to 10.7 mg/l and then dropped to 5.6 mg/l at site 3.

B-67 and Dukes were quite similar in chemical composition to the respective samples from survey 1 and showed the same relationships to each other noticed in survey 1 i.e. lower levels at Dukes, this time the decrease in Cl^- was 49 mg/l. Water samples from Bitch of a Ditch and Moons were also quite similar to levels observed for these sites in survey 1, while the sample from the Snowy River showed higher levels in all constituents except for Ca^{++}.

As described earlier, survey 2 was carried out well into an extended drought period (Table II). The only through stream still flowing at the time of survey 2, the Snowy River, showed concentration increases in all measured constituents (except as noted above) consistent with the known and widely reported (see, for example, Gregory and Walling, 1973) inverse correlations between dissolved species and discharge. Water quality data are available for both the Buchan and Snowy Rivers (S.R. + W.S.C., unpublished data) and are compared with the present results in Table VI. Note that results for the Buchan River in survey 2 lie outside the published range and confirm our observation that the pools are no longer connected to a flow system and are being concentrated by evaporation.

For the other sites we believe that these results represent extreme low flow conditions and as such are end members of the concentration ranges to be expected at these sites. Future studies will attempt to characterise seasonal and discharge-related behaviour. For the present results, the extent of variation within this relatively small limestone area is quite large and the explanations for it are not readily apparent. Little is known about the source of spring waters in this area other than the traced connection between B-67 and Dukes mentioned above. Possible causes of the observed differences include lithological variations within the limestones, and characteristics imposed on the waters prior to their entry into the limestone system. These characteristics could be derived from variations in the overlying soil cover, contributions from the neighbouring Snowy River Volcanics and, for the southern sites, from deposits of Tertiary sands and gravels which overlie the limestones in the south (Figure 1). Residence times of water in the limestones are not known and could be a contributory factor. Certainly those sites which continued to flow throughout the drought period must have very long residence times.

A further variation between the spring sites which has yet to be explained concerns the deposition of tufa. Tufa is being actively deposited at Scrubby Creek, M-4, and Bitch of a Ditch and although calcite rafts are present at Dukes, no tufa is being laid down. No consistent differences can be found between the tufa sites and those without it. Bitch of a Ditch, where extensive tufa deposits are present, is much closer in terms of water chemistry to Dukes and B-67 (which both lack tufa) than it is to the other tufa-depositing springs. The solution to this problem must await further detailed work in the area.

CONCLUSION

This paper reports the results of a preliminary study of water in a karst environment. The samples taken were representative of baseflow conditions and hence are end members of the concentration range to be expected. The between site variation in chemical composition is attributed to the differing lithology of the sample sites selected.

ACKNOWLEDGEMENTS

Appreciation is expressed to Nicholas and Sue White and to Elizabeth Gibson for their assistance on the sampling trips. Thanks are also due to the Chairman and staff of the Geography Department.

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DETERMINATION OF THE CAUSES OF AIR FLOW IN COPPERMINE CAVE, YARRANGOBILLY.

N.A. Michie

Abstract

Observations of air flow through Coppermine Cave, Yarrangobilly, are reported. A model is presented of the cave as a two entrance system with air flow dominated by air density differentials with little sensitivity to surface wind. The measurement technique and data analysis are described.

INTRODUCTION

The Coppermine Cave is an active outflow cave draining into the Yarrangobilly River at the northern end of the limestone at Yarrangobilly in the Kosciusko National Park, New South Wales. The limestone forms an undulating shelf within the Yarrangobilly River valley and is approximately 7 km long and approximately 1 km wide. The area and the cave have been described by Rose (1964); a detailed map of the cave is to be found in Hurst and Hurst (1982a, 1982b).

The Coppermine Cave is a nearly horizontal passage which follows a stream for about 200 m to where the stream sumps. The cave can be followed further at a level approximately 10 m higher than the stream bed for another 200 m. Some 250 m from the entrance there is a constriction of about 0.1 m^2 which provides a convenient cross-section for the measurement of air flow. At the far limit of access there is a small orifice in which air flow can be detected; survey has shown this point to be about 60 m below the surface. No second entrance to the cave is known. Pavey and Warild (1977) discussed the relationship of Coppermine Cave to other caves scattered over several square kilometres of catchment area but although the presence of some water connections has been established by water tracing there is no reason to assume that the air flow follows the water flow.

Air flow in the cave is obvious only at the far end of the cave and at the constriction where a locked bar has been installed to protect some of the cave from further vandalism. The rest of the cave has such a large cross section that the air flows at velocities too low to be perceived by people and even too low for most measuring instruments.

The causes of air flow in caves have been described by many authors. Balch (1900) described the two entrance cave with air flow induced by air density differences between inside and outside air columns; and credits his account to Parrot (1815). More recently, Trombe (1955), Gèze (1965), Wigley and Brown (1976), and Bögli (1980) have described the processes that cause air flow in caves. There are four main causes:

(a) Density differences between the air inside and outside a cave.

(b) Wind blowing over the cave entrance.

(c) Changes in barometric pressure outside the cave.

(d) Water flowing inside the cave.

In this case it is known from earlier work (Michie and Halbert, 1980) that the Coppermine Cave air flow responds to changes in external air density. This indicates that the cave has a second entrance and is a two entrance or chimney cave. Such caves may also be sensitive to surface winds.

The aims of this work were to further investigate the climate of Coppermine Cave and to continue the development of instruments and techniques. Measurements were sought of suitable reliability to apply objective methods of evaluating aspects of cave climates, in this case air flow and the determination of the influences of air density and surface wind.

PREVIOUS WORK

The difficulty of observation in caves is reflected by the relative lack of published material on cave observations compared to the amount of material published about theorised cause and effect. Conn (1966) examined Wind Cave and

Jewel Cave, Dakota, which respond to barometric pressure changes. Air flow was measured with an ingeniously constructed vane-pendulum coupled to a recording chart. Wigley et al. (1966) made periodic measurements of air flow to show the relationship to barometric pressure in Mullamallang Cave in the Nullarbor Plains, Australia. Dénes (1969) made periodic measurements of air flow with a cup anemometer at "Freedom" Cave, Hungary, to show the relationship between air flow and surface conditions. István (1976) used periodic measurements to establish relationships between air flow in caves and surface conditions for several caves in Hungary.

Halbert and Michie (1982), examined the Bullio Cave at Wombeyan, New South Wales. Continuous measurements were used to show the relationship between surface air temperature and cave air flow with temperatures recorded from a radiation shielded psychrometer mounted 1 m above ground level, and air flow recorded from an integrating vane anemometer in a constriction in the cave.

In January 1979 with similar equipment to that used at Wombeyan Caves (Halbert and Michie 1979), measurements were made of conditions at Coppermine Cave, Yarrangobilly. Periodic measurements were made of barometric pressure and continuous recordings were made of surface temperature, humidity and wind and cave air flow. In April 1979 (Michie and Halbert 1980), an attempt was made to collect improved data at Coppermine Cave using a 5 m mast to elevate the surface sensors. The result was frustrated by neutral weather and an equipment failure caused by an animal chewing out lengths of the plastic insulated cables between the instruments and the recorder. Although there was a significant improvement in the precision of the data no valid conclusions could be drawn about the contribution of effects other than air density.

THEORY

For a discussion of the physical models of the processes see Wigley and Brown (1976) or Bögli (1980).

"Reversal" temperature is a useful concept in discussion of chimney or multi-entrance caves with air flow induced by density differentials. Under conditions of constant barometric pressure, air density is largely determined by temperature. As external air temperature rises from a low value, previous air flow in the cave will decrease until at "reversal" temperature the flow will cease. With a further increase of temperature the flow direction reverses. When the outside temperature is below the reversal temperature cold air flows in to the lower entrance, conversely, with the outside temperature above the reversal temperature, warm air flows into the upper entrance.

When the air flow is stationary there are no pressure drops due to flow in the cave and the air is in equilibrium with the cave walls i.e. is at the same temperature as the walls and nearly at saturation if the cave is moist.

The reversal temperature is that value of surface air temperature for which there is no air flow. This definition is not complete unless the humidities of the two air columns are defined. If the outside column is saturated as is the inside column then the reversal temperature is equal to the temperature of the cave averaged over altitude. This can be of great use when, as in Coppermine Cave, part of the cave is not accessible. The reversal temperature can be determined by regression analysis of air velocity on outside air temperature.

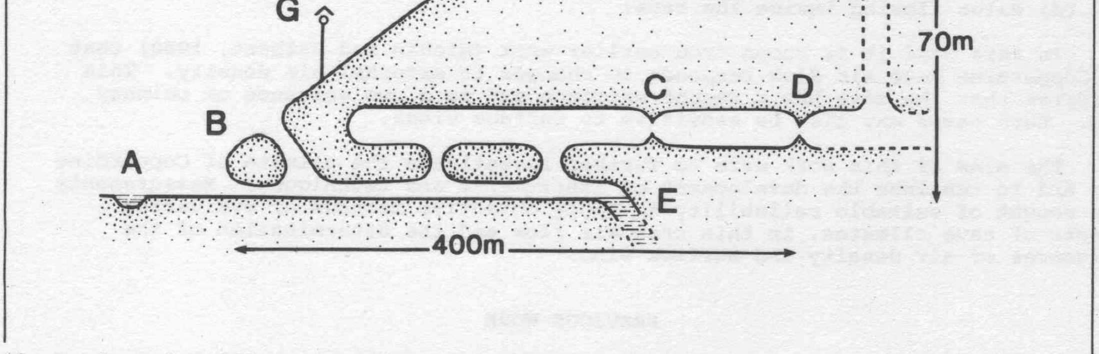


Figure 1. Simplified elevation of Coppermine Cave.
A. River B. Entrance C. Constriction D. Final impasse
E. Stream sump F. Upper entrance G. Surface sensors

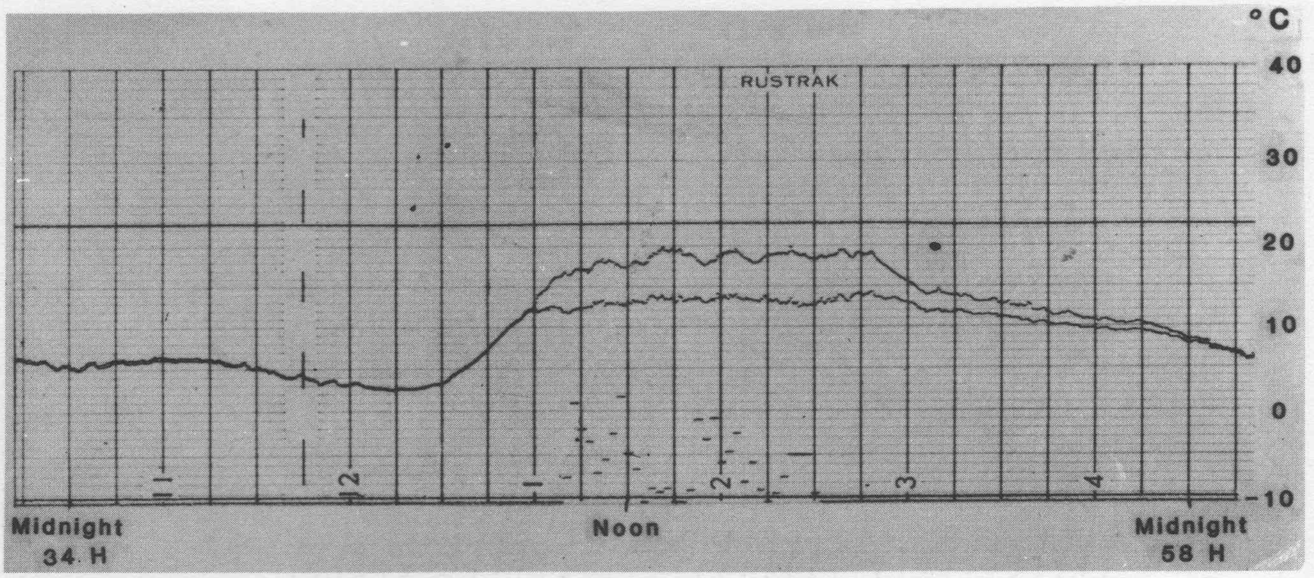


Figure 2. Surface conditions, Yarrangobilly 1982 data.

When the rate of air flow is very low at the time of reversal there is a suspension of another process which, for simplicity, will be called"intrusion". When air is drawn into a cave there is a delay before the air comes to thermal and hygral equilibrium with the walls. The higher the velocity of the air the further it intrudes into the cave before reaching equilibrium. This effect has been analysed by Wigley and Brown (1971), but only for the case with a boundary condition of constant wall temperature. In Figure 1 it will be noted that when cold air intrudes through the lower entrance into the horizontal section of the cave the conditions for reversal will not be changed until the temperature is affected in the vertical section. When warm air intrudes through the upper entrance into the vertical section there is an immediate increase in the average column temperature and a consequent reduction in the driving force of the flow. Intrusion is hard to quantify in Coppermine Cave but it is a potential source of non-linearity in the density - flow relationship. Another factor causing non-linearity in the relationship between flow and density differences is pressure drop due to turbulent flow which will have a square-law relationship with air velocity. As flow rates become less, the non-linearities will be less noticeable.

Wind may cause pressure differentials according to the square of the wind velocity (Bernoulli effect). However a similar opposing effect applies to both entrances. It is assumed that any wind effect can be detected by analysing the data for a linear relationship.

Barometric pressure changes result in a flow of air in or out of the cave which is proportional to the effective volume of the cave and the size of the pressure increment. In caves large enough to display the effect there may be time lags of many hours (Conn, 1966; Wigley et al., 1966). A linear relationship between rate of change of pressure and air flow is sought in this work but if a strong effect were detected then more complex time dependent analysis would be appropriate.

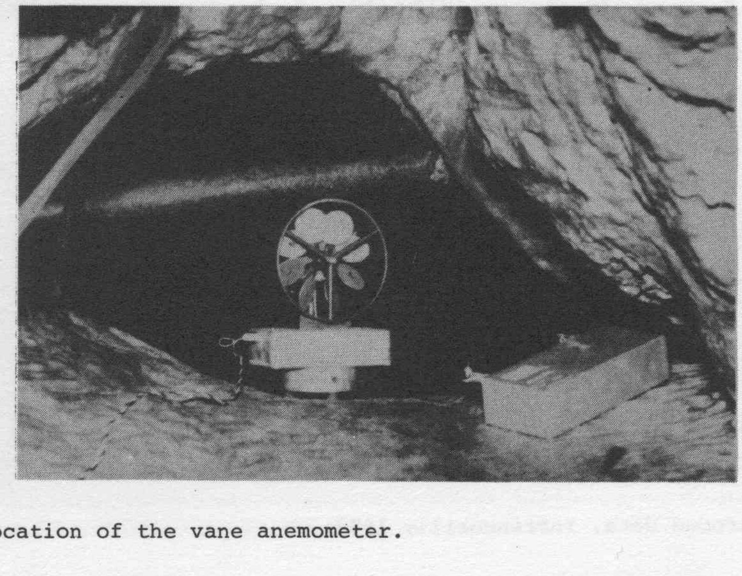


Figure 3. Location of the vane anemometer.

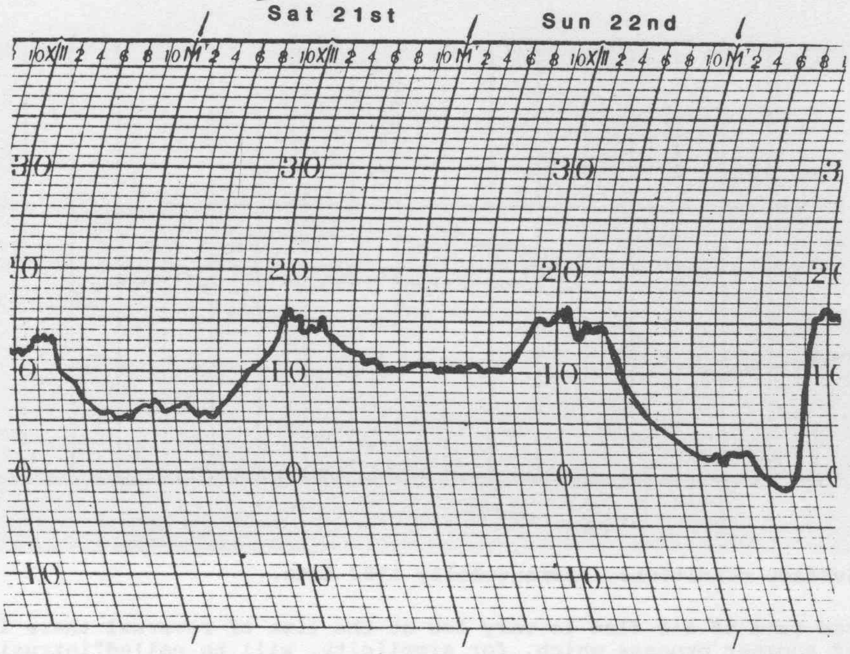


Figure 4. Temperature chart, Jenolan, April 1973

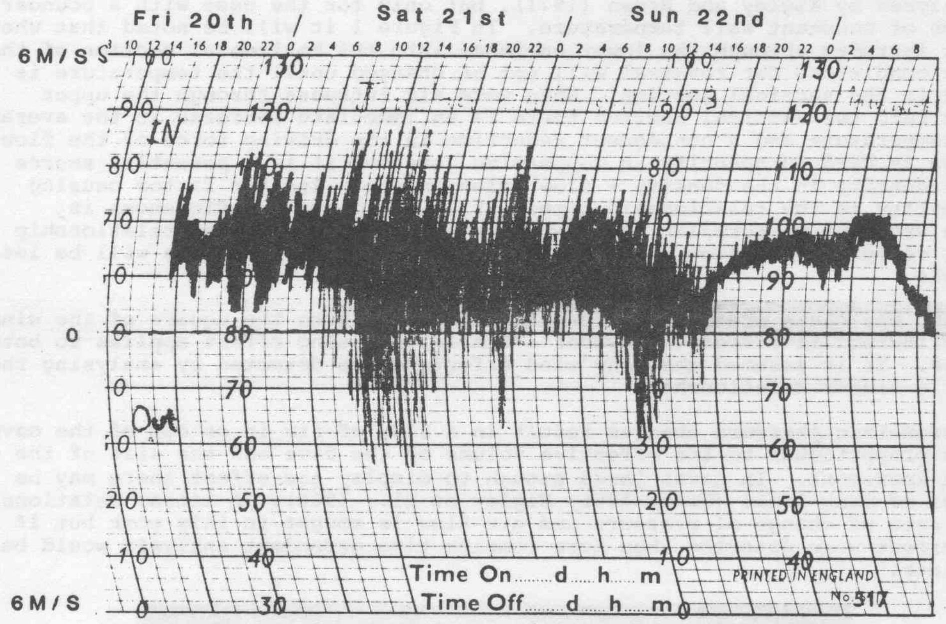


Figure 5. Cave air velocity, Cold Hole, Mammoth Cave Jenolan, April 1973

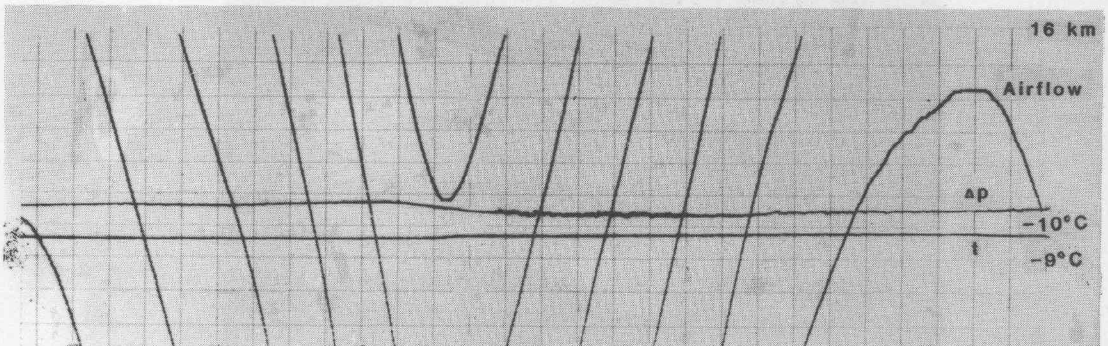


Figure 6. Underground data, Yarrangobilly 1982.

Water induced air flow will vary according to floods and drought. In short term observations such as in this work, the absence of a departure of the reversal temperature from the measured cave conditions should show the absence of air flow induced by water flow.

From the response of the cave to surface conditions and from the map of the known extent of the cave it is assumed here that the cave may be represented by Figure 1. The known entrances are at B and the other entrance is shown at F. Air flow in the cave is measured at C and surface conditions are measured at G.

It is reasonable to infer that the known lower entrance of the cave is the lowest entrance. The Yarrangobilly River is only a few metres below this entrance so it is very unlikely that any air filled cave could exist below the lowest drainage level in the area. The direction of air flow in the cave is consistent with this.

The shape of the cave beyond the final constriction is less certain. To shed more light on this, additional observations were made in the cave. At a time when there was strong air flow, the cave was blocked by inflating plastic garbage bags in the constriction and the pressure across the blockage was measured. Although only a rough pressure measurement could be made, there was agreement (within 20%) with the pressure expected if all air flow through the cave had been blocked, the inaccesible limb of the cave was at a similar temperature to the known section of the cave, and if the cave extended vertically to the surface above the final constriction.

The coefficient of sensitivity to wind may be small so that significant effects on the cave climate occur only when there are strong winds. The high level of precision of the observations should enable detection of small wind sensitivity effects under normal weather conditions.

A major observational difficulty is encountered when trying to determine the conditions in the external air column that may cause air movement in the cave. The outside air will at times be subject to stratification due to inversion that prevents vertical mixing. Either one point must be found that represents the average of the column conditions or multiple positions of measurement must be used to determine the average conditions.

METHOD

The equipment used for measurement has been developed over more than ten years. The data are recorded on miniature chart recorders of a type which prints points from a galvanometer needle onto pressure sensitive chart paper. These recorders are based on a commercially available unit but have been modified. The original electric motor is replaced by a D.C. micro-motor assembly which enables points to be plotted on demand. The operation is controlled by a quartz oscillator to maintain accurate time and is powered by dry cells. Each recorder can register up to eight channels from a variety of sensors.

The cave is located at the foot of a hill. About 40 m from the valley floor a steel mast 5 m high was erected to support the surface condition measuring sensors. These were a cup anemometer and what has become known as the "pigeon house" psychrometer. The psychrometer consists of a pair of semiconductor temperature sensors, one with a wet wick, mounted in an open heat shield consisting of an inner skin of aluminium foil, a layer of plastic foam and an outer wall of thin polished stainless steel. Above this heat shield, a roof of similar construction shields the heat shield from direct solar radiation and most of the sky radiation. The design is the result of a trial and error development comparing the temperature measured in the shield with the temperature measured with a similar sensor which replaced the thermometer in the aspirated housing of an Assmann type psychrometer. The comparison was made 1 m from the ground in full sunlight and resulted in differences which averaged in the order of 0.1 K only. At the base of the mast a miniature chart recorder made a record of dry bulb temperature, wet bulb temperature and wind. The recorder averaged the wind velocity over ten minute intervals. Figure 2 shows a part of this record.

In the cave at the constriction with the locked bar a second miniature recorder was set up. A semiconductor temperature sensor was used to monitor the air temperature, a micro-manometer to record the pressure differential across the constriction and a vane anemometer was placed in the constriction to measure air flow. The site of the vane anemometer is shown in Figure 3. The vane anemometer uses a bidirectional detector to maintain a continuous total of the air that has passed it and this total is plotted by the recorder. Later the total air flow for a period of typically one hour can be used to accurately determine the average air velocity for that hour. This is necessary to avoid recording random fluctuations. The air flow in a cave often has pulsations of duration between 0.5 and 2 minutes approximately. These are caused by turbulance in wind near the entrance. If these fluctuations are recorded on a wind velocity chart it is difficult to extract precise air flow information. Figures 4 and 5 show typical charts from instruments used before the current equipment was developed. From the illustration in the paper by Conn (1966) it can be seen that this may be a universal difficulty. When periodic measurements of flow are made with hand held instruments the same effects will be likely to add considerable random scatter to all data except those taken for very long sampling periods. The record of temperature, pressure and the integral of air flow are shown in Figure 6 for the same time period as Figure 2.

Later the charts from the recorders were used to compile a data set. A transparent cursor with a fine engraved line was placed over each hour's temperature record and was positioned so that half the recorder imprints were below and half above the line. The temperature was then read from the cursor to the nearest tenth of a degree. The total air flow for each hour was read between the marks on the chart at the hour intervals. The sensors had been calibrated before the expedition.

The data set was enlarged by calculating humidity and density. Density was calculated from temperature and humidity assuming a constant barometric pressure of 906 m bar, a typical value at the altitude of 930 m. Equalisation of pressure changes is assumed to be instantaneous in caves which have no indications of air flow related to barometric change. Graphical and statistical summaries of the data were generated by computer.

RESULTS

Observations were made on April 8-12, 1982 with the assistance of members of the Sydney Speleological Society. The weather was fine and sunny with clear nights with the exception of April 11. On the afternoon of that day there were scattered showers followed by a warm clouded night and morning fog.

The data of Easter 1982 are compared with the data collected on January 1979, (Halbert and Michie, 1979). On that occasion a careful record of barometric pressure was made. Similar observations were not practical on the later occasion.

The date collected in January 1979 are summarised in Figures 7 to 11. Analysis of the relationships between variables is shown in Figures 12 to 14. The variables can not be assumed to be independent. Air temperature, stability and wind all have dependence on insolation which varies diurnally. The relationship between cave air flow and wind is due - in part at least - to a common relationship to time of day through insolation and temperature. The lack of relationship of barometric pressure to cave air flow is important (Figure 14). Response to changes in barometric pressure may not be completely in phase but there is usually an appreciable in-phase component (Conn 1966). Such a lack of correlation indicates a lack of barometric response.

Data collected on the Easter 1982 expedition are summarised in Figures 15 to 18. The analysis of the relationships between variables is shown in Figures 19 to 22. Figure 22 shows the very close relationship between air density and air temperature. It is this close relationship which makes the relationship so strong between cave air flow and surface air temperature.

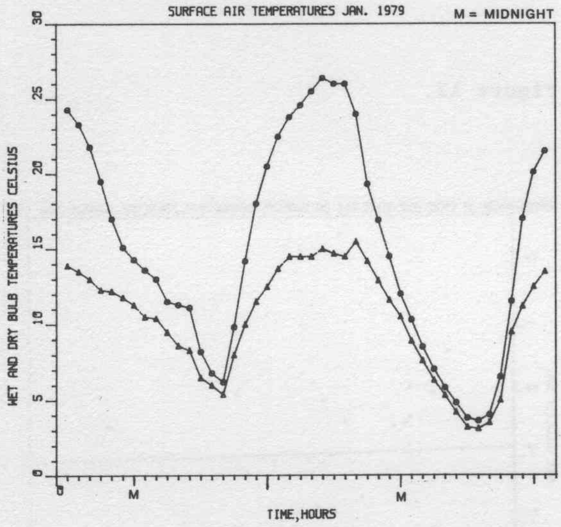
There were also some measurements made of pressure differentials in the cave. Pressure recorded across the constriction in the cave was intended to give information about pressure-flow relationships. The problem of fluctuations in flow makes the recording difficult to read and on this occasion the sensor had only two levels of sensitivity, one too low and one too high. Valid data over a period of only ten hours were obtained and were not included in this paper. The readings when the flow was blocked were informative. If it was assumed that the unknown section of the cave was at the same temperature and humidity as the known section, 9.9^{o}C, then the pressure of 17.6 Pa measured indicated a vertical extent of the cave of 54 m as the outside density at that time was 1.0796 kg/m^3 and inside was 1.1121 kg/m^3.

DISCUSSION

The improvement in the new data is shown by the higher correlation coefficient for the air density - air flow correlation. This is almost certainly because of the location of the station monitoring surface conditions. The layer of air that contains the column of air between the two cave entrances will be subject to cold downslope flows at night and warm convection currents by day. The position of the assumed upper entrance is unknown so the surface monitoring station can only be placed to monitor air which is likely to be representative of the area. Although the new position is only about 15 m higher above the valley floor than in January 1979 it is obviously more representative of the outside air column. A large part of this improvement is probably due to the additional 4 m that the sensor is located above the ground.

The new data show a reduction in random error and this now leaves only a small amount of variation that wind can account for. Multiple regression analysis was applied to the relationship between surface wind, density and cave air flow. The result was statistically very significant but it did little to reduce the residual errors and because of the known strong relationships between the variables no conclusion should be drawn. It is probable that the wind alters the average temperature of the air outside the cave while affecting the air stability and this is not adequately detected by the sensor which only measures temperature at one elevation.

The effect on the cave of the air flow can be predicted. As the only air that enters the lower entrance is below the reversal temperature that section of the cave will be cooled by advection and evaporation of water from the walls and stream. The only air that enters the upper entrance is above the reversal temperature and it will heat the cave walls by advection, will cool the walls by evaporation if they are moist or when the dew point of the incoming air is high enough, heat them by condensation. The net result of these processes will be to cause a temperature gradient along the length of the cave and an average cave temperature below the mean surface temperature by an amount determined by the net evaporation of water from the cave. Evaporation is often apparent near the known entrance and there is a distinct rise in air temperature at the measuring constriction as the flow changes from inwards to outwards (Figure 6).



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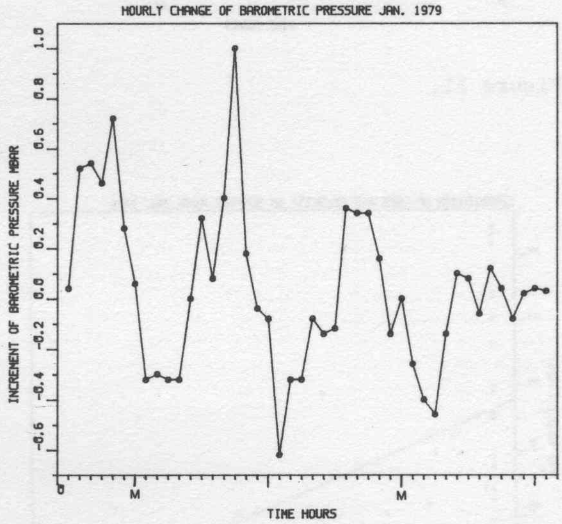

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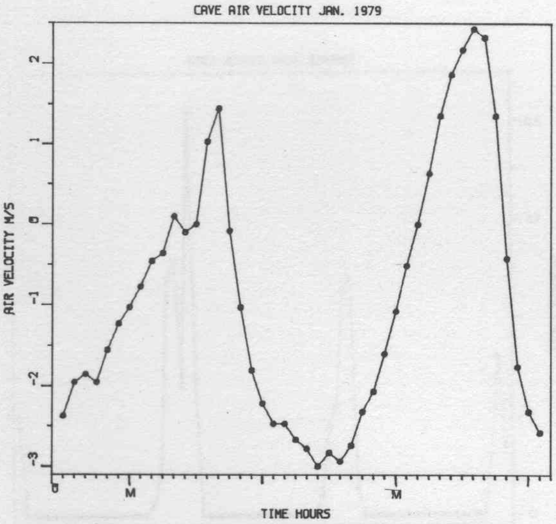

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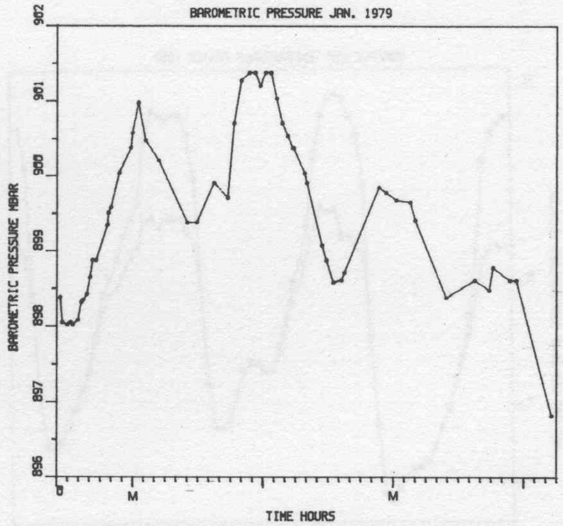
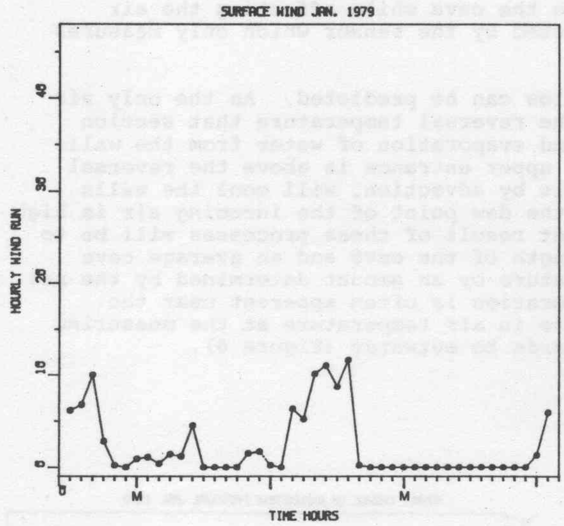


Figure 10.



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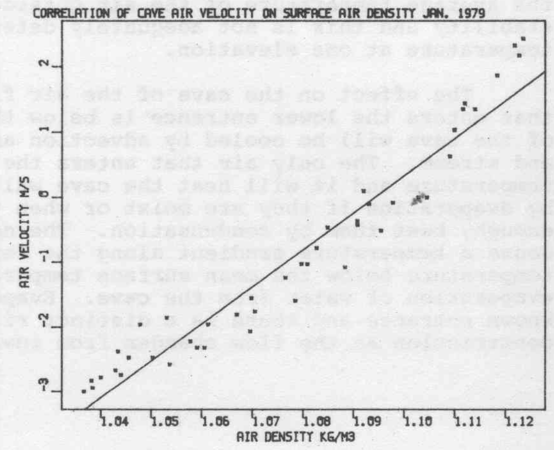

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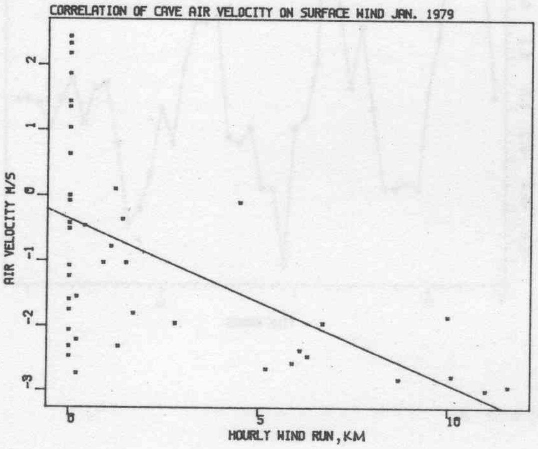

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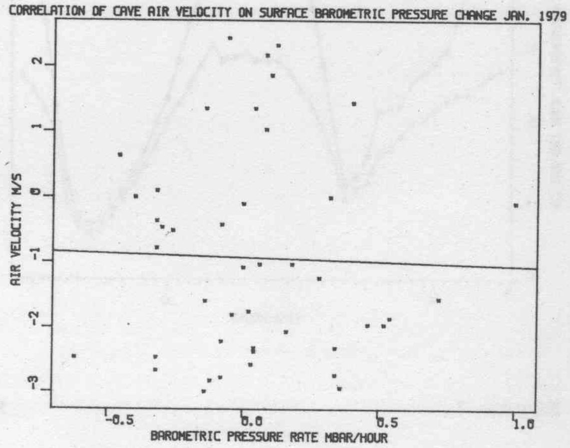

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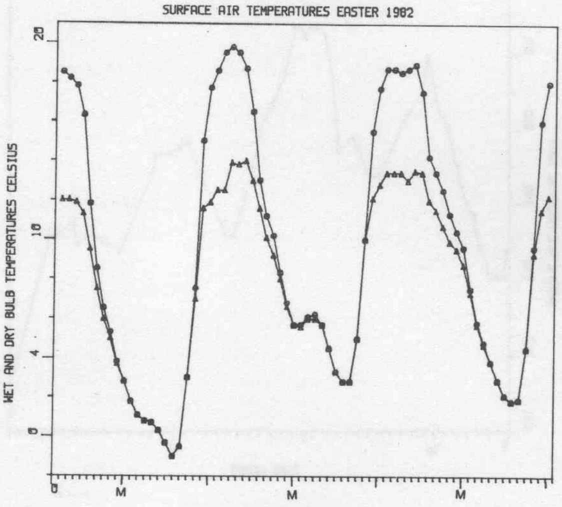

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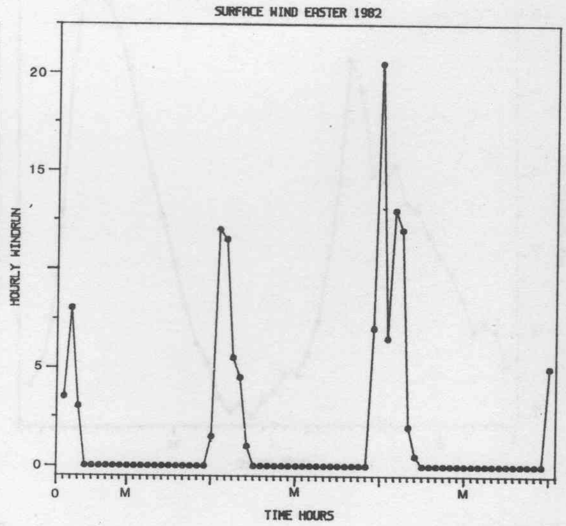

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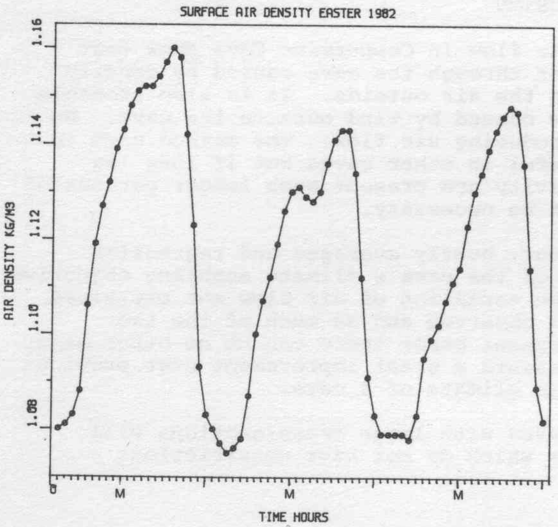

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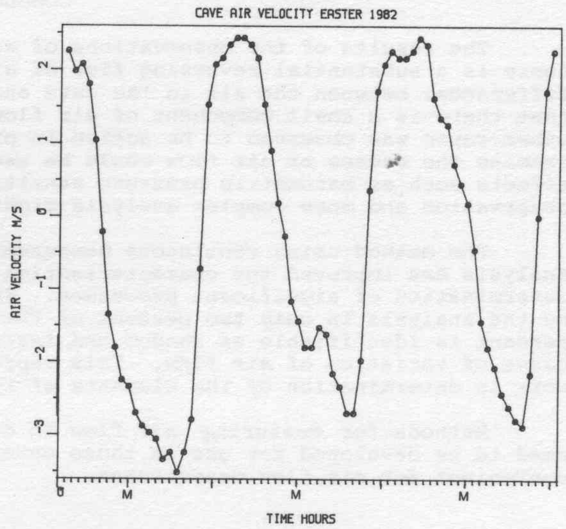

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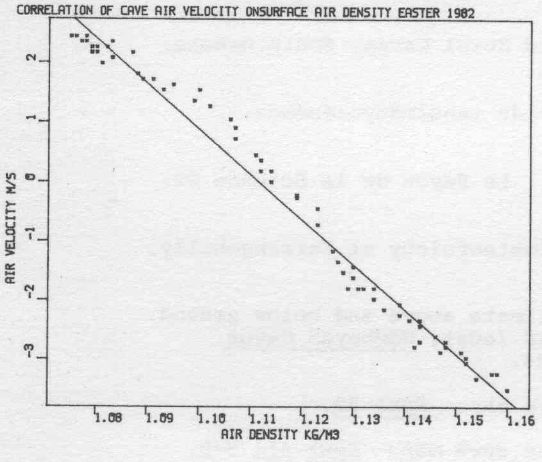

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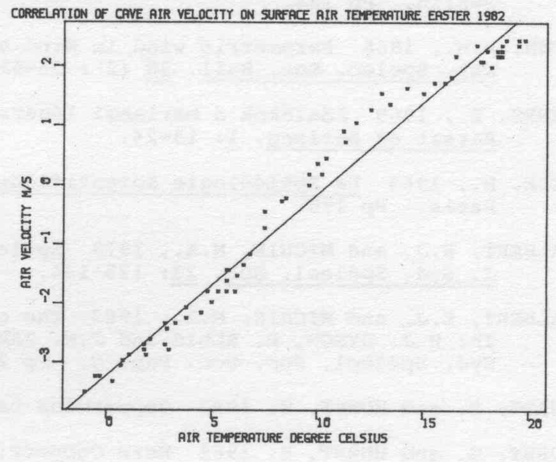

Figure 20.

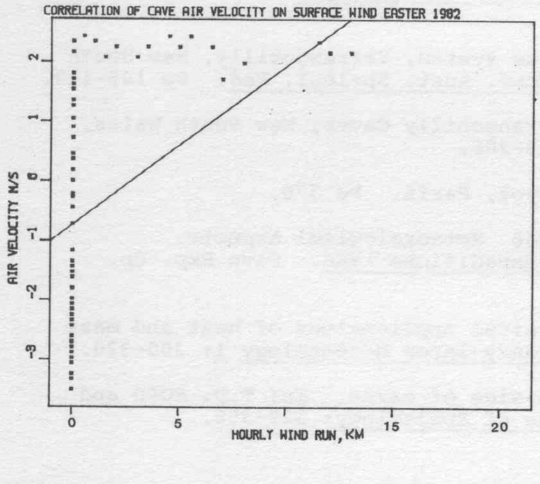

Figure 21.

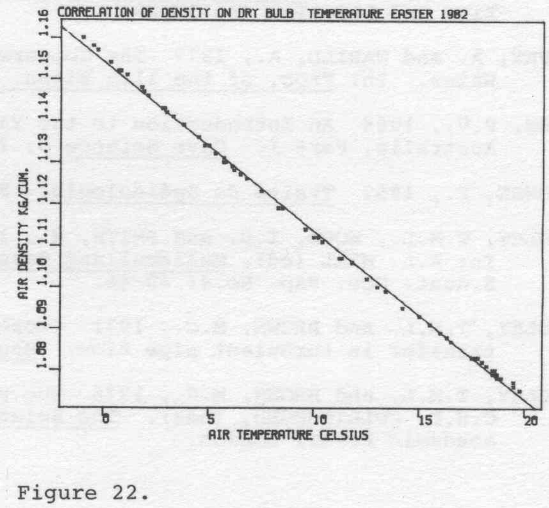

Figure 22.

CONCLUSION

The results of the observations of air flow in Coppermine Cave show that there is a substantial reversing flow of air through the cave caused by density differences between the air in the cave and the air outside. It is also probable that there is a small component of air flow caused by wind outside the cave. No other cause was observed to be active in producing air flow. The method used to examine the causes of air flow could be useful in other caves but if long lag effects such as barometric pressure sensitivity are present much longer periods of observation and more complex analysis might be necessary.

The method using continuous measurement, hourly averages and regression analysis has improved the characterisation of the cave's climate enabling objective determination of significant processes. The variation of air flow not explained by the analysis is only two percent of that observed and as much of the two percent is identifiable as random and instrument error there can be no other major cause of variation of air flow. This represents a great improvement over previous work in determination of the elements of the climate of a cave.

Methods for measuring air flow in caves with large cross-sections will need to be developed for use in those caves which do not have constrictions convenient for air flow measurement.

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THE AUSTRALIAN ROCK ART RESEARCH ASSOCIATION

An association promoting the study of prehistoric rock art is being established in Australia. Any person or organisation (in Australia or abroad) interested in this area of research is encouraged to request memberhip.

The principal objectives of the Australian Rock Art Research Association (AURA) are as follows: to provide a forum for the dissemination of research findings; to promote Aboriginal custodianship of sites externalising traditional Australian culture; to co-ordinate studies concerning the significance, distribution and conservation of rock art, both nationally, and with individuals and organisations overseas; to institute a Code of Ethics regarding research in this field and to generally promote awareness and appreciation of Australia's immovable cultural heritage.

Whilst AURA is concerned principally with the Australasian region, it also strives for international contact, communication and involvement. The Association intends holding regular general meetings at locations yet to be determined. It encourages the formation of State or regional chapters and will assist in the operation of these. A newsletter is already being issued, reporting current developments and matters of immediate importance, and serving as a direct communication channel. A journal will be published twice yearly, commencing in May or June 1984. It will feature research papers, short reports, reviews, letters, and a current bibliography.

Applications for membership or Journal subscription are invited from all interested parties, and should be sent to the Editor, Archaeological Publications, P.O. Box 216, Caulfield South, Vic., 3162, Australia. Membership fees will be kept to an absolute minimum, and are not expected to exceed $A 10.00. None, however, will apply before 1984.

R.G. Bednarik
Convener

Helictite

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