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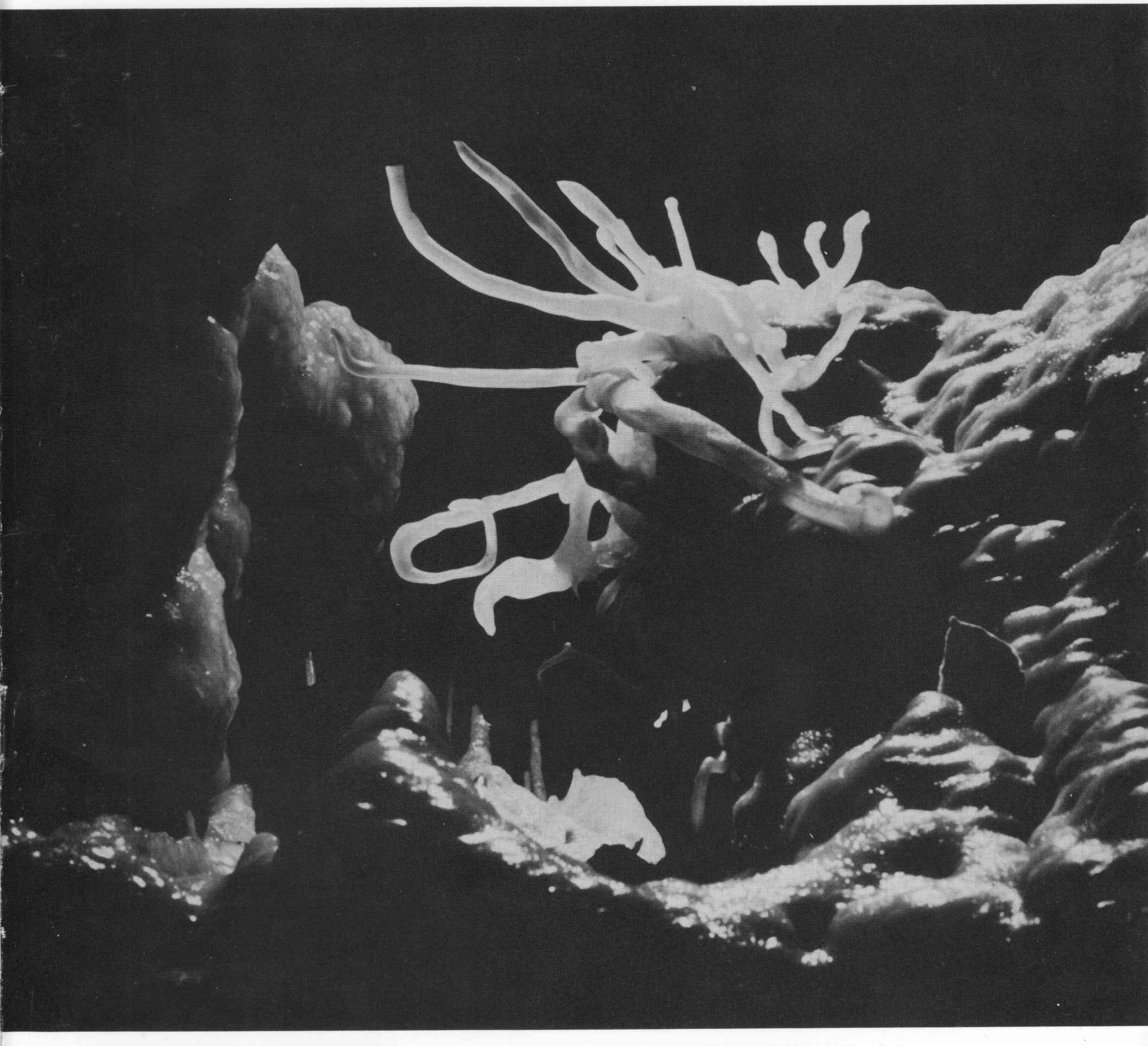
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Helictites, Bouverie Cave, Wombeyan, NSW.
Photograph by Les Field.

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.

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J.R. Dunkley 1972. - a detailed history and description.

CAVES THROUGH THE AGES. G. Hangay, J.M. James & M. Dorrell 1974.
- a colouring book for children.

PAPUA NEW GUINEA SPELEOLOGICAL EXPEDITION NSRE 1973. J.M. James 1974.
- the report of the 1973 Niugini Speleological Research Expedition to the Muller Range.

A BIBLIOGRAPHY OF THE JENOLAN CAVES. PART ONE: SPELEOLOGICAL LITERATURE.
J.R. Dunkley 1976. - a detailed reference list.

THE CAVES OF JENOLAN, 2: THE NORTHERN LIMESTONE. B.R. Welch (ed) 1976.

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CONTENTS

An Annotated Speleological Bibliography of Oceania - R. Michael Bourke 3

Observations on the Buchan Karst during High Flow Conditions - Brian Finlayson and Mark Ellaway 21

Deposition of Tufa on Ryans and Stockyard Creeks, Chillagoe Karst, North Queensland - D.L. Dunkerley 30

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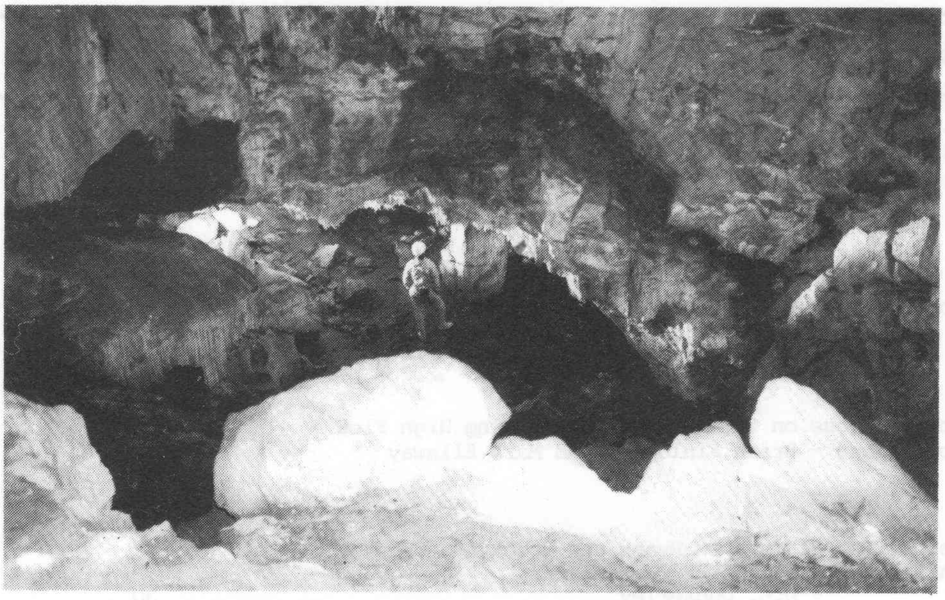

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AN ANNOTATED SPELEOLOGICAL BIBLIOGRAPHY OF OCEANIA

R. Michael Bourke

Abstract

A preliminary annotated speleological bibliography is presented for Oceania. The region covered extends from Irian Jaya (Indonesia) in the west to the Galapagos Islands (Equador) in the east. There are 268 references given from the following countries and territories: Antarctica, Belau, Cook Islands, Easter Island, Fiji, French Polynesia, Galapagos Island, Guam, Irian Jaya, Mariana Islands, New Caledonia, Niue, Solomon Islands, Tonga, Vanuatu, Western Samoa, Wallis and Futuna.

INTRODUCTION

Some 15 years ago I commenced assembling references to caves of Asia and Oceania. The region extended from Pakistan and Mauritius in the west to the most eastern islands of the Pacific Ocean, excluding only Australia, New Zealand and Japan. It is proposed to publish these bibliographies in three parts covering Oceania, Southeast Asia and Papua New Guinea. As Daniel Gebauer (Germany) and Claude Chabert (France) are compiling bibliographies of South and Southwest Asia, I do not plan to publish material for South Asia. It is not proposed to publish the material for East Asia because of language difficulties. This paper covers Oceania and is the first and smallest of a series of three papers.

Sources used are speleological abstracting journals (Table 1), references cited in papers, those provided by colleagues (see Acknowledgements) and systematic searches of Asian and Pacific journals such as Mankind, Asian Perspectives, Oceania and Science in New Guinea. Unlike the Papua New Guinea bibliography, those for Oceania and Southeast Asia are preliminary in that they are not exhaustive and not all references given have been sighted and checked. Generally geological surveys are not included, even though some comment on karst landforms. Papers on bats are only included if caves are mentioned. The cut off nominal year of publication is usually 1984.

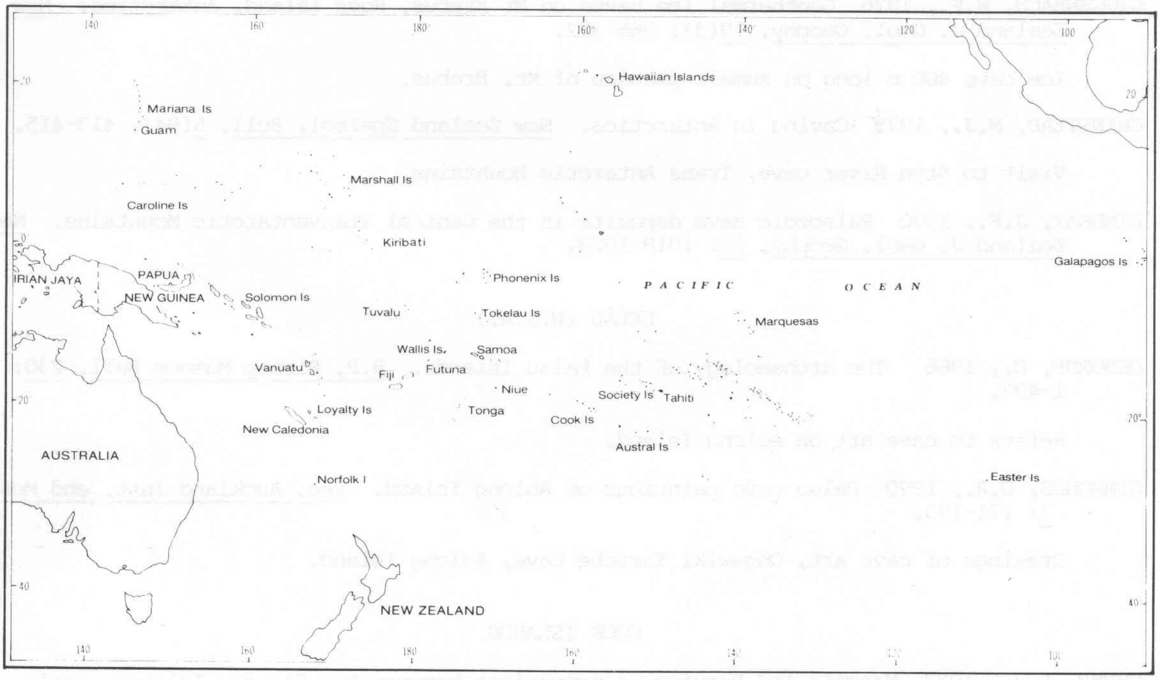

Figure 1. The main island groups and nations in Oceania.

OCEANIA

This paper covers the region from Irian Jaya (West New Guinea, a province of Indonesia) in the west to the Galapagos Islands (Equador) and Easter Island (Chile) in the east (Figure 1). Papua New Guinea, Hawaii, Australia and New Zealand are not included. The 268 references from 17 countries and territories are presented in Table 2

Aside from New Guinea, the land area in the region is small. Despite this and the small amount of systematic exploration by speleologists, reports of caves are relatively common in the literature. This is because many islands are formed from volcanic rocks or limestone. In addition caves are frequently used by islanders as sites for art, shelter and burial. They have thus received attention from anthropologists, archaeologists and other students of mankind. The scattered literature indicates that there is considerable potential for systematic exploration and recording by speleologists in the region.

Table 1. Speleological abstracting journals searched for Asian and Pacific papers.

Australian Speleological Abstracts. Sydney Speleological Society, Sydney. Nos. 1-9 (1970-1975).

Current Titles in Speleology. Manol Publications, Crymych, Wales. Nos. 1-16 (1969-1983).

Speleological Abstracts. (Great Britain). Vols. 1-7 (1962-1968).

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Series of probable cave deposits in the Ellsworth Mountains described.

FUNAKI, M., 1979 (Caves of the iceberg). Japan Caving 11(3/4): 31-39.

GIGGENBACH, W.F., 1976 Geothermal ice caves on Mt Erebus, Ross Island, Antarctica. New Zealand J. Geol. Geophy. 19(3): 365-372.

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Caves occur at Lake Tiriara and Tamorna, Mangaia.

WOOD, B.L., 1967 Geology of the Cook Islands. New Zealand J. Geol. Geophy. 10(6): 1429-1445.

Refers briefly to caves on Mangaia Island and Atiu Island.

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GEZE, B., 1975 Les cavernes de L'ile de Paques. Spelunca 15(3): 15-16.

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HEYERDAHL, T., 1958 Aku Aku. Allen and Unwin, London.

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Numerous references to caves.

KIERNAN, K., 1976 The caves of Easter Island. Southern Caver 8(1): 7-13. Tasmanian Caverneering Club, Hobart.

30 entrances to lava caves located.

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DERRICK, R.A., 1978 Some Fijian caves. British Caver 69: 23-25.

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p143-144 Burial caves, Lakemba.

FLOWER, W.H., 1881 On the cranial characters of the natives of the Fiji Islands. J. Royal Anthrop. Instit. 10: 153-173.

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GIFFORD, E.W., 1951 Archaeological excavations in Fiji. Anthropol. Rec. 13(3): 189-288. University of California, Berkeley.

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PAPP, L., 1984 Cavernicolous Milichiidae (Diptera): three new species from Fiji and Sri Lanka. Rev.Suisse Zool. 91(2): 241-247

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p61 Cave entrance seen 12 miles up Navua River, Viti Levu; p131-2 visit to cave on Lakemba Island used for breadfruit fermentation.

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ANON., 1975/76 Les "speleo" d'Orofara. Bull. Speleo Club de Lassalien 9/10.

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GAUGUIN, P., 1980 Noa-Noa. Marit. d'Outre Mer, Paris.

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OBSERVATIONS ON THE BUCHAN KARST DURING HIGH FLOW CONDITIONS.

Brian Finlayson and Mark Ellaway

Abstract

In late July 1984 heavy rain at Buchan in East Gippsland produced widespread flooding and activated the dry valley network and vadose cave system on the Buchan limestones. The heavy rainfall was caused by the movement southwards along the New South Wales coast of a low pressure centre which originated in southeast Queensland. Intensity - frequency - duration analysis of the rainfall event indicates that while the 24 hour fall on the day the flooding occurred had a recurrence interval of only 1.75 years, the 96 hour and the 120 hour durations had recurrence intervals of 3.8 and 8.0 years respectively. The flood peak in the Buchan River had a recurrence interval of 4.3 years. These analyses indicate that the dry valleys and vadose cave systems are hydrologically active quite frequently under present climatic conditions. Water quality observations were made on surface streams and springs in the Buchan area during the flood and the results are compared with similar data collected under low flow conditions.

INTRODUCTION

In any river system, the length of actively flowing channel is a function of moisture conditions in the catchment such that during and immediately following heavy rain the whole of the channel net becomes active while during dry periods the system contracts, the lower order streams ceasing to flow first (see for example, Blyth and Rodda, 1973). In karst areas this pattern of behaviour is complicated by the progressive development of subsurface flow routes so that through time, more and more of the flow occurs underground and the surface valley systems are gradually abandoned (Jennings, 1985). On impervious rocks the frequency of activation of the channel network is a function of climate. The same climatic effects apply to karst areas but the behaviour of the surface channels are also determined by the level of development of the subsurface flow network in fissures and caves. While individual instances of "dry valleys" in karst areas carrying flow have been reported in the literature (Hanwell and Newson, 1970; Trudgill, 1985) few attempts have been made to assess the frequency with which these surface systems become active.

The area of karst barrè at Buchan in East Gippsland (Figure 1) has a typical surface network of dry valleys. Small streams which flow from the surrounding impervious Snowy River Volcanics normally sink underground on reaching the limestones (e.g. Spring Creek and Back Creek, Figure 1), though the Buchan River itself maintains its flow in an alluvial channel across the limestone except during periods of extreme low flow. It is not known whether the subsurface system in the limestone is saturated to the level of the Buchan River (the lowest point in the landscape) or whether the Buchan channel is effectively sealed, though the former appears the more likely. The Murrindal River is similar, though under low flow conditions it sinks for a distance of approximately 1 km near the Pyramids (site 21 on Figure 1).

During a period of very heavy rainfall on the weekend of 28-29th July, 1984, the surface valleys at Buchan became active. This provided an opportunity to assess the relative frequency of such events and also enabled water quality measurements to be made under high flow conditions. In this paper the meteorological situation which caused the flooding is briefly described together with qualitative observations of runoff behaviour on the surface and in those parts of the cave systems to which access was possible. The only quantitative hydrological data available for this area are runoff records on the Buchan and Murrindal Rivers and daily rainfall observations at Buchan Post Office. No flow measurements are made on any of the surface tributaries, cave streams or springs in the area. The available records have been analysed in an attempt to characterise the flood of July 1984 in terms of relative magnitude and recurrence interval. For these purposes only the Buchan Post Office rainfall and Buchan River streamflow data are used. The record on the Murrindal River dates only from March 1976 and so is too short for reliable recurrence interval analysis. Water quality measurements are presented for a number of sites in the area and compared with similar data collected at intervals over a three year period during which no similar floods occurred.

Descriptions of the geology and climate of the Buchan area were presented by Ellaway and Finlayson (1984) and will not be repeated here. The same sample sites were used in this study as in the previous study except that some of the sites were inaccessible during the flood period and other sites (e.g. Fairy Creek and Wilsons Cave) had not previously been observed to carry any flow. Sampling sites are shown on Figure 1 and descriptions of them are given in Table I. The methods of sample collection and analysis described in the earlier paper were also used in this study.

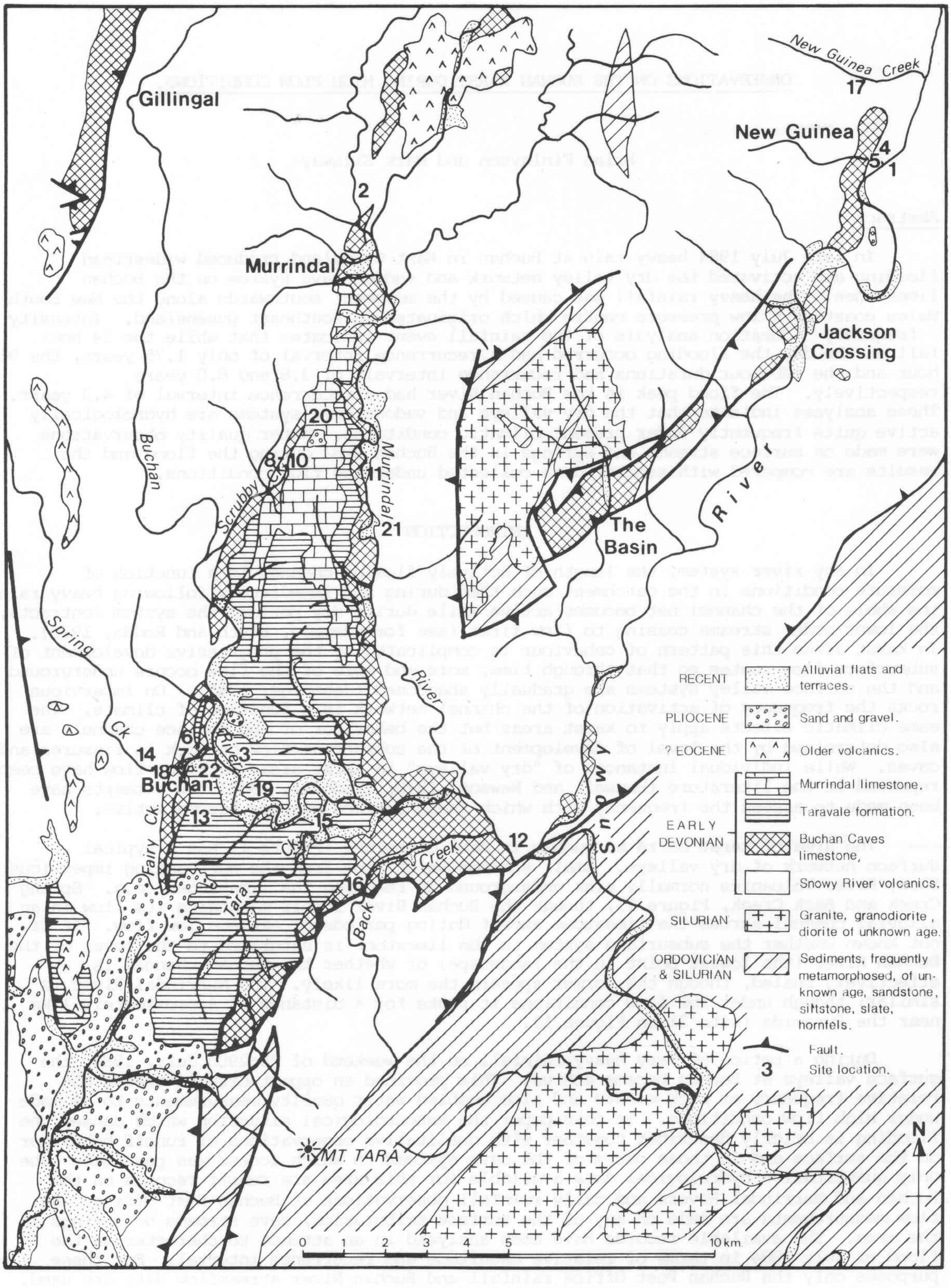

Figure 1. Geology of the Buchan area showing sample sites. (After Teichart and Talent, 1958).

METEOROLOGICAL AND HYDROLOGICAL CHARACTERISTICS OF THE FLOOD

For the six months (January to June) prior to the flood of July 28-29th 1984, the raingauge at Buchan Post Office recorded rainfall close to, but slightly below, the long term average for these months (354 mm as compared with 398 mm). January and February recorded monthly totals slightly above average and rainfall was below average from March to June. In July, for the 27 days prior to the flood producing rains of the 28th and 29th, 106.6 mm were recorded which is 62.2 mm above the long term average for that month. Daily falls for the 5 days preceeding the flood were 1.4, 11.2, 30.4, 2.0 and 0.0 mm respectively. Thus the rains which began on Friday 27th July fell onto an already wet catchment. (Note that daily rainfalls refer to readings made at 9.00 a.m. on the date given.)

In the early morning of Friday 27th July a weak low pressure centre was situated over southeast Queensland within a trough of low pressure extending down the east coast of Australia. The low moved south along the New South Wales coast during the day generating onshore southeast winds over coastal southern New South Wales and eastern Victoria. By late Friday night the low had deepened to 994 mb and begun to move offshore. It continued to deepen during Saturday 28th, the central pressure dropped to 984 mb, and it moved slowly southwards maintaining a moist, unstable south easterly airflow into eastern Victoria. Figure 2 shows the synoptic situation on the morning of Sunday 29th July when very heavy rain was falling at Buchan. The low then moved away to the southeast and ultimately weakened to become a trough of low pressure to the south of New Zealand by the morning of Tuesday 31st July. Buchan Post Office recorded 58.4 mm at 9.00 a.m. on Saturday 28th and 52.0 mm on Sunday 29th. Only 4.0 mm were recorded on Monday.

The effects of this rainfall in generating runoff in the Buchan area were quite dramatic. Most of the dry valleys on the Buchan limestones carried surface streams and surface runoff on the hillslopes was widespread. Much of this flow entered the vadose flow system of the limestones. Caves which had previously been reported to carry flow only rarely were observed to be flowing. Wilsons Cave (EB - 4), a vadose stream passage (normally dry), had a stream flowing through it and this was typical of many other similar caves. Discharge from the karst springs of the Buchan area, with one exception, rose rapidly and the flow issuing from them was highly turbid, indicating that they were connected to rapid vadose flow routes carrying surface runoff. The one exception was Bitch of a Ditch (EB - 49, site 12 on Figure 1) where the flow rate was little affected and the water remained clear. Mabel's Cave (EB - 1), normally a dry cave, carried a strong flow of highly turbid water.

Spring Creek, which flows through the Buchan Caves Reserve, has two major tributaries, Spring Creek itself which has most of its catchment on the Snowy River Volcanics, and Fairy Creek with a catchment on Buchan Caves Limestones and Taravale Formation (Figure 1) and which is normally dry. Both branches flooded, part of Fairy Creek flow entered the lower entrance to Whale Cave (B - 20), and the combined streams flooded the Buchan Caves Reserve and closed off vehicle access for five hours. Both tourist caves, Fairy Cave and Royal Cave, were closed by flood waters. Highly turbid flow was also observed in the lower levels of Federal Cave (B - 7), an old tourist cave, which connects via a sump to Dukes Rising (B - 4, site 7 in Figure 1).

The Buchan River flooded, reaching its peak on the night of Saturday 28th, with a maximum instantaneous discharge of 19,292 ML/day, a gauge height of 3.822 m. The Murrindal River also flooded, the W-Tree Falls, located on the Snowy River Volcanics just north of the limestone (near site 2 on Figure 1) providing a spectacular display. Maximum instantaneous flow of the Murrindal River was 32,700 ML/day at the gauge in East Buchan, a gauge height of 5.704 m.

RECURRENCE ANALYSIS OF THE EVENT

There is virtually no observational data available for the Buchan limestones on the frequency with which such runoff events occur in the caves and dry valleys. The one exception to this is the flood of June 1978 for which some general observations on flooding in the Buchan Caves Reserve are available. In the absence of such data it is possible to make recurrence estimates using the rainfall record and the runoff record for the Buchan River. Both these methods have limited applicability. Runoff is not a simple function of rainfall as this depends on antecedent wetness of the catchment and storm characteristics such as duration, intensity and path. Previous rainfalls of the same amount as in July 1984 would not necessarily have produced similar runoff conditions. The Buchan limestones occupy a small part of the downstream end of the Buchan catchment area and its flood behaviour is governed mainly by conditions upstream. Flood conditions in the Buchan River do not necessarily indicate local flooding on the limestones. In the absence of other data, an analysis of recurrence is presented here based on the rainfall and runoff record.

The rainfall record can be used to investigate the possibility that the extent of local runoff was due to an extreme precipitation event. The available data are limited in this regard since only daily rainfall totals are recorded though our experience of the event suggests that the rainfall was reasonably well spread across the two days and not unduly concentrated into a shorter period. An advantage of this approach is that reliable records have been kept at Buchan Post Office since August 1883 with very few missing data.

Daily rainfall totals for the period of record were supplied on magnetic tape by the Bureau of Meteorology in Melbourne and processed on the University of Melbourne's Cyber 730 computer. In each year of record the maximum 24, 48, 72, 96 and 120 hour duration falls were determined and assembled in rank order. For each duration the ranked rainfall

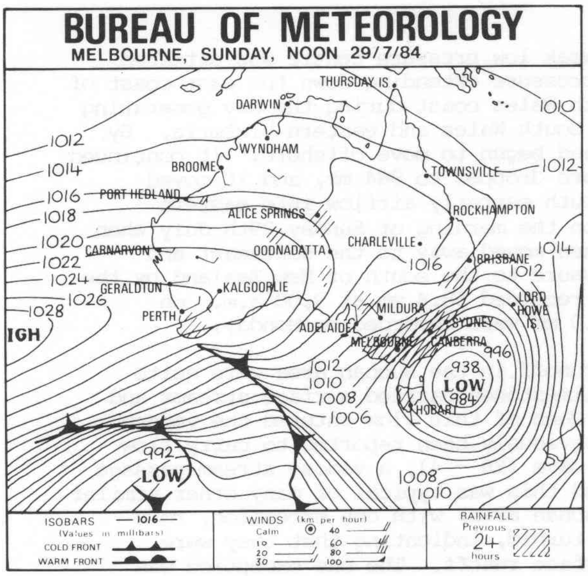

Figure 2. Synoptic chart for noon, Sunday 29th July,1984. (Source: "The Age", Melbourne, 30th July, 1984).

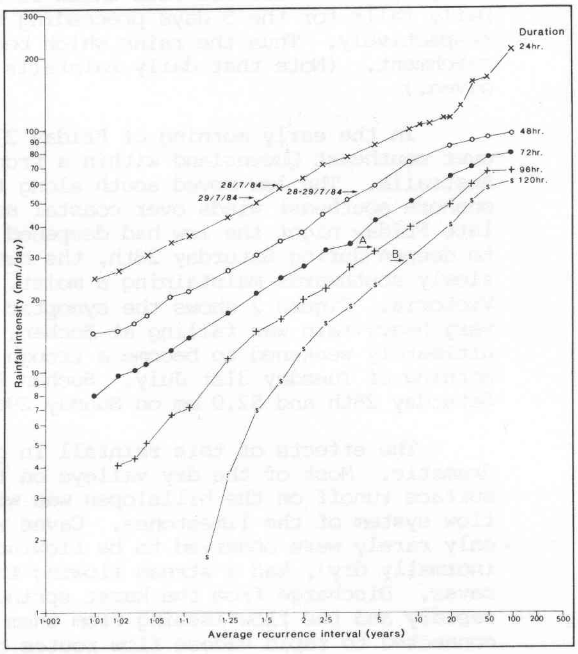

Figure 3. Annual exceedence series for rainfalls of 24, 48, 72, 96, and 120 hr durations at Buchan.

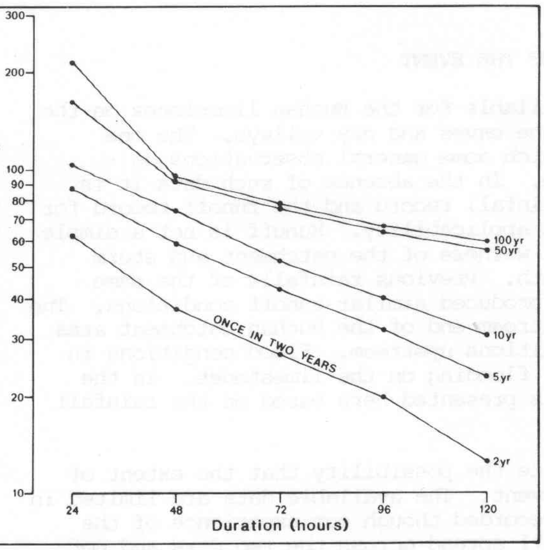

Figure 4. Rainfall intensity-frequency-duration curves for Buchan.

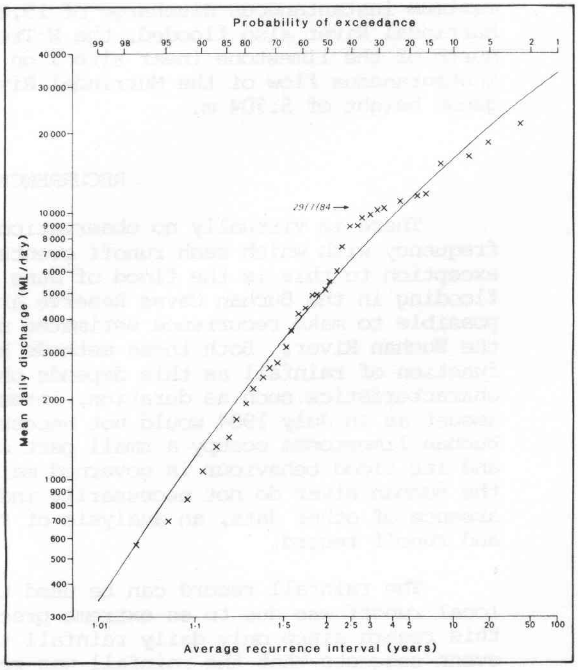

Figure 5. Flood frequency curve for the annual exceedence series, Buchan River at Buchan (Station no. 223207).

set is an annual series which can be plotted on intensity and probability axes. Probability of exceedence (P_i) is calculated from the ranks (i) as:

$$P_i = \frac{i}{N+1}$$

and the average recurrence interval (T_i) is the reciprocal of P_i (Institution of Engineers, 1977). The annual exceedance series for each of the five durations are plotted on log - probability paper in Figure 3 where the probability axis has been rescaled as average recurrence interval. For durations up to 96 hrs the data are log-normally distributed while the 120 hrs duration is markedly skewed. Figure 4, a conventional intensity - frequency - duration diagram has been derived from Figure 3. The 24 hr falls on the 28th and 29th July have average recurrence intervals of 1.75 and 1.5 years respectively. The 48 hr duration for those two days has an average recurrence interval of 4 years. These dates are marked on Figure 3. Extension to longer durations is not strictly justified since there was no rain recorded on the 27th. However, ignoring this fact and using rainfall on the 25th and 26th to give 96 hr and 120 hr durations (points marked A and B on Figure 3) gives recurrence intervals of 3.8 and 8.0 years respectively.

The rainfall analysis indicates that the two days of rain which produced the flood event were not particularly unusual. The 120 hr duration was less common and indicates that antecedent wetness of the catchment was an important contributing factor to the magnitude of local runoff on the limestone area around Buchan. As was mentioned earlier, even excluding the rain on the 28th and the 29th July, rainfall was significantly above average for the month. It should also be noted that in July evaporation and transpiration rates are low and this also plays an important role in determining antecedent wetness.

Runoff is the outcome of the integration of catchment and rainfall conditions and so represents a better way of looking at the magnitude and frequency of the event. In this case however, there are no runoff records which reflect conditions in the immediate vicinity of Buchan only, because of the large proportion of the catchment which lies on non-carbonate rocks and would be expected to dominate flood behaviour in the Buchan River. Discharge records for the Buchan River at Buchan (station no. 222206) were made by the State Electricity Commission between 1926 and 1930 using a daily read staff gauge. No records were kept between 1930 and 1947 when the State Rivers and Water Supply Commission (now Rural Water Commission) recommenced daily staff readings which were continued until 1964 when a recorder was installed. Ideally, an analysis of flood behaviour should be based on the annual series of maximum instantaneous discharges (c.f. the rainfall analysis described above). Such data are only available for the period since 1964. Prior to 1964, because the record is based on daily staff readings, only maximum mean daily discharges are available. In order to utilize the whole record period the analysis has been carried out using the annual exceedance series of mean daily maximum flows.

To test the reliability of the mean daily maximum series as compared to the maximum instantaneous series, these two series were compared for the 19 years of record (since 1966) for which both are available, using correlation analysis. The correlation coefficient is 0.95 (significant at the 99% level). With only one exception, 1982, the month of occurrence of the maximum instantaneous flow is the same as the maximum mean daily flow.

The annual exceedance series of mean daily maximum flows has been compiled and plotted on log-probability paper (see Figure 5) in the same way as the annual series of rainfall maxima described earlier. While the absolute values of discharge are lower than the instantaneous flows, the order and therefore the probabilities, are the same. The flood of 28th July is the largest for 1984 and its position in the series is shown on Figure 5. The fitted line in Figure 5 is a log Pearson Type III distribution with mean, standard deviation and skewness of the Buchan data (Institution of Engineers, 1977). The position of the flood of 28th July 1984 is shown in Figure 5 and has an average recurrence interval of 4.3 years.

On the basis of these estimates, the event under consideration has an average recurrence interval of between 4.0 and 8.0 years and therefore appears not to be particularly rare. On this basis it would appear that the dry valleys on the Buchan limestones and the vadose cave systems are active much more frequently than has previously been assumed, even if the 1984 event is taken to represent the minimum conditions for flow in these systems. Such an assumption is not really justified so it must be assumed that the dry valleys and caves are hydrologically active quite frequently under present climatic conditions.

WATER QUALITY OBSERVATIONS

The location of each sampling site is shown on Figure 1 and a brief description given in Table 1. In Table II the results of analyses of the flood samples from July 1984 are given together with the range observed on other occasions (where applicable). A selection of the results are plotted as time series together with monthly rainfalls in Figure 6. The results presented are the measured values of Ca^{++}, total hardness and temperature together with saturation indices for calcite (SI_C) and the partial pressure of carbon dioxide (PCO_2) as calculated by WATSPEC (Wigley, 1977). The surface stream sites e.g. site 1 on Figure 6 (Table II) are representative of flow from the Snowy River Volcanics. During the flood of July 1984 they all had low values of Ca^{++} and total hardness, water temperatures were either the same as that of the rainfall (9°C) or elevated by only 1°C as in the case of the Murrindal River and all were slightly cooler than the spring waters and were markedly undersaturated with respect to calcite.

TABLE I. SITE DESCRIPTIONS

Site number	
2	Murrindal river, upstream of limestone-volcanics contact.
3	Buchan River, at bridge in town.
5	Spring at New Guinea Ridge, receives water draining from volcanics, NG-2.
6	Spring at Moons Cave in Buchan Caves Reserve, probably receives water draining from the volcanics, B-54E.
7	Spring at Dukes Cave in the Buchan Caves Reserve, receives water draining from Buchan Caves Limestone and Taravale Formation, B-4.
9	Spring at top of extensive tufa terraces on Scrubby Creek, outflow of M-49.
11	Spring at outflow of M-4.
12	Spring at Bitch of a Ditch, EB-49.
13	Cave stream in B-67, linked by dye tracing to spring at Dukes.
14	Spring Creek, intermittent surface stream Buchan Caves Reserve; low flows sink at limestone-volcanics contact.
16	Back Creek, intermittent surface stream near Site 12.
18	Fairy Creek, surface stream in Buchan Caves Reserve that rarely flows.
19	Wilsons Cave, usually dry vadose stream cave, EB-4.
20	Stormwater Tunnel, cave near end of blind valley, M-43.
22	Surface runoff, water sample collected of runoff on Taravale Formation.

Cave numbers are taken from Mathews (1985).

Among the spring sites (which includes the cave stream B - 67) Bitch of a Ditch is unusual. Although all measured values for this site were near the lower ends of their previous recorded ranges, they showed much less response to the flood conditions than the other sites. Bitch of a Ditch alone retained a positive SI_C value and the water remained clear throughout the flood period. The rest of the springs were dramatically affected by the flood. In each case there was a rapid increase in discharge and the flow became highly turbid, suggesting rapid conduit connections with the surface flow systems. Jennings (1985) has suggested that this type of behaviour in karst springs may be characteristic of areas with unreliable rainfall coupled with a liability to high rainfall intensities. Despite this, temperatures remained higher than the surface streams by 2°C to 4°C and the Ca^{++} and total hardness values were also considerably higher. This is probably due to some combination of three processes: mixing of surface water with baseflow water already in the system; modification of the surface water after entering the conduits by transfer of sensible heat from the rock; and "shunting" of older water from the fissures and conduits. Absence of flow data make it difficult to explore these issues further. Moons Cave (B - 54E) flow was closer in concentration to the surface streams than the other springs and this is consistent with its longer term behaviour (see Figure 6). It is more variable than the other springs suggesting more frequent and direct inputs from rapid conduit flow systems, possibly from the Buchan River. Water temperatures at the spring sites show a general relationship to the decrease in total hardness at the time of the flood in July 1984. The higher the ratio of mean total hardness to flood total hardness, the lower the water temperature (Table III). This reflects the varying input of direct surface runoff to spring flow. The surface runoff has a water temperature similar to that of the rainfall (9°C) and low total hardness (Table I). Where hardness values during the flood are similar to the mean value (e.g. Bitch of a Ditch), the water temperature is close to the groundwater value and lower temperatures are associated with lower total hardness when expressed in proportion to means for each site.

The quickflow sites on the limestone (Table II) are generally intermediate between the spring sites and the surface stream sites and were probably receiving flow by both surface and shallow subsurface routes. Certainly Stormwater Tunnel (M - 43) has been observed carrying flow at other times when most of the surface net was not active and the water quality was similar to the nearby spring at Scrubby Creek (M - 49). This observation is also supported by the water temperatures.

CONCLUSIONS

The intense rainfall which produced flooding in the Buchan Caves area in July 1984 was produced by the southward penetration of a low pressure system from the tropical east coast of Australia. Such southerly incursions of tropical lows which bring warm unstable Pacific maritime air onto the highlands of East Gippsland are frequent causes of heavy rainfall there (Linforth, 1969; Gentilli, 1971). Analysis of both the rainfall and streamflow data indicates that the event of July 1984 was not particularly uncommon and had an average recurrence interval no greater than 8 years and probably less.

The surface dry valley network in the Buchan limestone area became active in this event as did the shallow vadose cave systems. The available data does not permit an assessment of the extent to which these systems are still active in the geomorphological sense though the relative frequency of occurrence tends to indicate that they are still undergoing active modification under the present climatic regime. The springs in the

TABLE II. RESULTS OF CHEMICAL ANALYSES

Site No.	Ca^{++} (mg/l)	Total Hardness (mg/l as $CaCO_3$)	Water Temperature (^{o}C)	SI_c	$\log(PCO_2)$
Surface Stream Site					
2) Murrindal River n = 8	16.2 - 54.7	73.4 - 204.5	10.0 - 31.0	-1.07 - 0.90	-2.80 - (-2.40)
July, 1984	3.9	15.4	10.0	-2.22	-2.98
3) Buchan River n = 9	2.6 - 70.1	12.6 - 235.5	10.0 - 21.5	-2.24 - 0.90	-3.25 - (-2.10)
July, 1984	2.9	14.2	9.0	-2.27	-3.01
14) Spring Creek n = 7	3.0 - 91.2	21.8 - 350.8	9.0 - 19.0	-2.26 - (-0.07)	-3.23 - (-1.55)
July, 1984	4.7	20.3	9.0	-2.01	-2.39
16) Back Creek n = 4	26.2 - 68.4	123.0 - 318.6	11.0 - 17.0	-1.13 - 0.23	-2.08 - (-1.44)
July, 1984	3.9	14.9	9.0	-2.28	-2.88
Quick Flow Sites					
18) Fairy Creek n = 1	15.6	60.3	13.0	-0.93	-2.88
July, 1984	5.9	25.8	11.0	-1.82	-2.91
19) Wilsons Cave, July 1984	6.7	27.0	10.0	-1.55	-3.10
20) Stormwater Tunnel n = 3	79.3 - 94.1	217.8 - 350.8	9.0 - 19.0	0.17 - 0.82	-2.69 - (-1.93)
July, 1984	18.3	48.8	9.0	-1.31	-2.39
22) Surface Runoff, July 1984	23.0	59.6	9.0	-1.09	-2.14
Spring Sites					
5) NG - 2 n = 8	14.0 - 73.5	44.9 - 237.4	12.0 - 15.0	-1.68 - 0.05	-3.04 - (-1.79)
no July 1984 sample	-	-	-	-	-
6) Moons n = 9	24.9 - 90.7	107.1 - 291.1	12.0 - 16.0	-1.21 - 0.64	-2.39 - (-1.87)
July, 1984	11.9	41.8	12.0	-1.32	-2.68
7) Dukes n = 11	64.5 - 178.3	206.0 - 594.2	15.0 - 18.0	-0.29 - 0.34	-1.99 - (-1.05)
July, 1984	60.5	199.7	13.0	-0.05	-2.14
9) Scrubby Creek 2 n = 10	48.7 - 124.5	133.9 - 343.8	14.0 - 17.0	-0.64 - 0.73	-2.38 - (-1.54)
July, 1984	27.0	72.0	11.5	-0.96	-2.28
11) M - 4 n = 8	54.3 - 109.4	160.3 - 334.1	13.2 - 17.0	-0.47 - 1.07	-2.78 - (-1.75)
July, 1984	35.8	100.5	11.5	-0.88	-2.12
12) Bitch of a Ditch n = 9	99.6 - 126.7	341.7 - 470.0	16.5 - 18.0	0.16 - 1.09	-2.34 - (-1.37)
July, 1984	103.5	326.3	16.0	0.04	-1.60
13) B - 67 n = 9	114.8 - 188.6	393.3 - 644.7	16.0 - 19.0	-0.01 - 0.38	-1.71 - (-1.25)
July, 1984	42.2	133.4	12.0	-0.69	-2.06
Rainwater (av. 4 samples)	0.65	1.99	9.0	N.A.	N.A.

N.A. = not analysed. n = number of samples.

TABLE III. COMPARISON OF TOTAL HARDNESS RATIOS AND WATER TEMPERATURES.

Site	Ratio of mean total hardness to total hardness in July 1984	Water temperature (°C)
Bitch of a ditch	1.3	16.0
Dukes	2.1	13.0
M-4	2.6	11.5
Scrubby Creek 2	3.4	11.5
B-67	4.1	12.0
Moons	4.4	12.0

Buchan area are known to be connected to diffuse flow systems in the limestone with large storage volumes since flow persists even during drought periods (Ellaway and Finlayson, 1984). Most of these springs are also connected to rapid flow vadose networks (the exception being Bitch of a Ditch) and experience varying contributions of surface and vadose flow to their total flow during flood events. It is also noteworthy that the effects of the flood of July 1984 on water quality in the Buchan area persisted for some months after (Figure 2). Jennings (1972a; 1972b) has drawn attention to the problem of high variability of rainfall and runoff at Cooleman Plains and its effect on karst water quality. This variability problem, probably unique to Australian climatic environment (McMahon, 1982), and its implications for karst water sampling will be discussed in more detail elsewhere.

While there appears to be no other data available with which to compare the recurrence interval analysis carried out here, the dry valley network and the shallow vadose cave systems appear to be active more frequently than might have been expected of a well developed karst system. Three factors may contribute to this in the Buchan area. Sweeting (1960) considered that the cave systems at Buchan were very young and if this is so then the short recurrence intervals for surface flow may be due to lack of development

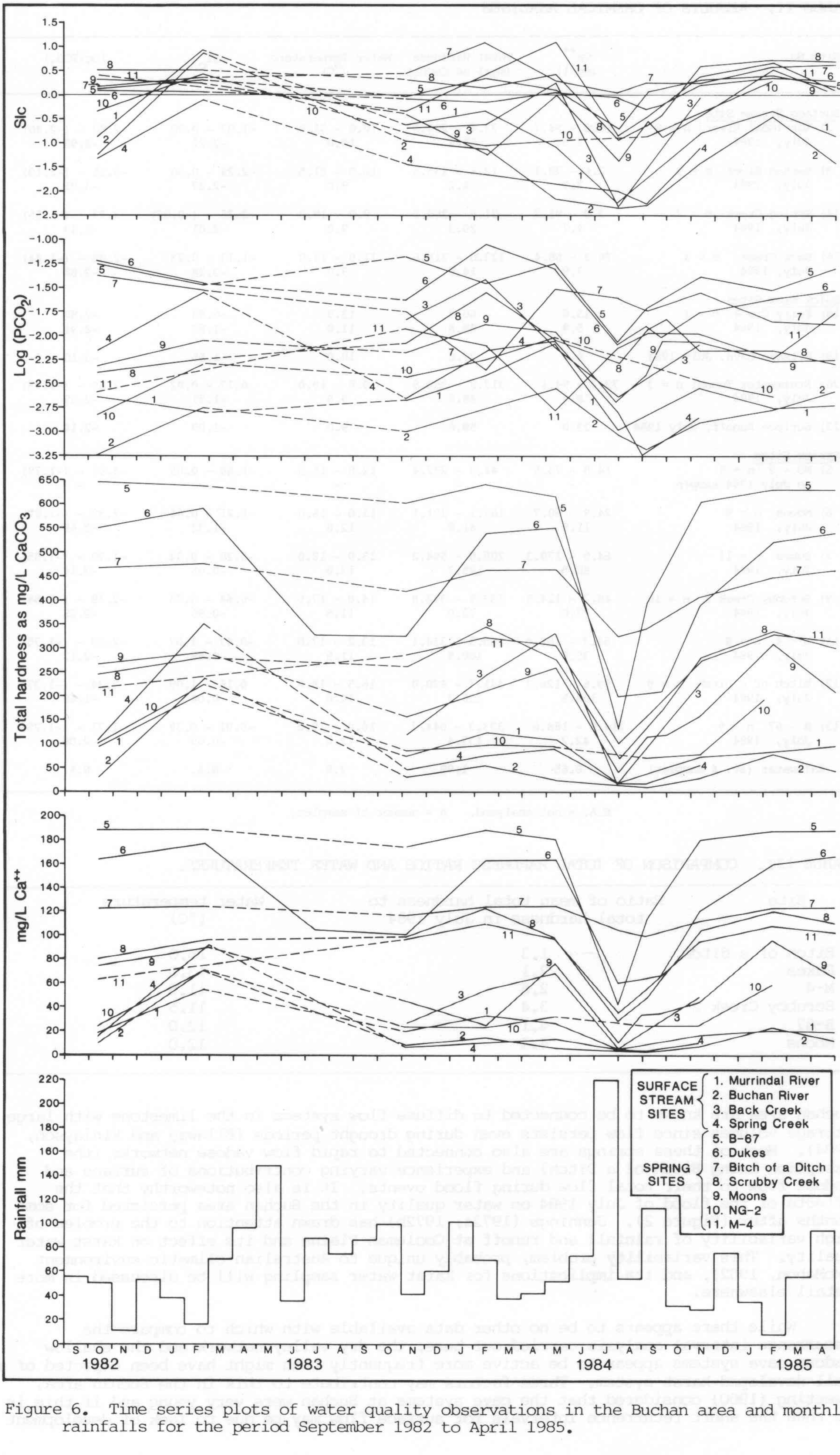

Figure 6. Time series plots of water quality observations in the Buchan area and monthly rainfalls for the period September 1982 to April 1985.

of the underground drainage. While no ages have yet been determined for caves in the Buchan area, and this is obviously an issue which could be explored further, general observations in the caves indicate a complex history of alternating phases of sediment accumulation and removal and the deposition and re-solution of speleothems which suggests that the caves may be relatively old. The Buchan limestones are unusual in that over much of the surface area the outcrop is mudstone of the Taravale Formation and not true limestone. This may affect the relative frequency with which surface runoff occurs. The fact that the Buchan area is a karst barré, or impounded karst (Jennings, 1985), rather than free karst may increase the frequency of surface runoff due to contributions of flow from the surrounding impervious Snowy River Volcanics.

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DEPOSITION OF TUFA ON RYANS AND STOCKYARD CREEKS, CHILLAGOE KARST, NORTH QUEENSLAND: THE ROLE OF EVAPORATION

D.L. Dunkerley

Abstract

A spring which feeds Ryans and Stockyard Creeks west of Chillagoe, north Queensland, was examined in order to understand the circumstances producing extensive deposits of tufa in the stream channels.The spring water was found to be of considerable hardness (300 ppm total carbonates) and to emerge only very slightly supersaturated with respect to calcium carbonate, but undersaturated with respect to dolomite. Both saturation levels rose very rapidly during the first 150 m of subaerial flow, as did pH and water temperature. In contrast to the reported behaviour of other limestone springs, carbonate hardness at this site does not decrease monotonically downstream, but rather locally undergoes significant increases. In particular, magnesium hardness at 1 km downstream is more than 4 times its value at the spring. These phenomena are explained in terms of evaporative concentration of the dissolved carbonates and in terms of possible chemical changes associated with the mixing of waters having contrasting characteristics at channel and pool sites along the streams.

INTRODUCTION

This study was undertaken in order to document the downstream chemical changes undergone by spring waters in a seasonally arid karst area of northern Australia. The spring is located on Ryans Creek in the central Chillagoe karst of north Queensland (see Figure 1). Extensive deposit of tufa (of secondary calcium carbonate laid down from the stream waters) occur along both Ryans and Stockyard Creeks below the spring. The deposits occur both as tufa dams (impounding in some cases very large, deep pools) and as diffuse encrustations in the sandy or rocky channel beds.

The deposition of secondary carbonates such as tufa involves a complex series of physico-chemical processes, not yet thoroughly understood. It is known that a degree of supersaturation is required in the depositing water body before the process of nucleation, in which minute crystal nuclei are formed, can take place (Walton 1967). For concentrations of dissolved carbonates lying between the equilibrium value and the minimum supersaturation level required for nucleation, the solution is in a metastable condition (Nancollas & Reddy 1976) and can remain in this state for considerable periods. For concentrations above the level required for nucleation or precipitation onto pre-existing crystals, the rate of deposition increases (all else being constant) as the degree of supersaturation increases.

In the closed-system environment of the permeable carbonate bedrock through which spring waters move, equilibrium conditions are progressively approached as limestone is taken into solution. If the residence time of the water in the subsurface zone is sufficiently long, the waters may emerge in a condition close to equilibrium. The altered conditions encountered upon emergence may then drive the solution into the region of supersaturation and initiate the deposition of tufa.

In a previous study (Dunkerley 1981) it was shown that tufa deposition along the stream below a tropical spring at Mt Etna near Rockhampton was driven largely by the degassing of carbon dioxide from the spring waters as they approached equilibrium with the atmosphere. The spring on Ryans creek studied in the present work is located in a substantially less humid area, where evaporation could be expected to play a role in concentrating the dissolved carbonates and in so doing force the water into the supersaturated state from which tufa deposition is possible. One aim of the present investigation was to document the role of evaporation in the production of tufa deposits below the Ryans Creek spring.

THE SPRING AND THE CHILLAGOE KARST

The spring lies in the central part of the Chillagoe karst area in northern Queensland. It apparently flows throughout the year, fed by slow diffuse movement of water through the bedrock, which is upper Silurian - lower Devonian reef limestone, in places contact-metamorphosed to marble by the intrusion of granite bodies during the Devonian (De Keyser & Wolff 1964).

Soils on the limestone are generally thin where present and bedrock crops out in many places. The water feeding springs in the karst presumably enters the bedrock over a substantial contributing area and moves down local hydrostatic gradients within the bedrock to the points of emergence in low-lying stream channels. Catchment boundaries for particular springs have not yet been identified.

The area experiences seasonal aridity, with the bulk of the 800 mm of rainfall received annually being delivered in the monsoon season from December to March (Dunkerley 1983). The vegetation consequently is open woodland with a ground cover of native grasses. A few permanent watercourses, including Stockyard Creek and Chillagoe Creek (which is also fed by springs) are associated with very localised communities of taller trees and shrubs, Melaleuca spp. being noteworthy.

During the dry season, Ryans Creek begins at the rising in an area of extensive grass and moss-rimmed pools. Downstream, tufa deposition has created a multitude of pools and cascades which combine to form a large body of fresh water. At the time the observations reported here were made (January 1983) the stream persisted for about 1.5 km before sinking entirely into sandy alluvium forming the bed of the channel. Below this point, isolated pools were present, which may have been connected by seepage through the alluvium. January 1983 was an atypical wet season month, with very little rainfall, and the creek remained in its dry season condition; the flow was estimated to be of the order of 100 litres per minute. During the wet season, accessions of surface runoff from the less permeable rocks in the headwater regions would undoubtedly alter both its appearance and chemistry.

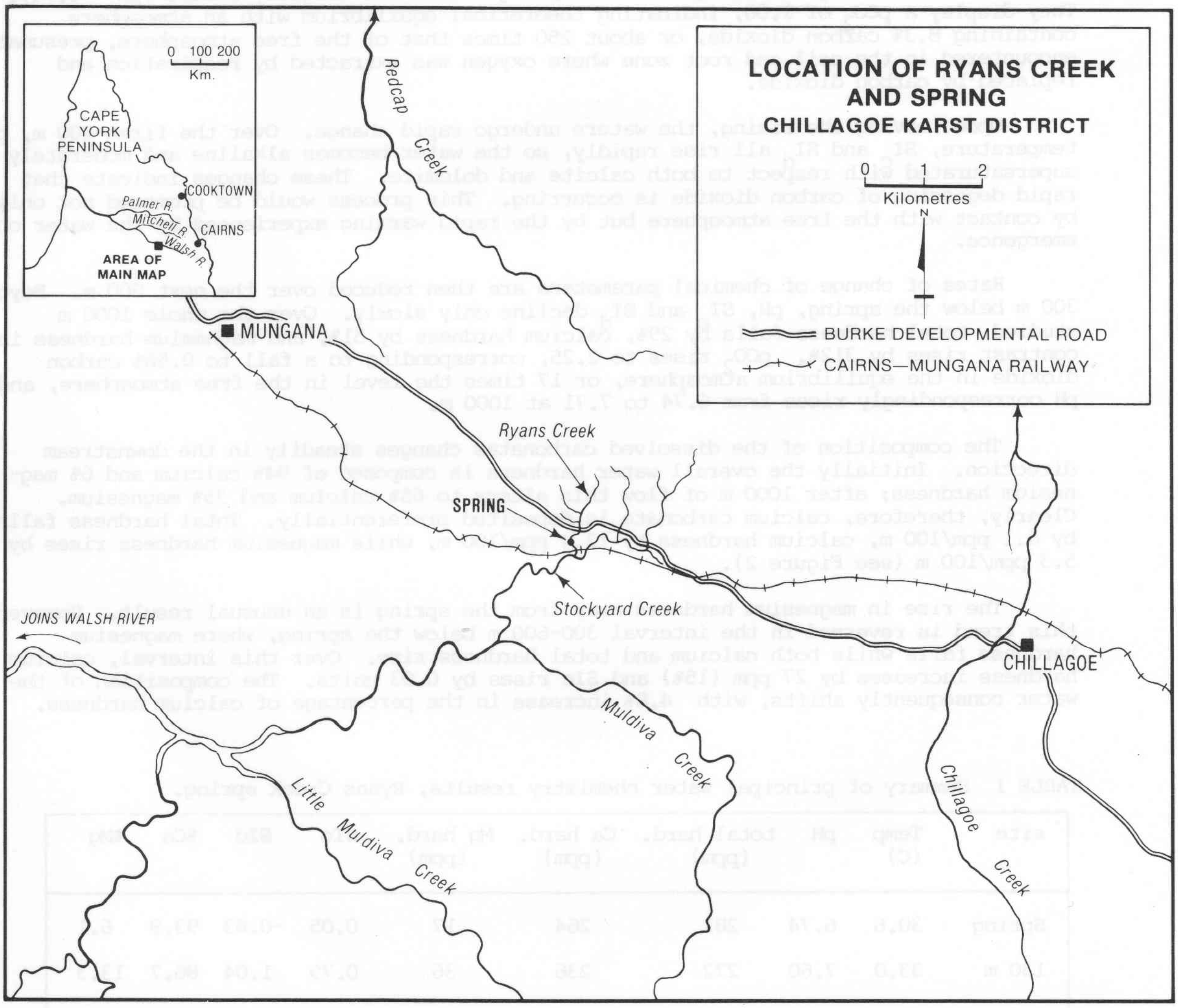

Figure 1 Location map showing Ryans and Stockyard Creeks, Chillagoe karst.

OBSERVATIONS OF WATER CHEMISTRY

Samples of spring water were collected on 6, 12, and 20 January 1983. The major analyses reported here are based upon samples collected on January 12. All samples were collected in rinsed 250 ml capacity polyethylene bottles which were completely filled to exclude air. Water temperature was recorded in the field and all other analyses were carried out at a field camp within 4 hours of collection.

Parameters determined for each sample included pH, electrical conductivity, total and calcium hardness and titration alkalinity. Conductivity was determined with a Metrohm model E587 conductometer and pH with a Metrohm model E588 pH meter using a Metrohm combination electrode standardised in fresh buffers at pH 7 and pH 9.2 prior to use. Hardness was determined by complexometric titration of 50 ml samples using standard BDH reagents. Alkalinity was determined by titration of 50 ml samples to the methyl orange point using 0.02 M HCl. All titrations were performed in white porcelain evaporating basins with continuous steady stirring. Saturation indices and carbon dioxide partial pressures required for equilibrium were determined through the use of the WATSPEC solution model (Wigley 1977).

RESULTS

The principal water chemistry results are presented in Table I and Figure 2.

At the spring, the waters carry a considerable load of dissolved carbonates (about 300 ppm as calcium carbonate), are almost in equilibrium with calcite ($SI_c = 0.05$), and are somewhat undersaturated with respect to dolomite ($SI_d = -0.83$). The spring water is also very warm (30-31°C) and this would act to reduce the uptake of carbon dioxide if typical of the underground stages. The spring waters are slightly acidic (pH = 6.74). They display a pCO_2 of 1.08, indicating theoretical equilibrium with an atmosphere containing 8.3% carbon dioxide, or about 250 times that of the free atmosphere, presumably encountered in the soil and root zone where oxygen was extracted by respiration and replaced by carbon dioxide.

Upon leaving the rising, the waters undergo rapid change. Over the first 200 m, pH, temperature, SI_c and SI_d all rise rapidly, so the water becomes alkaline and moderately supersaturated with respect to both calcite and dolomite. These changes indicate that rapid degassing of carbon dioxide is occurring. This process would be promoted not only by contact with the free atmosphere but by the rapid warming experienced by the water on emergence.

Rates of change of chemical parameters are then reduced over the next 800 m. Beyond 300 m below the spring, pH, SI_c and SI_d decline only slowly. Over the whole 1000 m studied, total hardness falls by 29%, calcium hardness by 51%, and magnesium hardness in contrast rises by 312%. pCO_2 rises to 2.25, corresponding to a fall to 0.56% carbon dioxide in the equilibrium atmosphere, or 17 times the level in the free atmosphere, and pH correspondingly rises from 6.74 to 7.71 at 1000 m.

The composition of the dissolved carbonates changes steadily in the downstream direction. Initially the overall water hardness is composed of 94% calcium and 6% magnesium hardness; after 1000 m of flow this alters to 65% calcium and 35% magnesium. Clearly, therefore, calcium carbonate is deposited preferentially. Total hardness falls by 8.1 ppm/100 m, calcium hardness by 13.4 ppm/100 m, while magnesium hardness rises by 5.3 ppm/100 m (see Figure 2).

The rise in magnesium hardness away from the spring is an unusual result. However, this trend is reversed in the interval 300-600 m below the spring, where magnesium hardness falls while both calcium and total hardness rise. Over this interval, calcium hardness increases by 27 ppm (15%) and SIc rises by 0.03 units. The composition of the water consequently shifts, with 4.8% increase in the percentage of calcium hardness.

TABLE I Summary of principal water chemistry results, Ryans Creek spring.

site	Temp (C)	pH	total hard. (ppm)	Ca hard. (ppm)	Mg hard. (ppm)	SIc	SId	%Ca	%Mg
Spring	30.6	6.74	281	264	17	0.05	-0.83	93.9	6.1
130 m	33.0	7.60	272	236	36	0.79	1.04	86.7	13.3
300 m	33.2	7.75	237	175	62	0.75	1.32	73.8	26.2
600 m	31.0	7.69	257	202	55	0.78	1.26	78.6	21.4
1000 m	31.0	7.71	200	130	70	0.53	1.06	65.0	35.0

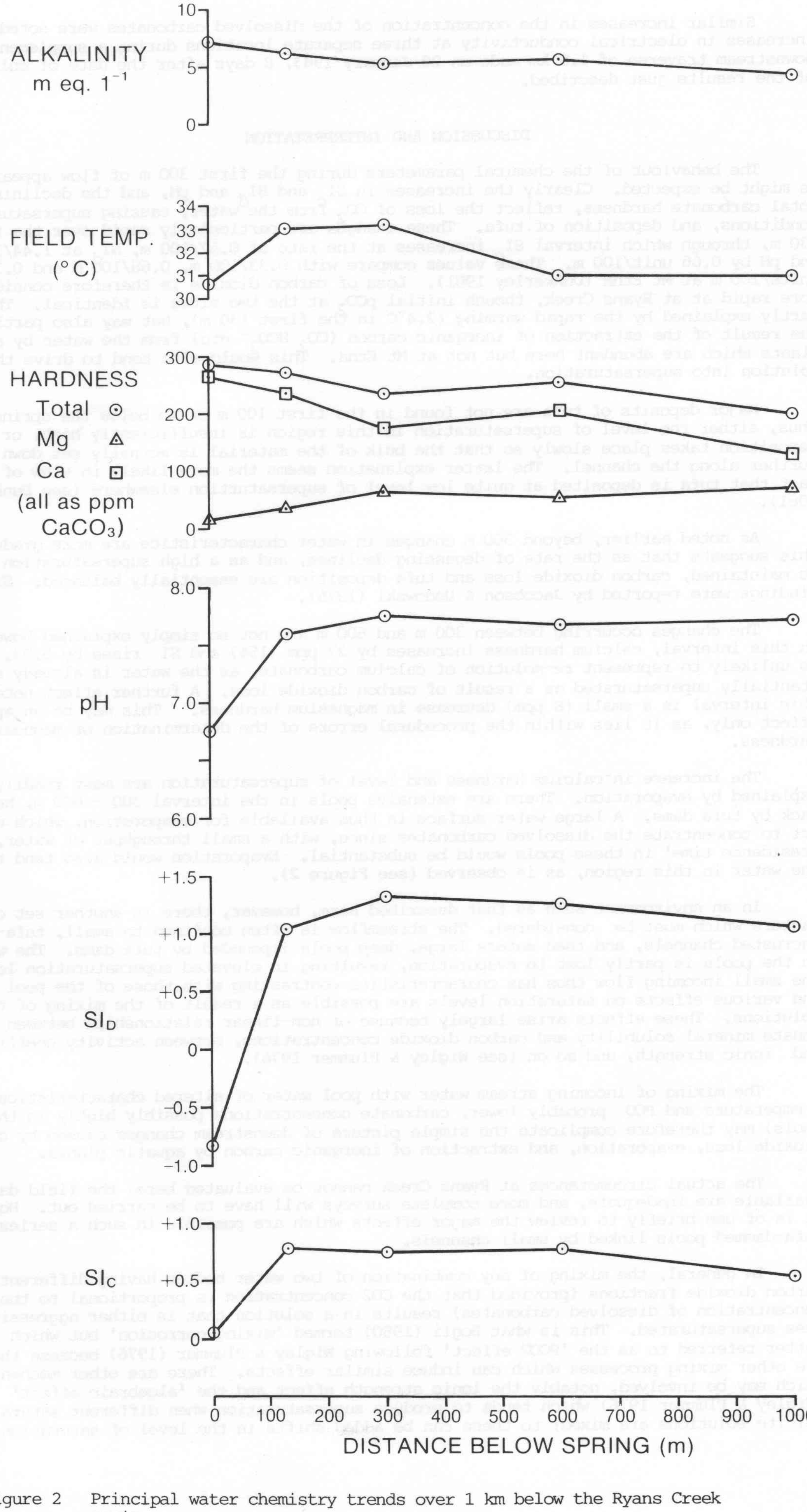

Figure 2 Principal water chemistry trends over 1 km below the Ryans Creek spring.

Similar increases in the concentration of the dissolved carbonates were noted by increases in electrical conductivity at three separate locations during a supplementary downstream traverse of 1.5 km made on 20 January 1983, 8 days after the date of collection of the results just described.

DISCUSSION AND INTERPRETATION

The behaviour of the chemical parameters during the first 300 m of flow appears much as might be expected. Clearly the increases in SI_c and SI_d and pH, and the declining total carbonate hardness, reflect the loss of CO_2 from the water, causing supersaturated conditions, and deposition of tufa. These changes are particularly rapid over the first 130 m, through which interval SI_c increases at the rate of 0.57/100 m, SI_d at 1.44/100 m, and pH by 0.66 unit/100 m. These values compare with 0.33/100 m, 0.68/100 m and 0.37 units/100 m at Mt Etna (Dunkerley 1981). Loss of carbon dioxide is therefore considerably more rapid at at Ryans Creek, though initial pCO_2 at the two sites is identical. This is partly explained by the rapid warming (2.4°C in the first 130 m), but may also partly be the result of the extraction of inorganic carbon (CO_2 HCO_3^- etc) from the water by aquatic plants which are abundant here but not at Mt Etna. This would also tend to drive the solution into supersaturation.

Major deposits of tufa are not found in the first 100 m or so below the spring. Thus, either the level of supersaturation in this region is insufficiently high, or the deposition takes place slowly so that the bulk of the material is actually set down further along the channel. The latter explanation seems the more likely in view of the fact that tufa is deposited at quite low level of supersaturtion elsewhere (see Dunkerley 1981).

As noted earlier, beyond 300 m changes in water characteristics are more gradual. This suggests that as the rate of degassing declines, and as a high supersaturation level is maintained, carbon dioxide loss and tufa deposition are essentially balanced. Similar findings were reported by Jacobson & Usdowski (1975).

The changes occurring between 300 m and 600 m are not so simply explained however. In this interval, calcium hardness increases by 27 ppm (15%) and SI rises by 0.03. This is unlikely to represent re-solution of calcium carbonate, as the water is already substantially supersaturated as a result of carbon dioxide loss. A further effect noted in this interval is a small (8 ppm) decrease in magnesium hardness. This may be an apparent effect only, as it lies within the procedural errors of the determination of magnesium hardness.

The increase in calcium hardness and level of supersaturation are most readily explained by evaporation. There are extensive pools in the interval 300 - 600 m, held back by tufa dams. A large water surface is thus available for evaporation, which would act to concentrate the dissolved carbonates since, with a small throughput of water, the 'residence time' in these pools would be substantial. Evaporation would also tend to cool the water in this region, as is observed (see Figure 2).

In an environment such as that described here, however, there is another set of factors which must be considered. The streamflow is often confined to small, tufa-encrusted channels, and then enters large, deep pools impounded by tufa dams. The water in the pools is partly lost to evaporation, resulting in elevated supersaturation levels. The small incoming flow thus has characteristics contrasting with those of the pool water, and various effects on saturation levels are possible as a result of the mixing of these solutions. These effects arise largely because of non-linear relationships between carbonate mineral solubility and carbon dioxide concentrations, between activity coefficients and ionic strength, and so on (see Wigley & Plummer 1976).

The mixing of incoming stream water with pool water of altered characteristics (temperature and PCO probably lower, carbonate concentrations possibly highly in the pools) may therefore complicate the simple picture of downstream changes caused by carbon dioxide loss, evaporation, and extraction of inorganic carbon by aquatic plants.

The actual circumstances at Ryans Creek cannot be evaluated here: the field data available are inadequate, and more complete surveys will have to be carried out. However, it is of use briefly to review the major effects which are possible in such a series of tufa-dammed pools linked by small channels.

In general, the mixing of any combination of two water bodies having different carbon dioxide fractions (provided that the CO2 concentration is proportional to the concentration of dissolved carbonates) results in a solution that is either aggressive, or less supersaturated. This is what Bogli (1980) termed 'mixing corrosion' but which is better referred to as the 'PCO2 effect' following Wigley & Plummer (1976) because there are other mixing processes which can induce similar effects. There are other mechanisms which may be involved, notably the ionic strength effect and the 'algebraic effect' (Wigley & Plummer 1976) which tends to produce supersaturation when different saturated calcite solutions are mixed; to these can be added shifts in the level of saturation of the mix depending on the temperatures of the separate components. Overall, this array of effects may lead to either lesser or greater saturation depending upon the actual solution characteristics and the volumes of each involved.

An additional effect which may be mentioned is the rejuvenated aggressiveness generated when solutions having different magnesium contents are mixed. According to the results of Picknett (1972), maximum calcite solubility occurs when there is dissolved Mg present to a level of about 10% that of calcium. Both lower and higher Mg concentrations reduce calcite solubility. Hence, mixing of waters with different Mg contents will tend to produce a solution which is more aggressive than either component: i.e., its aggressiveness is renewed. Mixing of waters to produce a solution containing 5-10% Mg should have a particularly marked effect (Picknett 1972).

Because the deposition of magnesium carbonate from saturated solutions is slow (because of still obscure kinetic effects) it is unlikely that solutions differing in Mg concentration could be produced in the length of subaerial flow involved at Ryans Creek. However, the proportion of Mg changes continually at this site because of both calium deposition as tufa and because of evaporative concentration (the magnesium hardness represents 6.1% of the total at the spring and 35% at 1000 m downstream). Similar results demonstrating the concentration of Mg were presented by Douglas (1965). Hence there is ample scope for the effect outlined to operate where, for example, upstream water having an Mg concentration equivalent to 10% that of calcium flows into large pool where evaporation and tufa deposition have increased the proportion of Mg to 20%.

CONCLUSION

This study of tufa deposition in a seasonally dry karst area has demonstrated that both carbon dioxide degassing and concentration of solutes by evaporation are significant factors leading to the deposition of tufa. Carbon dioxide degassing generates the largest increases in saturation levels, found in the first 150 m or so of subaerial flow. Tufa deposition in this region does not proceed sufficiently fast, and the level of disequilibrium increases downstream. Over the remainder of the reach of channel studied, changes in water chemistry are slower. A monotonic decline in solute concentrations is not displayed, however, because of the effects of evaporation. Local increases in solute concentration result at several points along the channels where large pools facilitate water loss. Tufa deposition is probably enhanced at these sites. However, the complex sequence of pools and small channels created by the tufa deposition may have led to more complex reactions not identified here. In particular, the contrasting character of the water entering a tufa dam and the bulk of the water impounded may lead to local increases or decreases in the level of supersaturation. A fuller field survey, incorporating flow measurments and pool volume surveys, will be required to evaluate these effects.

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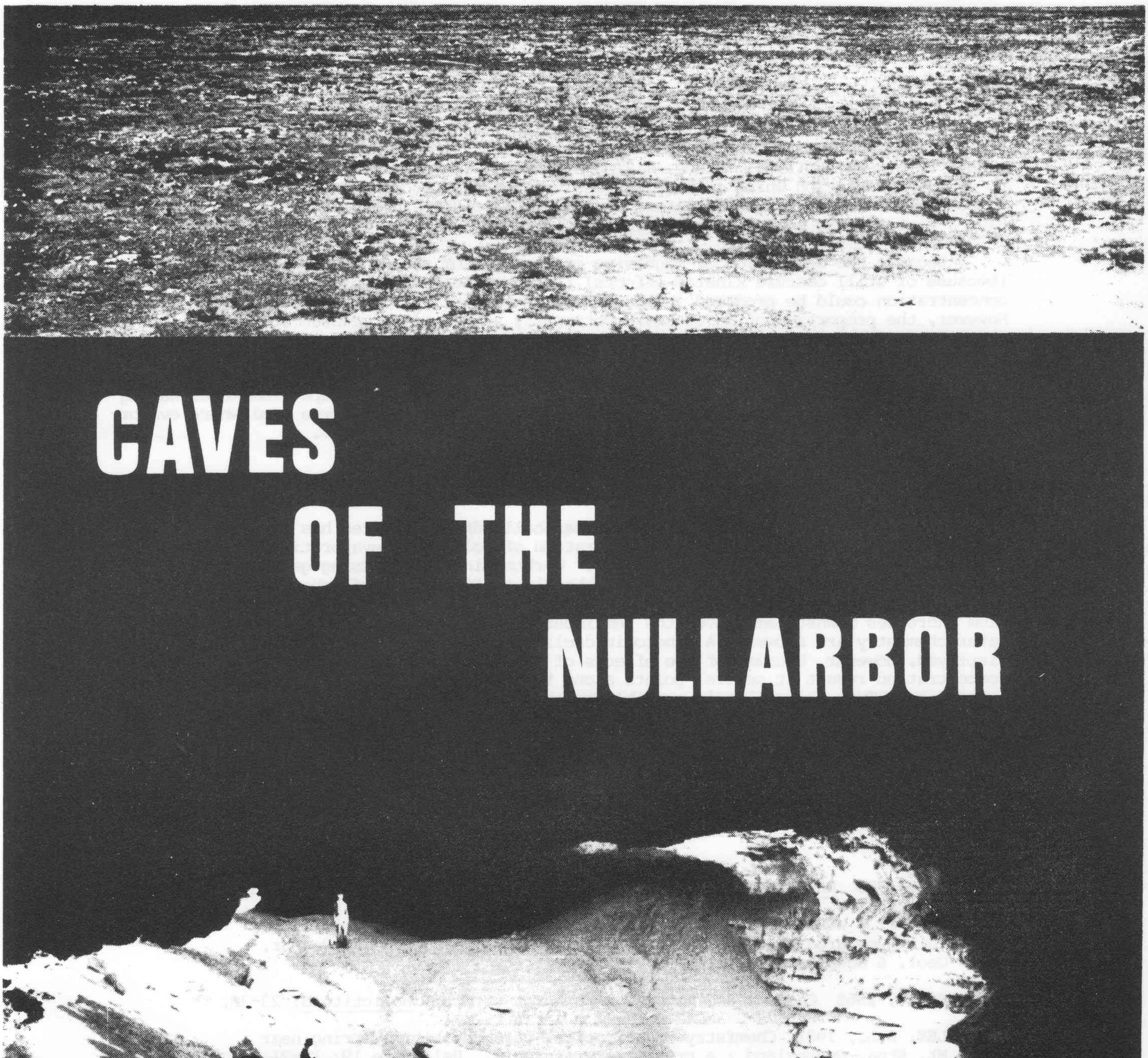

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VOLUME 25(1) 1987

CONTENTS

An Annotated Speleological Bibliography of Oceania
- R. Michael Bourke 3

Observations on the Buchan Karst during High Flow Conditions - Brian Finlayson and Mark Ellaway 21

Deposition of Tufa on Ryans and Stockyard Creeks, Chillagoe Karst, North Queensland
- D.L. Dunkerley 30

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