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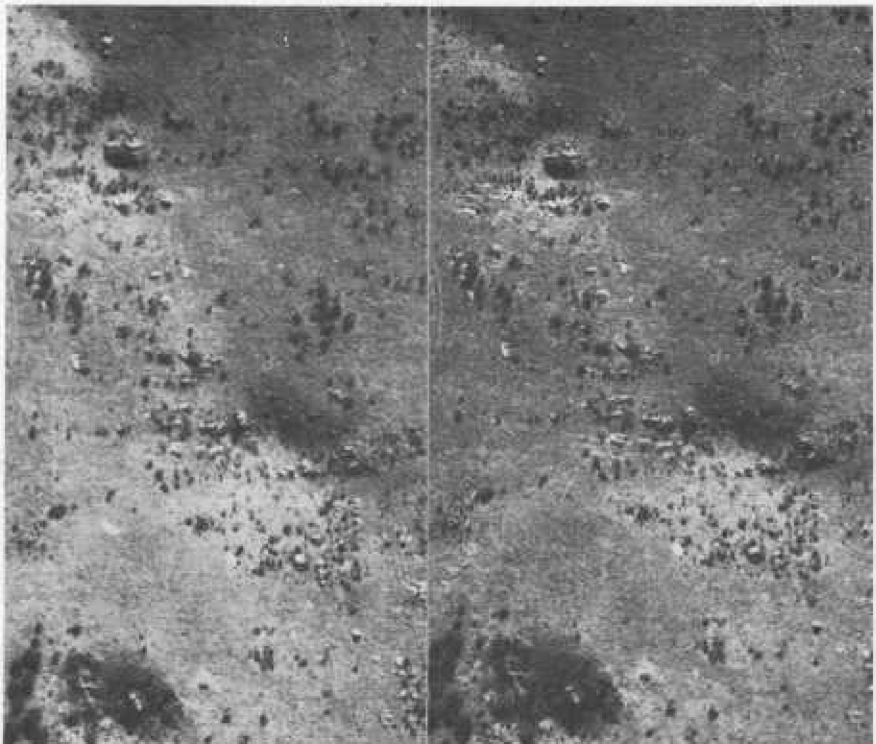
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Stereopair of dolines above Murray Cave, Cooleman Plain, N.S.W.

Photographs from a helicopter by Adrian Davey.

HELICTITE

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

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

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A BIBLIOGRAPHY OF THE JENOLAN CAVES. PART ONE: SPELEOLOGICAL LITERATURE.
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CONTENTS

The cover photograph shows the three dolines at Cooleman Plain studied in the paper by Jennings and Haosheng (page 3). The pictures may be viewed with a pocket stereoscope, but many cavers will find it useful to practice viewing stereo pairs unaided. To do this, simply stare at the photographs until the images fuse and become three-dimensional. If this is difficult, hold a piece of thin card between your nose and the line between the two photographs.

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DETERMINING DOLINE ORIGINS; A CASE STUDY

J.N. Jennings and Bao Haosheng

Abstract

Cases where there is clear evidence about the origin of a doline are less frequent than those where the indications are uncertain. Three dolines above Murray Cave, Cooleman Plain, which are at first sight similar but which in fact include both solution and collapse dolines, are examined to illustrate the strengths and limitations of different kinds of evidence for doline origin. Wherever possible, underground evidence should be sought.

INTRODUCTION

Dolines, closed depressions of simple though varied form, range from a few metres to several hundred metres in dimensions, and are greater in area than depth. They are the most characteristic and numerous of medium-sized karst landforms. Several processes may contribute to their formation and these may alter in relative importance as dolines change with time. Consequentially, there may be "form-convergence" in a strict sense, namely that originally different forms may evolve to a common one (Jennings, 1978, p.38, endnote 20). This may render it impossible to determine origin by the study of form alone. Combining pattern with shape of individual dolines can increase the constraints on interpretation but even then may leave at least two choices of origin. Thus shape measures and pattern analysis permitted a reduction to the two hypotheses of solution and subsidence for dolines at Craigmore and Mt. Cookson in Canterbury Province, New Zealand (Jennings, 1975). Augering demonstrated that in fact two generations of dolines were present, younger subsidence dolines in loess being nested within older solution dolines in underlying limestone. In neither area could dolines be correlated with cave passages, even though there are springs in both areas. At Wee Jasper, New South Wales, both surface and underground morphology are known in a clear case of a young collapse doline (Jennings, 1963) but the nature of two other dolines immediately proximate, for which only surface information is available, and that ambiguous, remains obscure. Reliance on surface morphology and cave form and structure did not prevent one of the present authors (Jennings, 1966) from wrongly interpreting a doline above Easter Cave in Western Australia as a solution doline; later surface augering proved instead that it is a subsidence doline (Lowry, 1967). This note will provide a case study in the analysis of evidence appertaining to the genesis of dolines by reference to a neighbouring trio of dolines from Cooleman Plain, New South Wales.

THREE DOLINES AT COOLEMAN PLAIN, NEW SOUTH WALES

This trio is situated in the southern centre of this plain in the angle formed by the junction of the North Branch and South Branch of Cave Creek. Here both branches are incised well below the flat interfluves which transect a basin structure of Upper Silurian Cooleman Limestone. The interfluves are remnants of a planation surface of probably Lower Tertiary age (Rieder, Jennings and Francis, 1977). In the neighbourhood of the dolines in question, this pure limestone varies from medium to thick bedded, and from fossiliferous to largely recrystallised. Stylolites are also common in parts of the section with impurities gathered along them. On a slightly higher part of the interfluve west of the dolines, there are patches of loose, river gravels (Jennings, 1967). There are also blocks of ferruginous sandstone scattered over the area, though on parts of the plain's margins they form a continuous cover. The ferruginisation is regarded as pedogenic in origin. In addition, there are many blocks of Devonian Rolling Grounds Latite around, not only on the interfluve but extending down the sides of dry valleys cut below it. They were no doubt geliflucted downhill in the last Pleistocene cold period.

Although there are numerous dolines on Cooleman Plain, they are mostly small and there are no fields of dolines, only small groups, alignments and isolated ones. Many are situated along dry valleys. A common location is near the contact between the limestone and impervious rocks; where the ground is steep in this belt, they are often in colluvium or gelifluction covers. Some of the larger and more vigorous ones occur below the thresholds in blind valleys and semiblind valleys; in the latter case they are likely to receive water from the stream when heavy storms fall after soils are saturated or accompany snow melt.

Dolines are fewer on the flat interfluves but the three to be discussed here fall into this category. For Cooleman Plain they are large though on a broader view they must be regarded as small. It was early realised that they probably overlie an extension of Murray Cave (Jennings, 1967). This was verified when drought opened up a watertrap in 1968. This had defied earlier attempts to dive it but had been open previously in 1902-3 during the great drought at the turn of the century (Jennings, Nankivell, Pratt, Curtis and Mendum, 1969).

It was these few facts about the three dolines that led one of the present authors to assert that 'collapse origin is likely' for them (Jennings, 1967). However, well-based studies such as that of Palmer and Palmer (1975) show that though the density of dolines may be greater near cave passages this by no means implies they are necessarily of collapse origin. About the only sure thing that can be deduced from doline pattern on its own is that a close-set field of dolines is unlikely to include more than a few collapse dolines. Large cave systems do not have regular nets of big rockpiles resulting from roof infall of large chambers; these occur sparingly and at best form alignments. So in the case in question distribution does not enable us to exclude even one genetic type. However, other simple facts do; the lack of overlying bedrock formations eliminates the possibility of subjacent (or interstratal) karst dolines and the thinness of soils and superfical covers puts out of count an origin by subsidence (Jennings, 1971).

What can a close analysis of shape tell us? For this a detailed contour map is necessary. Interpolation of formlines between an array of fixed heights involves a subjective element when this is done manually in the field, whilst computer interpolation, though objective, cannot take account of what they eye can see. Therefore contours in a strict sense were surveyed with an AGA geodimeter mounted on a Wild T2 theodolite (a theodolite of such precision is not necessary, of course, but this was the only one available adapted for geodimeter mounting). Two hundred and twenty points were fixed within an area of about 23,000 m^2, a mean density of nearly one per 100 m^2. Plotting was done in the field on a small drafting board with parallel arms. Therefore the resulting map (Figure 2) is considered a good rendering of the ground. The absolute height above sea level is approximate, however, resting on reading contour height from the most detailed published map available (SMHA Sheet 302186 1:15,840) for a datum at Murray Cave entrance.

The northern doline (A) and the central one (B) form a compound closed depression within a 1255 m ring contour and this is aligned along the strike of the rocks, the individual dolines being elongated in the same trend. The lowest part of the rim for both is on the southeast side leading to a dry valley heading away in that direction. Doline A is the shallower of the two, reaching about 3.5 m below that lip. Its steepest slope (30°) is on the northwest side: this asymmetry is hard to explain. It has a large flat floor arranged in a horseshoe around a mass of rock projecting WNW into the middle of the doline.

Doline B is about twice as large and has a depth of 7 m below the same lip. Although the northwest is partly steep in this doline also, the eastern side is both the steepest (30°) and straightest; this is the anti-dip side, a common cause of doline asymmetry. Its floor is saucer-shaped with less flat surface than in A.

Doline C has about the same area as A but its depth below its lowest rim is 6 m. It is circular in plan. All its slopes are steep (30-40°) with the eastern anti-dip side the steepest. Its flat floor is about the same size as that of B (a correction to Jennings et al., 1969).

On this evidence from form, none of the dolines can be firmly related to a given mechanism of formation, since cliffs, which collapse produces, weather down, given time, to the same sort of slope as is characteristic of solution dolines. However, the vigour of doline C makes it the most likely one to be a collapse doline.

The detail of the surface may be considered next. Bedrock outcrops are most frequent and extensive in doline B, less prevalent in doline A and least in doline C where, however, accelerated erosion exposes thicker soil and colluvium than is typical of the other two. Six measures of dip in the northern doline ranged from 23° to 27° to the east, with a mean of 25.5° and a standard deviation of 2.1°. These measurements were made from high on the flanks to the bottom of the doline. In the larger middle doline, twelve dips ranged from 20° to 29°, with a mean of 25.3° and a standard deviation of 3.2°. Again the distribution was general. From this it is inferred that the true dip is about 25° in an azimuth of 80°.

These figures, together with the wide spread of undisturbed bedrock as a whole in the two dolines, mean that cave roof collapse cannot have contributed much to their formation.

Doline C presents a different picture. On the eastern side, two measures of dip gave 21° to the east, which cannot be disassociated from the dips in the previous two dolines. However, there were also dips of 15° and 16°, the latter from a 3 m high buttress. These could mean a tilting back towards the void of the doline. On the western side is a substantial mass of rock with a dip of 41° to the SSW and strike of 300, and a small block, only partly exposed, has a dip of 85° to the south with a strike of 250°. These two measures point to much disturbance of the bedrock and the strong possibility that collapse has contributed dominantly to the formation of the doline.

Doline C is also distinguished by the presence of large blocks of ferruginous sandstone on its slopes and on its rim. Nothing like this is found in the other two. It is to be associated with the thicker soil and sediment on the slopes in C. These facts fit with the idea that doline A and B are of solutional origin, with prolonged and progressive removal of surface materials down enlarged joints, whereas with doline B, a collapse origin of comparatively late date let down a thicker waste cover in one spasm into the depression and this has not yet been much removed through the blockpile beneath into a partly diverted cave river.

This interpretation would retain some degree of uncertainty were this not removed by the underground evidence (Jennings et al., 1969). Where Murray Cave runs under doline A (Figures 1, 2) it has a low, intact bedrock roof and there is no evidence of collapse whatever. Just north of the doline, a short branch leads back from the main stream passage to the northern flank of the doline. Rising from this passage are two blind fissures of estimated heights of 24 and 33 m. Probably insoluble residues and small rubbles have been fed into the cave river from the doline by these routes.

The cave is wider beneath doline B but most of it has a low bedrock roof. There is, however, a tall blind shaft of at least 15 m height. Once again the evidence points to a surface solutional origin for this doline.

As the cave heads towards doline C, the roof rises considerably and then ends in a tall rockpile due to cave breakdown and this is situated just under the northeastern rim of the southernmost doline. Low passages lead off the eastern side of this big boulder choke; still largely filled with water in the 1968 drought, they were not penetrated. However, it is known from water-tracing that there is connection with River Cave beyond to the south. In times of high flood River Cave overflows into Murray Cave, where a great torrent is encountered along its normally dry main passage. Thus the evidence as a whole points conclusively to doline C being dominantly a collapse doline, despite the 20 m of depth which separates the roof of the cave at the rockfall from the floor of the surface depression.

It was not thought worthwhile augering in the bottom of the dolines to provide further evidence, despite its demonstrated usefulness in the case of some New Zealand dolines (Jennings, 1975). It could indicate variations in thickness of fill on their floors (known to be greater than 0.7 m in all cases) but this alone would not help much. It is unlikely, however, that in these circumstances it would be possible by augering to distinguish between large fallen blocks due to collapse from an irregular surface of solution in undistrubed bedrock.

CONCLUSION

Palmer and Palmer (1975) wrote 'contiguous sinkholes of similar topographic form can differ in origin and many are the products of both processes (surface solution and cave collapse) combined'. The Cooleman Plain dolines discussed here could scarcely have had origins attributed to them on the basis of form alone despite some differences between them in this respect. On the other hand, the whole evidence means that one is a collapse doline and the others are solution dolines.

Of course, roof collapse implies that creation of a cave below and solution has played the prime role in this, though a train of coarse, igneous gravel through the cave and mounds of sand here and there point to an important mechanical attack also. The present form of the doline is indicative of some subaerial but mostly subsoil solution of its flanks. In addition there will have been settling through the rockpile of soil and covering sediment that fell in with the roof. In the case of the solution dolines also, it is not a question of one process exclusively - subaerial and subsoil solution-dominant though this has been. Joints and bedding planes have been progressively enlarged by solution to permit evacuation of water, solutes and residues from the surface depression to the cave passage below. This will not only have been by washing down but also by settling of these materials down bedrock fissures and shafts. Small cavities will have developed from time to time in the fill and subsidence of this fill will have contributed to the development of the landform. Nor will the fissures and shafts have always been so full so that some solution-freed blocks will have toppled down. Similar blocks will also have been dragged into the bodies of material settling down these routes to produce gash-breccias - sticky, awkward mixtures well known to cavers trying to penetrate towards the surface from below.

Despite such considerations, the dolines considered here are probably as simple as are likely to be encountered and warrant categorisation in the sense that this has been done here.

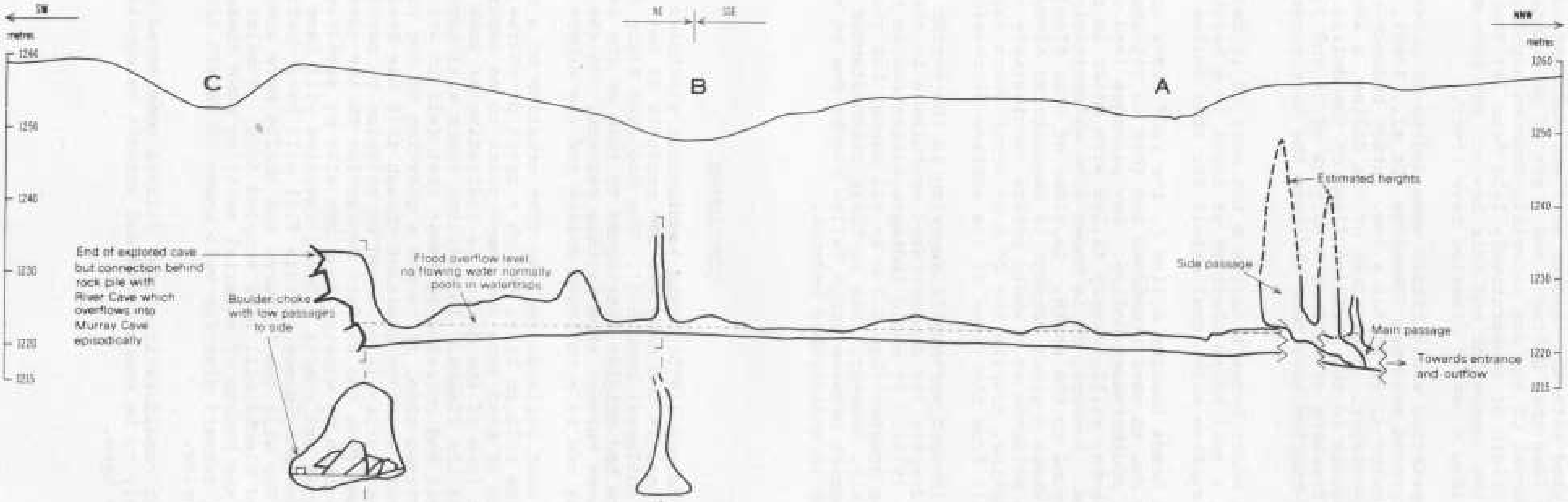
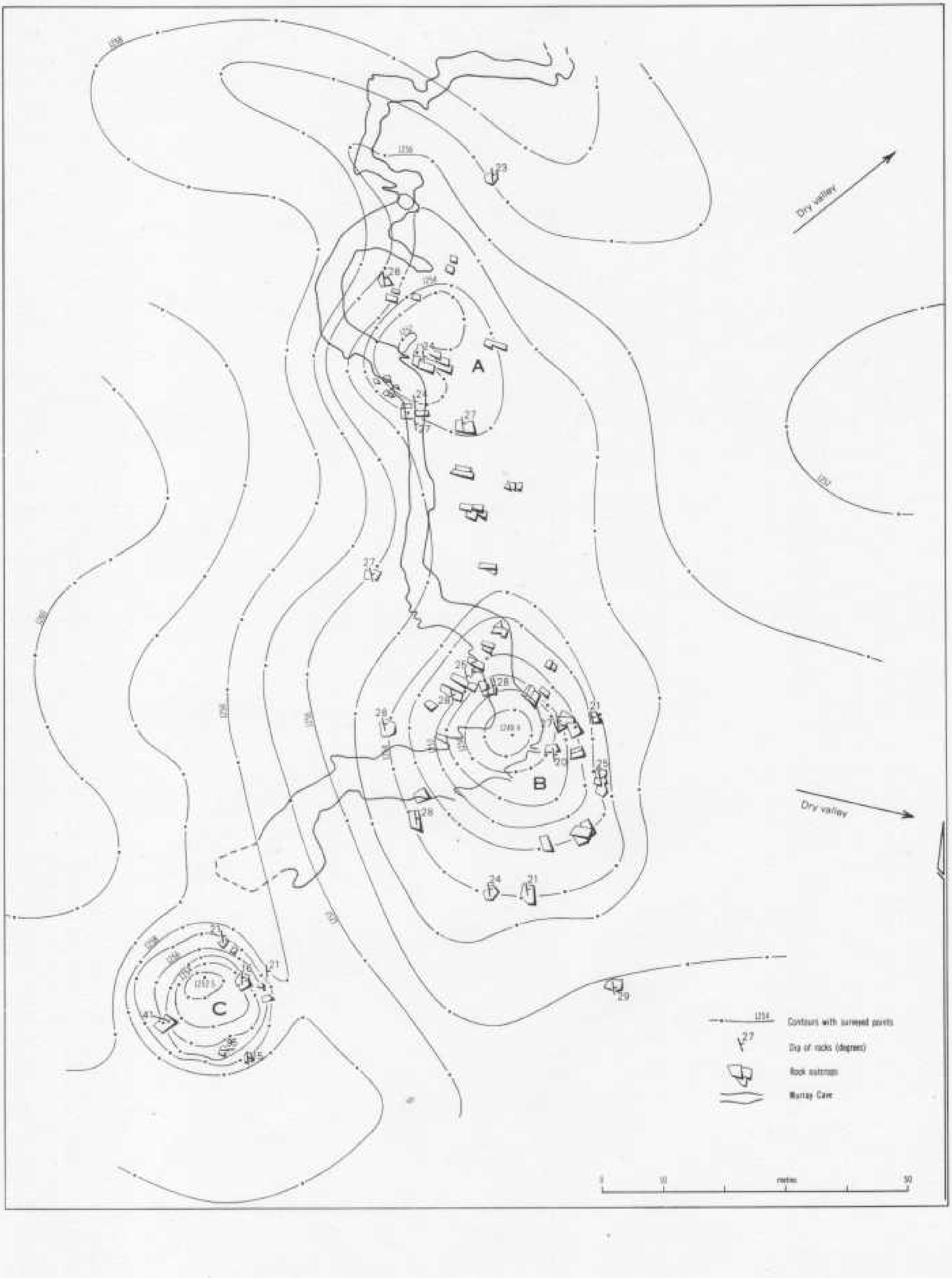


Figure 1 Cross-section through Murray Cave and dolines above it. Cave in extended section taken from Jennings and others 1969. Surface survey by present authors .Final drawing by Pam Millwood,Department of Human Geography, ANU.

Figure 2 (on opposite page) Plan of part of Murray Cave and dolines above it. Outline of cave from Jennings and others 1969. Surface survey and field drawing by present authors. Final drawing by Pam Millwood ,Department of Human Geography,ANU. Only selected rock outcrops in and around dolines mapped.


1258
1256
23
Dry valley
28
1254
A
24
21
27
27
1252
27
21
28
28
1249.4
27
B
21
25
28
Dry valley
24
21
23
18
21
C
1252.5
41
36
15
29
1254
Contours with surveyed points
27
Dip of rocks (degrees)
Rock outcrops
Murray Cave
0
10
metres
50

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WATER CHEMISTRY OF THE ATEA KANANDA AND THE RELATED DRAINAGE AREA

Julia M. James

Abstract

The Ca^{2+}, Mg^{2+}, alkalinity, pH and temperature have been measured in water from the Atea Kananda cave and related surface sites on the Muller Plateau (Papua New Guinea). A wide variation in the Ca^{2+} and Mg^{2+} values was found and this has been attributed to the lithology and nature (open or closed) of the water courses. From alkalinity measurements anions other than bicarbonate, probably sulphate are expected to be present in significant quantities in the cave waters. Most of the waters are aggressive. The $Ca^{2+}/Mg^{2+} \times 10$ ratio is shown to be a useful tool in predicting the origin of unknown waters in the cave. The variations of the measured and calculated parameters for groups of related surface and underground sites are presented and discussed. Tentative solution erosion rates for the Muller Plateau have been calculated and the conclusion reached that where the erosion can be placed as largely occurring on pure limestones these are high. Impure limestones and noncalcareous rocks in their catchments give anomalously low results for the main rivers. A scheme for cave development on the Muller Plateau by solution mechanisms is presented.

INTRODUCTION

The Atea Kananda is a cave located on a plateau which lies between the peaks of the Muller Range and the Strickland Gorge in the Central Highlands (Southern Highlands Province) of Papua New Guinea (Figure 1). This water chemical study was part of the scientific programme of Atea 78, an expedition to the Atea cave in July and August, 1978, (James, 1979).

The Atea Kananda takes its main water flow from Yu Atea (Atea River) and the drainage areas of this river and the Atea Kananda have been defined (James, King and Montgomery, 1976). These areas are covered with tropical montane rainforest and minor areas of montane grassland. Temperatures in the area vary from below 0°C to above 30° and the air temperature in the cave during the period of the expedition was 14°. This will conform to the average annual mean temperature for the area at the altitude of the cave entrance. The annual rainfall is estimated to be at least 3500 mm, distributed fairly evenly throughout the year; evapotranspiration probably lies between 1250-1750 mm (James, Worthington and Innes, 1980). These conditions enhance the production of carbon dioxide in the soil throughout the year, although it has been noted that the partial pressures of carbon dioxide retained in tropical soils in areas of high relief are usually no higher than those in temperate regions (Atkinson and Smith, 1976).

The volumes of water flowing through the Atea Kananda are immense (an average flow of at least 6 $m^3 s^{-1}$) and their corrosive and abrasive power was expected to be correspondingly large. The purpose of the Atea 78 chemical investigation was to find out as much as possible about the corrosive aspects of erosion in this area, specifically to find the locus of limestone solution and to estimate rates of erosion.

Conditions were excellent for field chemical analyses at Atea Gana Anda (Base Camp). A more ambitious programme would have been possible had this been anticipated and more than a minimum of chemical apparatus taken. Analyses were carried out for calcium ions magnesium ions, alkalinity, pH, and temperature of various waters. Aggressiveness was measured using the Stenner method (Stenner, 1969), as analysis for other ions was not undertaken.

METHODS

Water samples were collected in plastic bottles from the following sites:

A. Sites along surface and underground course of Yu Atea (Figure 2, Table I)

1. MR320 - the Yu Atea streamsink. The Yu Atea sinks over a distance of 80 m into its bed, finally disappearing in a log and silt filled pool.
2. MR309 - an Atea Outflow Cave.
3. MR310 - the largest of the Atea Outflow Caves.
4. MR311 - an Atea Outflow Cave, probably an overflow of MR310.

5. MR312 - a bedding plane cave containing multiple springs of the Yu Atea.

6. MR314 - an Atea Outflow Cave.

7. MR315 }
} - two internally connected Atea Outflow Caves.
8. MR316 }

9. Doline Plunge Pool - Atea Kananda entrance.

10. The Ship Canal - a deep wide section of Yu Atea (Figure 3) in the Atea Kananda and 500 m from its entrance.

11. MR345 - the Atea Resurgence.

B. <u>Other surface sites</u> (Figure 2, Table II)

12. Nali Gorge Flow - a small stream which collects from a number of springs in the gorge and joins the Atea Resurgence waters to become the Yu Nali.

13. Atea Gorge Stream - collects in the Atea Gorge from a number of seeps and trickles. At the base of some of these sources are tufa cones. The streams flow over the surface and down a 10 m waterfall and under boulders to the collection point.

14. MR317 - a stream which flows out from under boulders at the base of the Atea Gorge wall. The source of this water is believed to be the Yu Wadaga.

15. MR355 - Base Camp water supply. A spring issuing from a small limestone cave.

16. MR356 - seepage spring in the Atea Doline which is producing a considerable tufa deposit.

17. MR357 - description as for MR356.

18. MR358 - a seepage spring below the Nali camp site depositing tufa.

C. <u>Other Atea Kananda sites</u> (Figure 3, Table III)

<u>Streams</u>

19. Ooze Cruise - the largest stream other than the Yu Atea in the Atea Kananda. Water tracing has shown that it is connected to the Yu Atea.

20. Slot Stream - a stream which flows into the Mill Series and is fed from the Yu Atea.

21. Hidden Inlet - a tributary stream entering Ooze Cruise not fed by the Yu Atea.

22. The Defector - a tributary stream which enters Yukebo, not fed by the Yu Atea.

23. Yukebo I - a collection point above the Defector stream junction on the Yukebo tributary of Ooze Cruise, which contains much sediment and is not fed by the Yu Atea.

24. Yukebo II - collection point in the same stream as 23 but above Strawberry Fields stream junction.

25. Austral stream - a slow moving collection of lakes containing much sediment, not fed by the Yu Atea.

26. Ugwapugwa stream - collects water from a number of sources, drips and blind shafts and one large inlet, Ugwakete.

27. Ugwakete stream - the major feeder of the Ugwapugwa stream. It was sampled at The Spout.

28. Yaragaiya stream - the minor feeder of the Ugwapugwa stream. It is largely a collection of waters from showers in shafts.

<u>Roof inlet streams</u>

29. Ugwapugwa - a shower descending between calcite covered walls.

30. New World.

31. Primrose Hill.

32. Strawberry Fields.

Speleothem deposition sites

33. Ugwapugwa - drips from speleothems exhibiting re-solution.

34. Yaragaiya - a stalactite drip.

35. Rafting Ground - still pools covered with calcite rafts.

The time of collection of the surface samples was close to midday. Collection times for the underground samples were erratic, but usually in the late afternoon or evening. The time of collection may be significant for the response of the cave waters to rain is rapid. Heavy rain generally falls in the afternoon and this should be taken into account in future studies. One sample was taken at each site unless aggressiveness tests were to be made. Samples were analysed as soon as possible, usually on the following day.

Deionised water for the volumetric solutions was prepared by collecting rain water on plastic sheeting and passing it through a Calgon ion exchanger. The results presented in Table IV show that there were insignificant amounts of Ca^{2+} and Mg^{2+} in the collected rainwater with the exception of the last sample, in which there appears to be some contamination. Carefully collected rainwater could have been used without purification for Ca^{2+} and Mg^{2+} analyses. Rainwater purified by passage through the ion exchanger always gave water of a suitable standard.

Ca^{2+} and Mg^{2+} analyses were carried out by EDTA titrations using conventional indicators (Vogel, 1968). A 2 cm^3 microburette was used. All analytical chemicals were weighed in Sydney and sent to Papua New Guinea in sealed containers. The maximum error in the Ca^{2+} and Mg^{2+} titrations is ± 0.01 m moles ℓ^{-1}. Alkalinity was determined by titration with 0.01 M HCl using methyl orange as the indicator. The results for this titration are not very reliable as analyses were not immediate.

pH was measured using a Lovibond Comparator or with BDH Narrow Range pH paper. Temperature was measured with uncalibrated mercury in glass thermometers. Some flow rates were measured, others were estimated (James and Martin, 1980). Rainfall and air temperature were measured at Atea Gana Anda (James et al., 1980) each day during the period of the experiment. Where data are treated statistically, Q-tests have been used for significance.

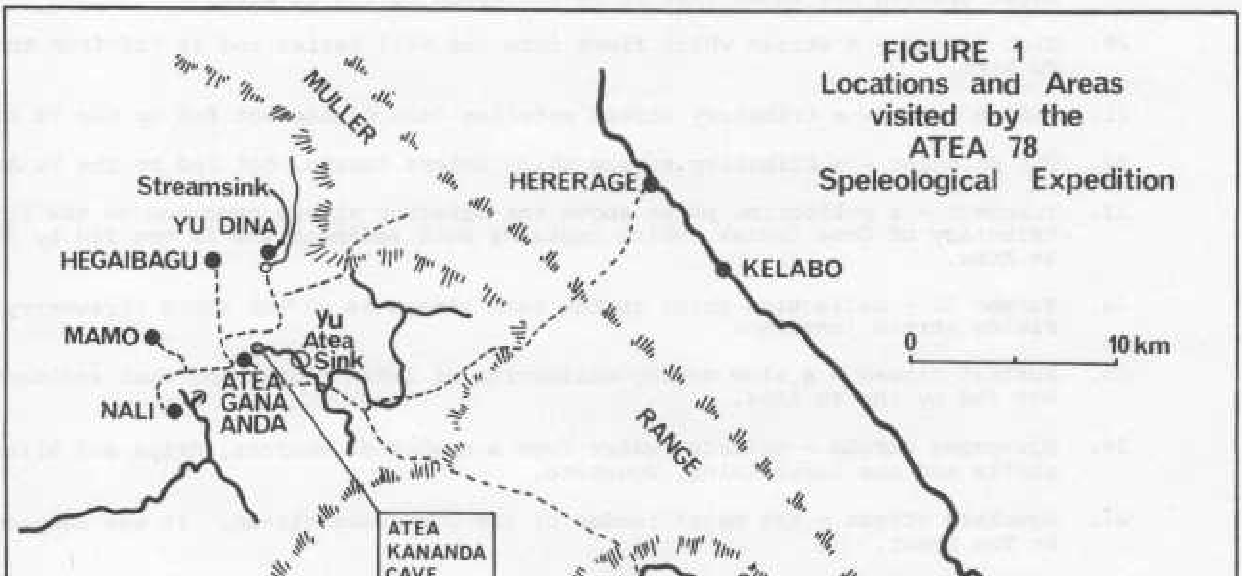
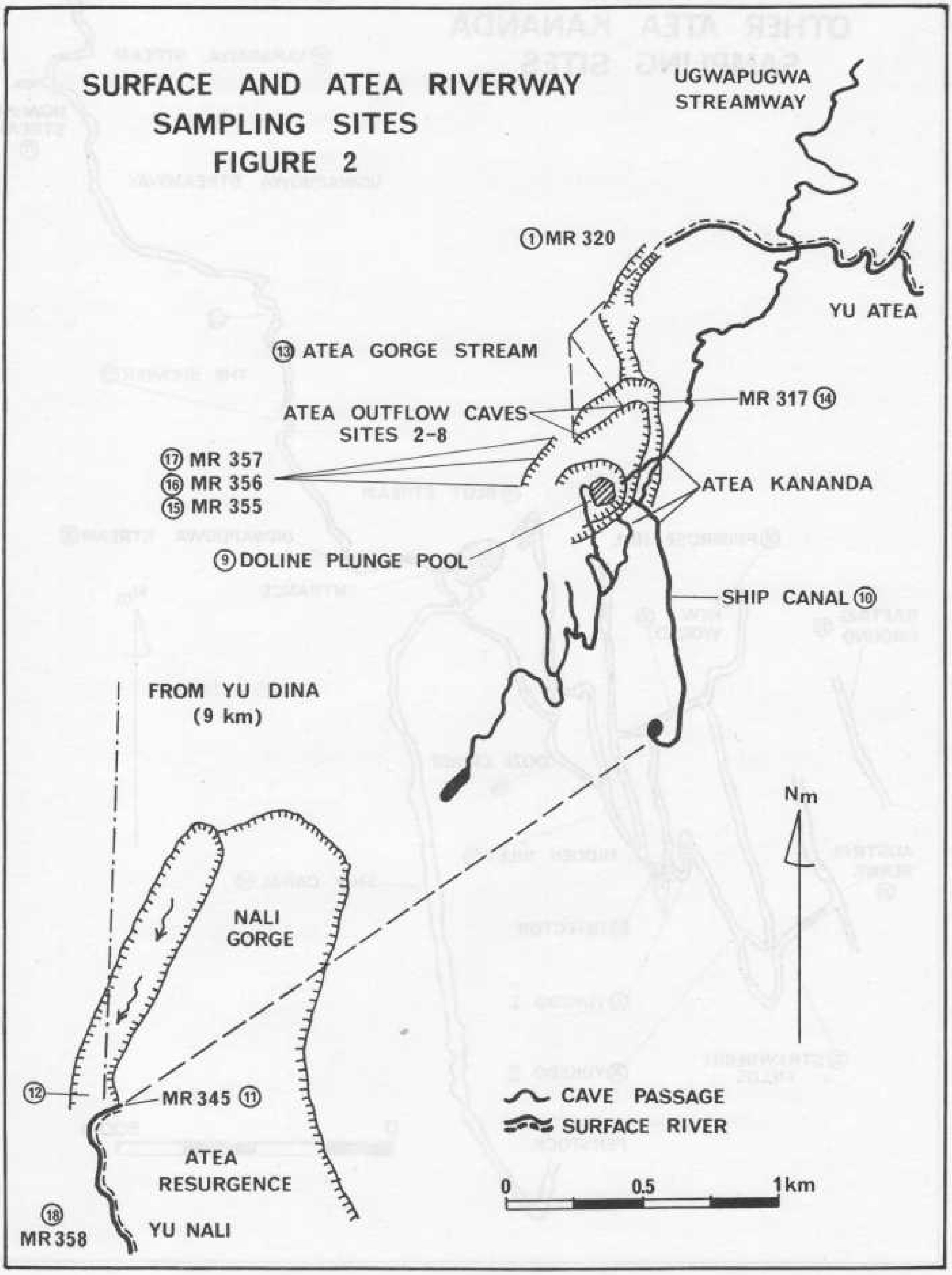


FIGURE 1
Locations and Areas visited by the ATEA 78 Speleological Expedition



SURFACE AND ATEA RIVERWAY SAMPLING SITES

FIGURE 2

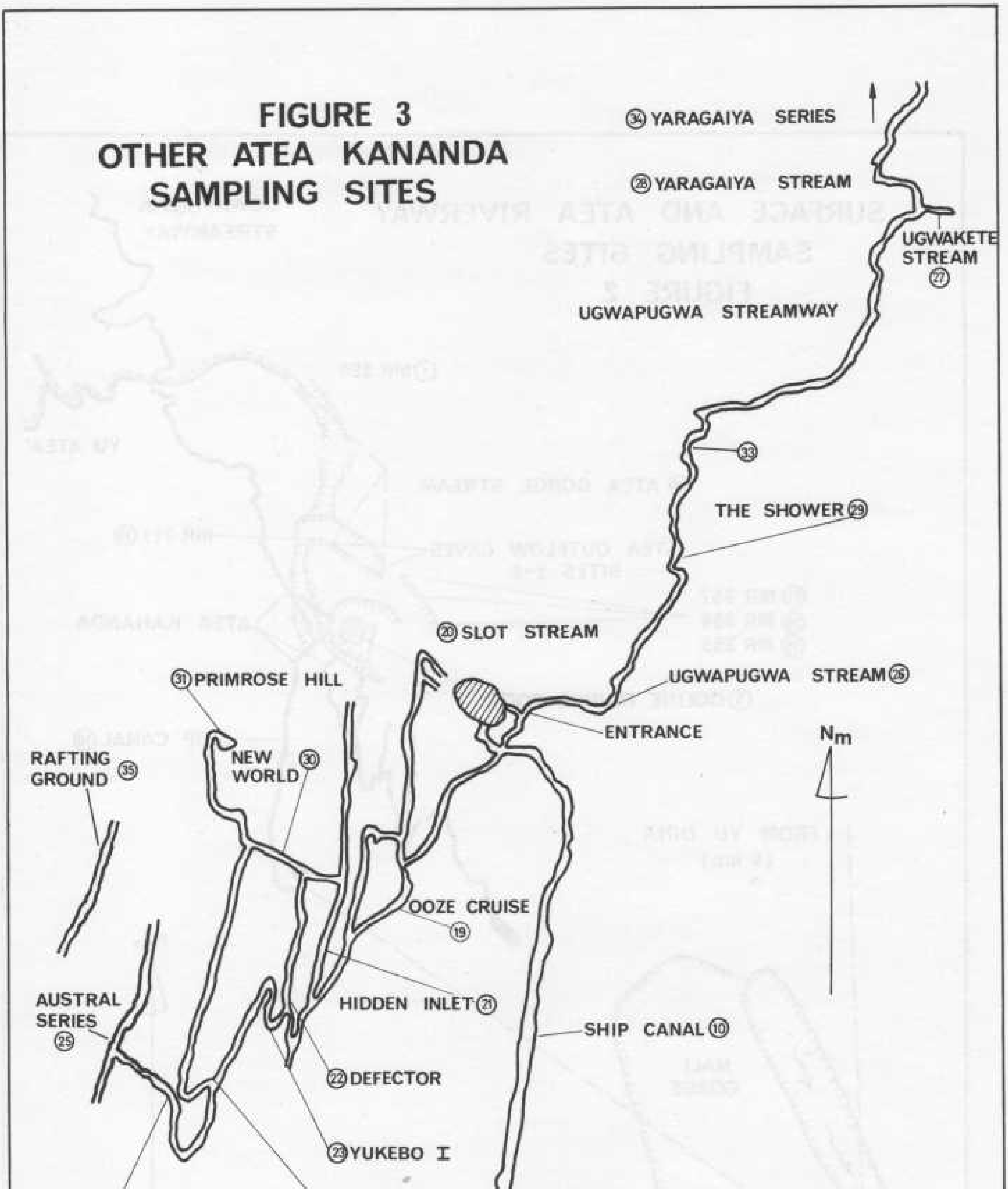


FIGURE 3
OTHER ATEA KANANDA
SAMPLING SITES

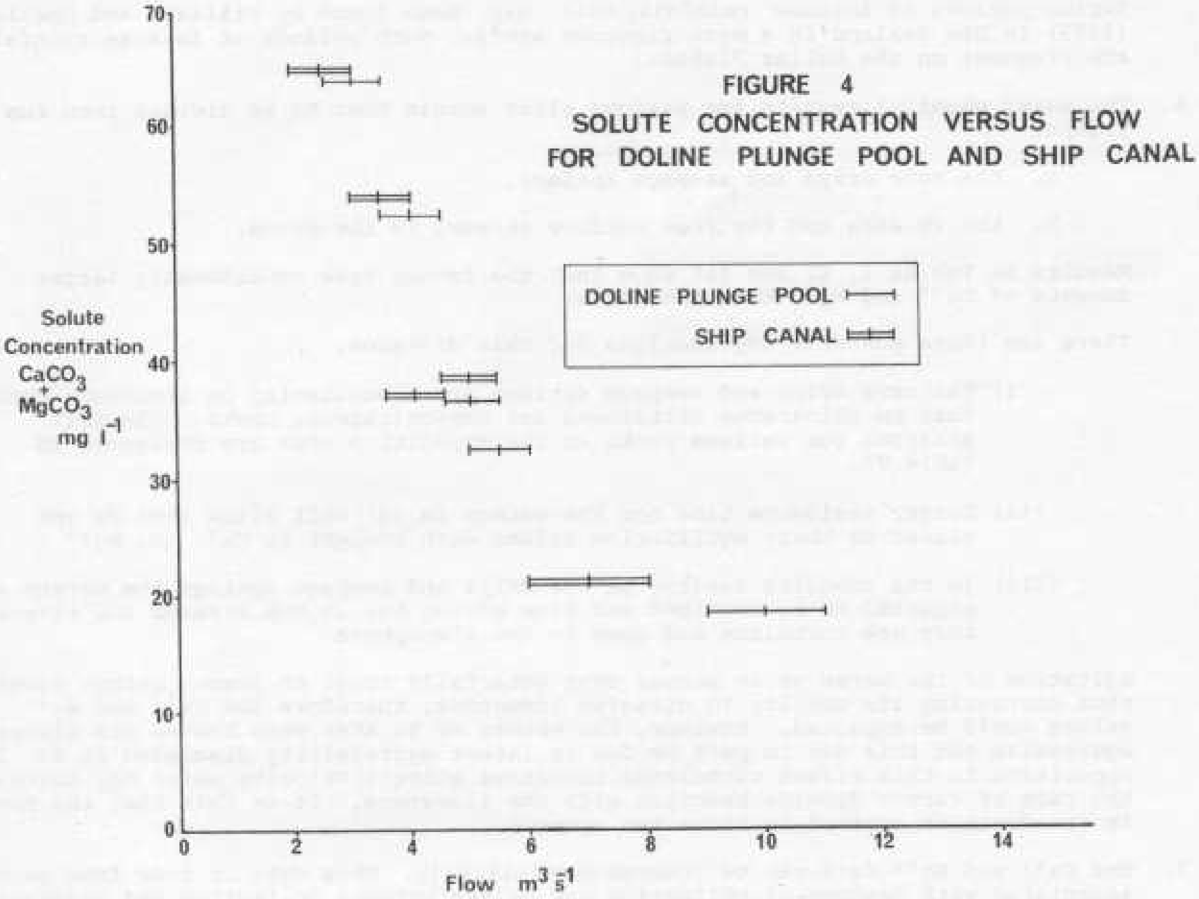


FIGURE 4

SOLUTE CONCENTRATION VERSUS FLOW FOR DOLINE PLUNGE POOL AND SHIP CANAL

RESULTS AND DISCUSSION

The results obtained from the water chemical analyses are presented in Tables I, II and III.

General trends in the chemical data

1. The mean pH for the waters in the area was 7.1, a result obtained from 72 measurements, the range being 6.4 to 7.9.

2. The results obtained on Atea 78 are similar to the only previously published data on the water chemistry of areas in PNG that have similar terrain and climate to the Muller plateau, those from the Australian Star Mountains Expedition (Shepherd, 1965; Jennings, 1972a) and from the British Expedition to PNG (Brook, 1976).

3. In all analyses the Ca^{2+} and Mg^{2+} concentrations do not balance with the calculated hydrogen carbonate from the alkalinity titrations. The alkalinity titrations are not exceptionally reliable (see Methods). However, it is felt that there is also a major contribution from another anion. The large deposits of gypsum in the caves indicate that this anion may be sulphate leached from the pyrite-containing siltstones and limestones.

4. Almost all of the waters tested (Table V) are aggressive. The values obtained are of low accuracy and may only be taken as a qualitative indication of aggressiveness since no effort was made to ensure the waters were at equilibrium. Similar values were obtained in Telefomin (Brook, 1976). Tropical waters usually contain large amounts of organic matter and bacterial decomposition of this would imply a latent aggressiveness. Certainly the deposited sediment in the Atea Kananda is rich in organic matter (c. 5 to 10%, Gillieson, pers. comm.). If the significance of this in cavern development had been realised, it could have been tested in two ways, either by repeated analyses on the same sample over a period of days or by taking the equipment necessary to measure biological oxygen demand.

5. The figures for the Doline Plunge Pool and the Ship Canal (Table I) show that there is a decrease in total $CaCO_3$ and $MgCO_3$ with increasing flow at a specific site (Figure 4). The error bars on the figure demonstrate the considerable errors in the measurement and assessment of the flow (James and Martin, 1980). The total $CaCO_3$ + $MgCO_3$ can be plotted against the measured rainfall figures and a similar decrease with increased rainfall is observed as a flow dilution effect. The flow figures despite their huge errors give the internally consistent graph. The relationship of flow to total $CaCO_3$ + $MgCO_3$ appears to be almost linear although a flattening of the curve is observed in high flow. If this levelling effect in periods of high flow can be proved, then there is a considerable increase in erosion

during periods of intense rainfall; this has been found by Williams and Dowling (1979) in New Zealand in a more rigorous study. Such periods of intense rainfall are frequent on the Muller Plateau.

6. The water chemical results for various sites enable them to be divided into two groups:

   a. the cave drips and seepage springs,

   b. the Yu Atea and the free surface streams in the caves.

Results in Tables I, II and III show that the former have considerably larger amounts of Ca^{2+} and Mg^{2+} than the latter.

There are three possible explanations for this division.

(i) The cave drips and seepage springs are accumulating on limestone rather than on calcareous siltstones and non-calcareous rocks. Chemical analyses for various rocks in the expedition area are presented in Table VI.

(ii) Longer residence time for the waters in (a) will allow them to get closer to their equilibrium values with respect to Ca^{2+} and Mg^{2+}.

(iii) In the conduits leading to the drips and seepage springs the waters are expected to be confined and slow moving but in the streams and rivers they are turbulent and open to the atmosphere.

Agitation of the water as it passes over waterfalls tends to remove carbon dioxide thus decreasing its ability to dissolve limestone, therefore low Ca^{2+} and Mg^{2+} values could be expected. However, the waters of Yu Atea when tested are always aggressive but this may in part be due to latent aggressivity discussed in 4. In opposition to this effect turbulence increases solvent velocity which may increase the rate of carbon dioxide reaction with the limestone. It is felt that the former is the dominant control in these two systems.

7. The Ca^{2+} and Mg^{2+} data can be treated statistically. This data is free from problems associated with methods of collection and delays between collection and analysis. When presented as the ratio

$$\frac{\text{m moles } \ell^{-1}\, Ca^{2+} \times 10}{\text{m moles } \ell^{-1}\, Mg^{2+}}$$

this will be called the Alkaline Earth Mole ratio and will be referred to in the text as AEM ratio and in the tables as AEMR. In the Yu Atea drainage system the AEM ratio remains reasonably constant for given sites regardless of flow conditions. Examples in Table I are the Doline Plunge Pool and the Ship Canal which both have low AEM ratios and the Atea Resurgence (MR345) with much higher values of the ratio. It is possible to relate the AEM ratio to the type of rock being dissolved. Table VII shows the AEM ratio for the pure limestones, the intermediate composition rocks and the non-calcareous rocks. It is noticeable that the pure limestones have the highest and the non-calcareous rocks the lowest AEM ratio. There are exceptions in each of the groupings and this results in high standard deviations.

The observation that Ca^{2+}/Mg^{2+} ratios in karst waters are a good index to whether the groundwater flow has been chiefly in limestone or in dolomite, has been made previously (Jacobson and Langmuir, 1970). When the AEM ratio is related to the Muller Platea geology (Francis, 1980) it can be used as a crude chemical tool for predicting the origin of unknow waters in the area. This is expanding the concept to a greater variety of rock types including some non-karst rocks, hence the variables in the system are greater and the reliability is lower.

Specific groups of samples

Atea River water

Because of its large volume and flow the Yu Atea dominates the water chemistry from streamsink to resurgence despite the chemical differences of the small tributaries joining it. However, gradual changes in water chemistry can be observed between the Atea Streamsink, the Atea Outflow Caves and the Atea Resurgence (Table I).

The Yu Atea waters are always aggressive and carry only small quantities of Ca^{2+} and Mg^{2+} for carbonate rocks. The following three points will all contribute in some way to these low values.

(i) In much of the catchment area and in the cave passages the aggressive waters are prevented from reaching limestone bedrock by insoluble residues from the impure limestones and the non-calcareous rocks.

(ii) The residence time of the water in any part of the river system is short (James and Martin, 1980).

(iii) The known surface and underground courses of the Yu Atea are turbulent. The way each of these effects operates is discussed under the heading "General trends in the chemical data" points 6 and 7.

The Yu Atea waters sink and divide to resurge at the Atea outflow caves; that the waters are all from the same source has been proved by a dye trace (James and Martin, 1980). The chemical analyses for these outflow caves are remarkably similar and hence the seven sources have been summarised and treated as one set of data in Table I. The pick-up value for calcium and magnesium carbonate was calculated for the water passing between the Atea Streamsink and the Atea outflow caves. This was done by comparing the Ca^{2+}/Mg^{2+} data for the two stations on 10-8-78, using flow data from this date. The calculated value was 0.3 mg ℓ^{-1} per 100 m of underground course. This is the same value as that obtained for swallet waters in County Clare, Ireland (High, cited in Atkinson and Smith, 1976). This calculation has a systematic error in that no other ions were taken into account, although significant quantities of them are probably present.

There is no significant increase in the AEM ratio between the Atea Streamsink and its Outflow Caves. These caves are perched on a band of muddy grey-black biomicrite (Francis, 1980) that has a low AEM ratio (Table 6) and the chemical yields from this are probably similar to those from the variety of rocks in the Yu Atea catchment above the Atea Streamsink.

The waters of the Yu Atea leave the Atea Outflow Caves, join waters from the Atea Gorge and MR317 and flow over waterfalls to the next sampling spot, the Doline Plunge Pool. The chemistry of the waters does not change in any significant way between these two surface sites 200 m apart.

The sections of the Yu Atea that were most frequently sampled were in the Doline Plunge Pool at the Atea Kananda Entrance and the Ship Canal. Despite the fact that these lie in the best explored part of the cave, there is no water budget for them. One set of measurements shows a large increase in Ca^{2+} and Mg^{2+} between the Doline Plunge Pool and the Ship Canal and the other two show a decrease; the first measurement is likely to be in error. To calculate any erosion rate within the cave and in a river of such huge dimensions as the Yu Atea requires accurate flow measurements. Even with such improved flow measurements a carefully designed experiment would be needed to obtain reliable erosion rates because the preliminary results indicate that corrosion proceeds slowly. There is no significant change in AEM ratio between the Doline Plunge Pool and the Ship Canal, again consistent with the perching of the Yu Atea on muddy and silty calcareous interbeds with low AEM ratios.

Between the Ship Canal and the Atea Resurgence there is a significant change in water chemistry (Table I) with both the Ca^{2+}, Mg^{2+} and AEM ratios increasing. Unfortunately no conclusions about the unentered cave between the Penstock and the Atea Resurgence can be drawn because all the known Atea Kananda streams have higher Ca^{2+} and Mg^{2+} values and AEM Ratios than the main river and some of these join the Yu Atea between the end of the cave and the Atea Resurgence.

Other surface waters

The Nali Gorge flow in low flow is chemically different from the water that emerges from the Atea Resurgence. It has much lower Ca^{2+} and Mg^{2+} values and AEM ratios. Its chemical characteristics are those of a collection of surface runoff waters, but some of the flow does come from caves and springs. These springs in the Nali Gorge are thought to be a resurgence for the waters which collect in Hadia Yaneabogairi, a cave on Mamo (Figure 1). However, to reach this spring the Mamo cave waters would have to travel a similar distance and through comparable rock types to those of the Yu Atea, and higher values would thus be expected for these three parameters.

The Wadaga Spring MR317 and the stream which collects in the Atea Gorge were carrying similar amounts of Ca^{2+} and Mg^{2+} during the sampling period. However, the Wadaga Spring AEM ratio is considerably lower than the Atea Gorge stream. The Atea Gorge stream occasionally deposits calcium carbonate as is shown by the scattered deposits of tufa along its course. There is no tufa in the Wadaga Spring course between where it emerges from below a cliff to where it joins the Yu Atea. The Wadaga Spring has a chemical composition similar to some of the free surface streams in the Atea Kananda (Table III) which may indicate that it flows through vadose cave passage also.

The camp water supply MR355 contains more dissolved Ca^{2+} and Mg^{2+} and has a high AEM ratio than the open streams. The seepage springs, MR356, MR357 and MR358, all producing considerable tufa deposits, have both the highest Ca^{2+} and Mg^{2+} and the highest AEM ratios. This probably results from the closed nature of their descent through the limestone. Despite the 900 m difference in altitude and subsequent drop in temperature between the higher springs MR356 and MR357 (14°) and the lower spring MR358 (16°) there is little chemical difference.

Other Atea Kananda waters (Table III)

The water chemistry and water traces (James and Martin, 1980) of the Atea Kananda streams allow them to be divided into three groups

1. Ooze Cruise has been proved to be a braid of the Yu Atea, and the Slot Stream is believed to be one. Their water chemistry is consistent with this and it strongly reflects that of their parent the Yu Atea.

2. Hidden Inlet, The Defector, Yukebo and Austral streams probably drain small areas between Atea Gana Anda and the Yu Dina dry valley. It has been proved by water tracing that they are not distributaries of the Yu Atea. They all carry considerably more Ca^{2+} and Mg^{2+} and have higher AEM ratios than the river. The Austral stream has the lowest flow and exhibits the highest values.

3. The Ugwapugwa stream, whose major feeder is Ugwakete, has a course that passes under the Yu Atea twice at a depth of about 60 m, once close to where Ugwakete enters the known passage and the other above where the Shower enters the streamway. It was thought that both these inputs might derive their source from the Yu Atea. Both these inputs into Ugwapugwa Streamway rise dramatically during the afternoon rains. A comparison of the results for Ugwakete with those of the Yu Atea (Table I) and Ooze Cruise (Table II) indicates that the Yu Atea could be the source of its water although a slightly higher AEM ratio could indicate a restricted route allowing some uptake from purer limestone. The only other stream of a size suitable to be the source of the water in Ugwakete is one that sinks high up the Yu Dina valley. This would have a considerable distance to travel underground and hence its water chemistry would then be expected to be similar to the Atea Resurgence (Table I). In addition a dye trace between these two streams was negative, also indicating that this stream was not the source of Ugwakete (James and Martin, 1980). The Shower could be an Atea overflow but, if it is, then its chemistry has changed considerably in such a way as to indicate an indirect and confined route between the source and the point of emergence in the cave. The stream that flows into Ugwapugwa from Yaragaiya is a collection of water from showers and trickles of water in blind shafts. Its water chemistry resembles that of a roof inlet stream.

The roof inlet streams have higher Ca^{2+} and Mg^{2+} and AEM ratios than most of the streams found in the cave. Sources are expected to be collections of water from limited catchments such as a single doline, a slow but direct route into the cave through small bedrock fissures.

Only three speleothem deposition sites were sampled. The Ugwapugwa speleothems are being dissolved and water pours out of hollow stalactites at a fast rate. The chemistry is similar to that of the roof inlets. In Yaragaiya the speleothems are active and dripping slowly. As expected for this environment, the Ca^{2+} and Mg^{2+} values are high.

The Rafting Ground pools have lower Ca^{2+} and Mg^{2+} content than expected for waters depositing calcite. This site is difficult to sample and, as for many cave sites, only one water sample was taken.

Erosion rates

The question that the geomorphologist wants answered by the chemist is: What is the erosion rate of this tropical karst area? From the insufficient data collected, it is impossible to put a precise figure on this rate. Even in detailed and comprehensive studies carried out over several years, for example the experiments of Williams and Dowling (1979) in New Zealand, the errors are in the order of 25%. However, the water chemical results presented in this paper do allow an informed estimate of erosion rates in this tropical area to be made, though it must be stressed that these figures are tentative.

In Table VIII two sets of erosion rates are presented. The first set has been calculated using a modified Corbel formula presented in Atkinson and Smith (1976) and thus enables them to be compared with the collected data in that paper. The second set uses a modified "Williams" formula (Williams and Dowling, 1979). In these two formulae the following generalisations have to be made:

(i) only the erosion rates due to the solution of limestone can be estimated using water chemical results. A comprehensive evaluation of erosion in a karst region requires consideration of both chemical and mechanical activity (Newson, 1971).

(ii) that the Ca^{2+} and Mg^{2+} values can be expressed as carbonates. In a rigorous study it is necessary to make more complete chemical analyses of the waters to verify that this is a safe assumption. Sulphate ion is especially important in this system.

The use of the Corbel formula requires estimates of mean annual evapotranspiration and mean annual rainfall. The methods used for arriving at the limits of these figures are discussed in James et al. (1980). This formula also as presented in Atkinson and Smith (1976) requires a minimum of 50 measurements, and there is no site on the Muller Plateau for which this number of measurements was taken. The data for the Atea Outflow Caves and the Doline Plunge Pool give 29 results which produce an average carbonate value of 50 mg ℓ^{-1} and this is the figure which has been used in Table VIII, part 1. The figure of 40 mg ℓ^{-1} for carbonates used in part 2 of the same table is probably a more realistic value as it is derived from the rainfall and average flow figures for a year. The period July-August is a drier period for the Muller Plateau, hence the higher figure. These figures give low erosion rates when compared with those collected by Atkinson and Smith (1976). This version of the Corbel formula produces different figures for the erosion rates on the Muller when samples are collected at the Doline Plunge Pool and the Atea Resurgence; these are expected to be similar.

The formula derived by Williams appears to be a more reliable way to calculate erosion rates on the Muller Plateau. Erosion rates derived by this method give comparable values for data collected at the Doline Plunge Pool and at the Atea Resurgence (Table VIII, part 2). The Williams formula uses parameters that are obtained from data collected in the expedition area and despite the short collection period this data appears to produce more reliable rates. In addition any assumptions made can framed so that a minimum estimate of erosion rate can be made. The approximately linear relationship between flow and solute concentrations (Figure 4) means that errors in estimating an average flow from a site are in part compensated for by the opposite change in concentrations of calcium and magnesium carbonates. In calculating the drainage area maximum figures have been obtained from the air photos (James et al., 1976). The specific gravity of limestone has been taken as 2.71.

The low figures obtained from both formulae at the Atea Doline Plunge Pool and the Atea Resurgence reflect the large proportion of the Yu Atea catchment which is on non-calcareous and calcareous siltstone (Francis, 1980). It is not possible to include a factor in either formula for the area these rocks cover as it is not clearly defined. In addition the considerable amount of detrital material these produce prevent the aggressive waters having access to the bedrock even when the flow is over limestone.

Geomorphological studies (Francis, Gillieson and James, 1980) indicate that karst development in the Atea 78 expedition area is rapid. An erosion rate consistent with this is obtained from the data for the seepage sites, believed to drain largely Darai Limestone. Using the Corbel formula and nine seepage values much higher rates of erosion (Table VIII, part 1) are achieved and these agree fairly well with what would be expected for this area with high surface runoff from a complete soil cover. The Williams formula gives a figure of 200 $m^3km^{-2}yr^{-1}$ (Table VIII, part 2). It is felt that this figure, engineered by approximations to be a minimum, is indicative of the very high erosion rates possible in the tropics when solution is taking place on pure limestone. This figure with its associated runoff of 1750-3250 mm may be compared with that found by Jennings (1972b) for Cooleman Plain, Australia of 24 $m^3km^{-2}yr^{-1}$ for a runoff of 448 mm and by Williams and Dowling (1979) for Takaka, New Zealand of 100 ± 25 $m^3km^{-2}yr^{-1}$ for a runoff of 1659 mm. The Muller Plateau figures appear consistent.

Cavern development

The chemical results allow us to present a preliminary scheme for cave development by solution on the Muller Plateau. The rainwater falling on clean rock surfaces dissolves little limestone because of its low contact time. In addition many of the rock surfaces contain a weathering rind from which the carbonates have been leached (Francis et al., 1980). If these waters infiltrate the soil rather than run off into the rivers and surface streams, they then come into contact with the large volumes of CO_2 that must be being produced by the luxuriant vegetation but almost certainly is being rapidly flushed out and then, finally into contact with the bedrock. In the bedrock, rapid solution occurs and minor solution cavities are formed, such as the shafts and small caves found over the whole Atea 78 expedition area. As soon as the cavities enlarge sufficiently to allow fast passage of waters, enlargement by solution appears to slow down. Loss of CO_2 must occur, as tufa deposits form on cave and shaft walls. Where there are streams with entrained soil materials flowing down the shafts, enlargement continues largely by mechanical means. Where the conduits are horizontal as in the Atea Outflow Caves, chemical enlargement continues at a substantial rate for longer. However, once these horizontal passages are large enough and the waters are channelled into a single conduit, there is access for large amounts of readily available abrasive materials (Gillieson, 1980) and the daily rains cause high water flows which move them through the system. Chemical enlargement is now very slow because these abrasive materials prevent the aggressive waters reaching the bedrock. Turbulence in the streams makes it more likely that any CO_2 still contained in the water will be lost. Passage enlargement must be rapid by these mechanical means; morphological and sedimentological observations support this. The rapid transport of limestone particles through the system means that they do not dissolve completely before they reach the surface. To verify this picture of cavern development on the Muller, and to test the judgement of all who have seen the Atea Kananda that the development of the modern stage of this cave was a rapid process, three further experiments need to be carried out. A study needs to be made of the quantities and composition of the Atea Kananda sediment load, and microerosion meter sites need to be established at a variety of places especially in the Riverway of the Atea Kananda, and the flattening of the solute concentration versus flow graph at high flows (Figure 4) needs to be confirmed.

CONCLUSION

The results of the Atea 78 expedition as a whole indicate that the rates of erosion in tropical areas such as this are fast. The chemical data discussed here contribute to this overall conclusion. They are inadequate for various reasons to quantify these other observations. However, it is felt that the Muller Plateau is not a suitable area in which to carry out further chemical studies to measure tropical erosion rates. The difficulty of access together with the complex geology of the area, the size of the catchments and the resulting immeasurable large flows in the rivers mean that it will be extremely difficult to quantify most of the necessary parameters for such measurements in a satisfactory manner.

There are however a number of chemical experiments that can be planned on a much smaller scale that would produce a great deal of information about the sources and underground routes of the waters in the area and give more information about the daily cycles within the cave, and cave and karst feature development.

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TABLE I SITES ALONG SURFACE AND UNDERGROUND COURSE OF YU ATEA

Sample	Date 78	Ca^{2+} mmoles ℓ^{-1}	$CaCO_3$ mg ℓ^{-1}	Mg^{2+} mmoles ℓ^{-1}	$MgCO_3$ mg ℓ^{-1}	AEMR*	Flow $m^3 s^{-1}$
MR320 Atea Streamsink	10-8	0.422	42.2	0.052	4.4	81	4.0
MR309-312,315,316 Atea Outflow Caves 7 sites	6-8	0.578(0.009)	57.8	0.066(0.004)	5.6	88	2.5
	8-8	0.458(0.046)	45.8	0.053(0.009)	4.5	86	3.4
	10-8	0.479(0.008)	47.9	0.052(0.005)	4.4	92	3.4
Doline Plunge Pool	16-7	0.338	33.8	0.031	2.6	109	5.0
	18-7	0.298	29.8	0.032	2.7	93	6.0
	23-7	0.332	33.2	0.035	3.0	95	5.0
	6-8	0.575	57.5	0.068	5.7	85	3.0
	8-8	0.480	48.0	0.057	4.8	89	4.0
	10-8	0.479	47.9	0.054	4.6	89	4.0
	22-8	0.168	16.8	0.025	2.1	67	10.0
						mean=90	
						sd=12	
Ship Canal	16-7	0.485	48.5	0.082	6.9	59	4.0
	18-7	0.355	35.5	0.038	3.2	93	5.0
	23-7	0.343	34.3	0.043	3.6	78	4.0
	6-8	0.582	58.2	0.068	5.7	86	2.5
	8-8	0.520	52.0	0.063	5.3	83	3.5
	10-8	0.515	51.5	0.055	4.6	94	3.5
	22-8	0.191	19.1	0.029	2.4	66	7
						mean=80	
						sd=12	
MR345 Atea Resurgence	29-7	0.508	50.8	0.035	3.0	145	-
	7-8	0.615	61.5	0.042	3.5	146	3.0
	9-8	0.560	56.0	0.039	3.3	144	5.5

* Alkaline Earth Mole Ratio

TABLE II OTHER SURFACE SITES

Site	Date 78	Ca^{2+} mmoles ℓ^{-1}	$CaCO_3$ mg ℓ^{-1}	Mg^{2+} mmoles ℓ^{-1}	$MgCO_3$ mg ℓ^{-1}	AEMR	Flow m^3s^{-1}
Nali Gorge Flow	29-7	0.383	8.3	0.062	5.2	62	-
	7-8	0.578	57.8	0.098	8.3	60	0.5
	9-8	0.406	40.6	0.091	7.7	45	1.0
Atea Gorge Stream	6-8	0.982	98.2	0.061	5.1	161	0.01
	8-8	0.795	79.5	0.045	3.8	177	0.02
	10-8	0.801	80.1	0.042	3.5	190	0.02
MR 317	6-8	1.17	117	0.098	8.3	120	0.05
	8-8	0.898	89.8	0.073	6.2	123	0.07
	10-8	0.901	90.1	0.063	5.3	143	0.07
MR 355	6-8	1.21	121	0.074	6.2	163	
	8-8	1.18	118	0.071	5.9	166	
	10-8	1.32	132	0.082	6.9	161	
MR 356	6-8	1.69	169	0.091	7.7	185	
	8-8	1.56	156	0.082	6.9	190	
	10-8	1.62	162	0.081	6.8	200	
MR 357	6-8	1.71	171	0.091	7.7	188	
	8-8	1.62	162	0.080	6.7	203	
	10-8	1.59	159	0.083	7.0	191	
MR 358	7-8	1.54	154	0.083	7.0	186	
	9-8	1.67	167	0.079	6.7	211	

TABLE III OTHER ATEA KANANDA SITES

Site	Date 78	Ca^{2+} mmoles ℓ^{-1}	$CaCO_3$ mg ℓ^{-1}	Mg^{2+} mmoles ℓ^{-1}	$MgCO_3$ mg ℓ^{-1}	AEMR
STREAMS						
Ooze Cruise	6-8	0.341	34.1	0.039	3.3	87
	8-8	0.486	48.6	0.058	4.9	84
Slot Stream	8-8	0.492	49.2	0.058	4.9	85
Hidden Inlet	8-8	0.821	82.1	0.045	3.8	182
Defector	8-8	0.648	64.8	0.068	5.7	95
Yukebo I	27-7	0.72	72.1	0.061	5.1	118
Yukebo II	27-7	0.845	84.5	0.057	4.8	148
Austral	24-7	0.817	81.7	0.056	4.7	146
	27-7	0.924	92.4	0.058	4.9	160
Ugwapugwa Stream	6-8	0.598	59.8	0.054	4.6	111
	8-8	0.502	50.2	0.045	3.8	112
	10-8	0.515	51.4	0.043	3.6	120
Ugwakete Stream	6-8	0.545	54.5	0.054	4.5	100
	10-8	0.515	51.5	0.052	4.4	99
Yaragaiya Stream	6-8	0.896	89.6	0.074	6.2	121
ROOF INLETS						
Ugwapugwa	6-8	1.06	106	0.023	1.9	460
New World	22-7	1.21	121	0.053	4.5	228
Primrose Hill	22-7	1.04	104	0.062	5.2	168
Strawberry Fields	22-7	1.22	122	0.039	3.3	313
SPELEOTHEM DEPOSITION						
Ugwapugwa	6-8	0.981	98.1	0.032	2.7	306
Yaragaiya	23-7	1.54	154	0.121	10.2	127
Rafting Ground	24-7	1.38	138	0.061	5.1	226

TABLE IV RAINWATER AND DEIONISED WATER

Sample	Date 78	Ca^{2+} mmoles ℓ^{-1}	$CaCO_3$ mg ℓ^{-1}	Mg^{2+}
Rainwater	6-8	0.002	0.2	beyond limit of detection
	8-8	0.001	0.1	
	10-8	0.020	2.0	
Deionised water	6-8	0.001	0.1	
	8-8	0.000	0.0	
	10-8	0.001	0.1	

TABLE V AGGRESSIVITY (24 or 48 hours)

Site	Date 78	$CaCO_3$ + $MgCO_3$ mg ℓ^{-1}	Additional $CaCO_3$ mg ℓ^{-1} (24 hr)	Additional $CaCO_3$ mg ℓ^{-1} (48 hr)
Atea Sink MR 320	10-8	46.6	+22	-
Atea Outflow Cave MR 310	8-8	52.1	-	+24
Atea Outflow Cave MR 316	8-8	37.5	-	+18
Wadaga Stream Mr 317	8-8	95.4	-	+16
Atea Gorge Flow	8-8	83.3	-	+12
Doline Plunge Pool	8-8	52.8	-	+32
Ship Canal	8-8	57.3	-	+14
Nali Gorge Flow	7-8	66.1	+18	-
Atea Resurgence MR 345	7-8	65.0	+22	-
Atea Resurgence MR 358	7-8	161	+ 2	-
Atea Resurgence MR 355	10-8	134	+ 6	-

TABLE VI CHEMICAL CHARACTERISTICS OF ROCKS FROM THE EXPEDITION AREA**

Sample Site	Rock type	% insoluble material	% $CaCO_3$ *	% $MgCO_3$ *	AEMR
Yu Tagana crossing	cream algal - foraminiferal biomicrite	1.8	93.8	1.3	608
Atea Doline	grey algal - foraminiferal biomicrite	2.8	86.4	2.6	280
1.5 km NE of Ponganepo	cream algal - foraminiferal biomicrite	4.4	93.1	1.9	413
2 km NW of Mt. Legari	cream microsparite	6.6	95.2	1.3	617
Atea Gana Anda	muddy grey recrystallised limestone	9.2	88.5	1.4	533
Atea Gana Anda	muddy grey biomicrite	12.3	86.5	1.8	405
0.5 km SW of Ponganepo	muddy cream biomicrite	25.7	64.9	2.0	274
Atea Kananda Winchester Chamber	silty grey biomicrite	29.4 29.5	66.5 62.1	1.4 1.5	400 350
Atea Kananda Silver Hammer Chamber	silty grey biomicrite	30.2 30.8	54.9 63.7	2.4 2.4	193 224
0.8 km W of Anu Pass	silty grey biomicrite	34.4	56.3	2.9	164
Band below Atea Outflow Caves	muddy grey-black biomicrite	41.8 35.8	50.8 58.4	1.6 1.6	268 308
200 m NE of Anu Pass	muddy grey biomicrite	41.7	55.8	2.1	224
Yu Atea Sink	dark grey calcareous siltstone	52.3	40.2	2.7	126
500 m N of Yu Dina Sink	laminated quartzose siltstone	90.2	1.1	2.6	4
Yu Atea crossing 1.3 km SW of Ponganepo	grey silstone with chert nodules	92.2	0.7	1.8	3

Other siltstone and limestone analyses in the area can be found in Caffyn (1974).

* Calculated from analyses for Ca^{2+} and Mg^{2+}.

** Analyses on air dry samples.

Collection and identification of rock types G. Francis and J. Webb.

TABLE VII AEM RATIOS FOR VARIOUS ROCK GROUPS

	No. of samples		AEMR Range	AEMR Mean	AEMR sd
Pure limestones	11	5 this work 6 Caffyn (1974)	707-280	503	138
Intermediate rock types	12	11 this work 1 Caffyn (1974)	404-126	256	91
Non calcareous siltstones	2	this work	4-3	3.5	

TABLE VIII EROSION RATES

Part 1

Site	$CaCO_3 + MgCO_3$ mg ℓ^{-1}	Precipitation mm	Evapo-transpiration mm	Erosion Rate Corbel* $m^3km^{-2}yr^{-1}$
Atea Resurgence	60	3500-4500	1250-1750	40-80
Doline Plunge Pool	40	"	"	30-70
Doline Plunge Pool + Atea Outflow Caves 29 measurements	50	"	"	35-75
Seepage Sites 9 measurements	169	"	"	120-220

Part 2

	$CaCO_3 + MgCO_3$	Flow	Catchment Area	Williams Formula** $m^3km^{-2}yr^{-1}$
Atea Resurgence	60	6 $m^3 s^{-1}$	165 km^2	25
Doline Plunge Pool	40	4 $m^3 s^{-1}$	90 km^2	26
Seepage Spring M357	170	2 ℓ/s	0.5 km^2	200

* Corbel Formula (Atkinson and Smith, 1976) used without a factor for the % of the area that is karst.

** Williams Formula (Williams and Dowling, 1979) used without a factor for the % of the area that is karst; specific gravity taken as 2.71.

THE ORIGIN OF DEEPDENE NEAR AUGUSTA, WESTERN AUSTRALIA

J.N. Jennings

In a paper on the mammal fauna from bones in two small caves in the eastern cliff of the Turner Brook gorge, known as Deepdene, in the Pleistocene aeolian calcarenite of the southwest of Western Australia, Archer and Baynes (1972) report observations which lead them to suggest a mode of formation for the gorge alternative to that proposed by Bain (1962) and supported by Jennings (1968).

In the earlier interpretation of Bain and Jennings, Turner Brook persisted in a prior course to the sea despite the inland movement of beach sand to form a line of dunes. This process is found at an earlier and unmistakable stage in King Island, Tasmania, where such defiles through dunes have been called 'gorges of construction' (Jennings 1957). At Deepdene, the dune ridge became indurated. Reasons for rejecting a collapsed cave origin for the Deepdene gorge were given.

Archer and Baynes (1972) found near the base of the Deepdene cliffs 'rounded heads of granite cobbles that resemble coastal cobble beds' and along the Brook sediments containing fragments of marine echinoids, bryozoans, molluscs and benthic foraminifera. Also the roofs of small caves or pockets in the cliffs are made of cemented limestone rubble foreign to the aeolian calcarenite. On these grounds they suggested that the cliffs were formed by the sea in a previous higher stand of sea level. The new facts must, of course, be accommodated by any interpretation of the geomorphology but it will be argued here that there are difficulties about the evolution proposed by Archer and Baynes and that a simpler explanation of the new facts is feasible without change to the hypothesis favoured by Bain and Jennings.

At least two readings can be placed on Archer and Baynes' remarks. In the one, the gorge is taken to be entirely the product of marine erosion in a coastal dune ridge indurated before this erosion. This implies that the sea cut a channel about 100 m wide, 600 m long and up to 60 m deep through a dune limestone ridge near its northwestern end (Figure 1), leaving only about 300 m of the ridge beyond. The direction of this channel makes an angle of about 60⁰ with the trend of the dune ridge and the present coast.

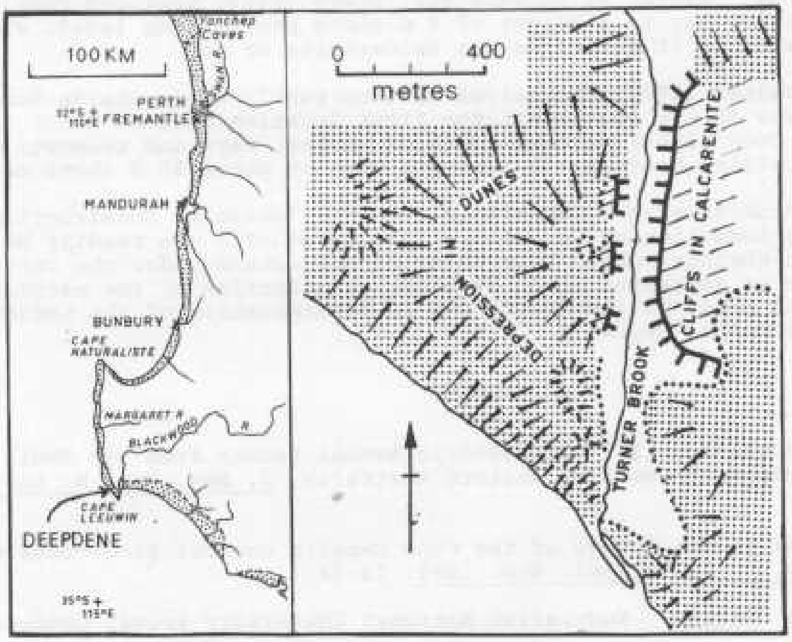

Figure 1. Locality map and sketchmap of Deepdene.

To begin with, a geo must have been cut back on the seaward side, eventually to break through and leave the free end of the ridge as a large stack or islet.

Such geos are found where differential erosion has taken place for geological reasons, waves working back along a plane of weakness such as a fault or eroding a dyke or a bed of weaker rock where beds are steeply inclined (Bird 1972). Sometimes that erosion first produced a sea cave of which the roof fell in later. No faults are known in the aeolian calcarenite of the southwest, and although joints can be found, they are only incipiently developed and no one has recorded them having any geomorphic effect, for example, on cave morphology. Variations in the consolidation and mechanical strength of the dune limestone are vertically, not laterally, arranged so they cannot promote the cutting of an inlet. Therefore a structural basis for the formation of the sort of sea channel required is lacking.

Moreover, if such a channel had formed, the projecting end of the dune ridge could hardly have become a sea stack without its other exposed sides becoming cliffed also. There is no sign of such cliffing, even allowing for some fresh sand plastering the relief where the Turner Brook could not keep it out as it does along the gorge. Thus arguing from the general principles of coastal geomorphology it is unlikely that marine erosion has created the gorge.

A second reading of Archer and Bayne's remarks is that the Turner Brook had maintained its course across a growing dune line to produce a gorge of construction and at a later stage the sea rose and entered the gorge, depositing the materials they have identified and cliffing formerly less steep valley sides in the consolidating sands. This avoids the difficulties set out above. However, it is hard to see how at one and the same time, waves cut these cliffs as required and yet deposited rubble, eroded from the aeolian calcarenite, in layers within it, which were subsequently undercut by weathering to form the small caves.

A more likely explanation supported here is that the relevant high sea level preceded the dune ridge formation, that the marine materials underlie the aeolian calcarenite and that Turner Brook has failed to remove all of them as it subsequently extended its course seawards with falling sea level, exposing, of course, fresh supplies of them as it cut laterally from time to time to steepen the gorge walls.

There is evidence of similar deposits under the aeolian calcarenite at other places in the southwest. At Cowaramup Bay, crystalline cobbles are exposed beneath the limestone, composing the Cowaramup Conglomerate of Fairbridge and Teichert (1952). These authors also figure conglomeratic beach rock to a height of 3 m above HWM between the cobble conglomerate and the aeolian calcarenite. Archer and Baynes' cemented rubble bands could be such calcareous conglomerate. Fairbridge and Teichert also cite marine horizons in the same stratigraphic relationship at Cape Naturaliste, reaching 7 m above their datum of Low Water Springs. Nearby at Bunkers Bay, Lowry (1967) mentions conglomerate like that at Cowaramup Bay to a height of 9 m above present sea level, without, however, stating whether it underlies the calcarenite or not.

Archer and Baynes (1972) themselves mention rubble bands inside Mammoth Cave and other caves in the southwest; the first location must be about 40 m above sea level. Cook (1963) reports teeth of sharks, rays and teleosts in sands on the crystalline basement in Strong's Cave at about 30 m above sea level.

All these occurrences are compatible with the 'gorge of construction' explanation of the formation of Deepdene. This hypothesis can readily be tested by a search to see whether cobble beds do or do not extend under the calcarenite cliffs of Deepdene as suggested here, by closer examination of the nature of the cemented rubble bands in its cliffs and by determination of the heights above sea level of these marine deposits.

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