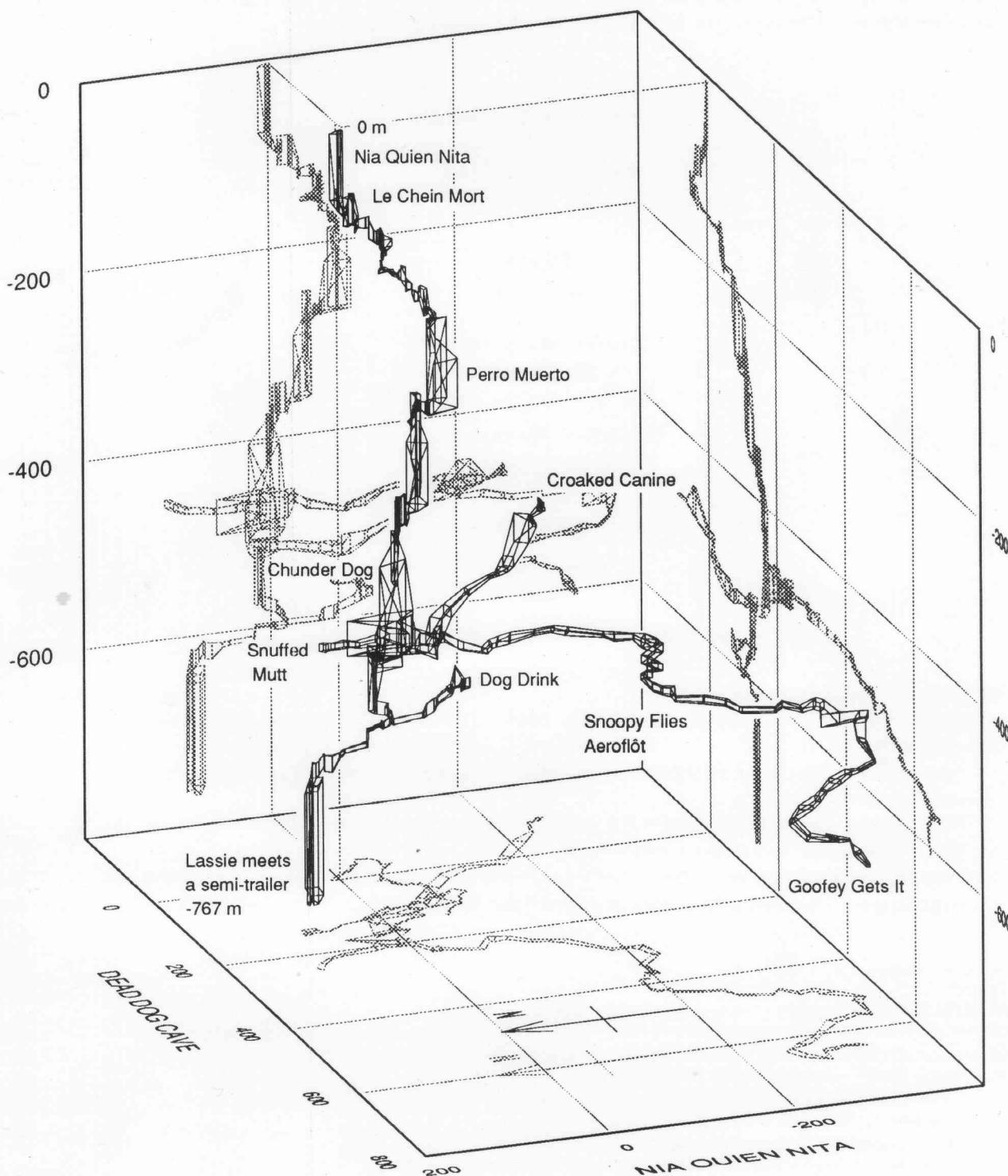


Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



HELICITITE

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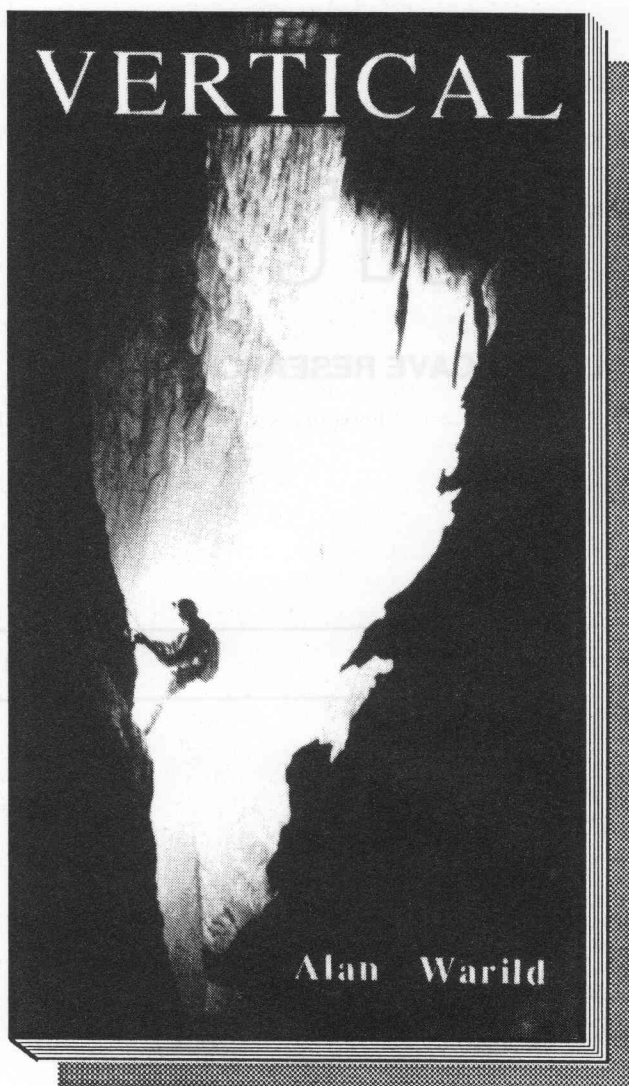
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KARST WATER CHEMISTRY - LIMESTONE RANGES, WESTERN AUSTRALIA.

M. Ellaway, D.I. Smith, D.S. Gillieson, and M.A. Greenaway

Abstract

Detailed chemical and physical analyses are presented for forty-two karst water samples. These were collected in the Limestone Ranges of the Kimberley region in northern Western Australia during May 1988. The collection sites are classified into spring, groundwater and miscellaneous. The springs sites include samples collected downstream of the risings in order to provide information to aid an understanding of the mechanisms of tufa deposition which is a marked feature throughout the region. A general pattern of physical and chemical effects was found for such sites but further progress will require interdisciplinary studies between hydrologists, chemists and biologists. A tentative estimate is presented for a regional rate of limestone solutional erosion. The limited time available for the collection of samples, at the beginning of the dry season, restricts the value of the conclusions. The results however, are of interest given the paucity of water analyses from this and other semi-arid areas of karst in Australia. Comparisons are made to the pioneering work of J.N. Jennings and M.M. Sweeting in the same area in 1959.

INTRODUCTION

In the early 1960s Jennings and Sweeting (1963) produced an excellent account of the karst geomorphology of the Limestone Ranges of the Kimberley region in northernmost Western Australia. This remains as one of the few detailed accounts for an area of tropical semi-arid karst. Their study included chemical analyses of karst water samples, however only 15 samples were collected, the analyses were undertaken in Canberra some weeks after collection and the range of ions analysed was limited. Nevertheless the study was one of the first to use methods of analysis that are still regarded as acceptable. A search of the groundwater records of the Department of Mines, Western Australia confirms that the data collected by Jennings and Sweeting are the only available published information for the Limestone Ranges region. It is interesting to note that the Hydrogeology Map of Australia (Lau *et al.*, 1987) does not show the Limestone Ranges as a limestone aquifer. We understand that was partially due to the paucity of water quality information. Details are presented for 42 samples, some of which were collected from sites identical to those of Jennings and Sweeting.

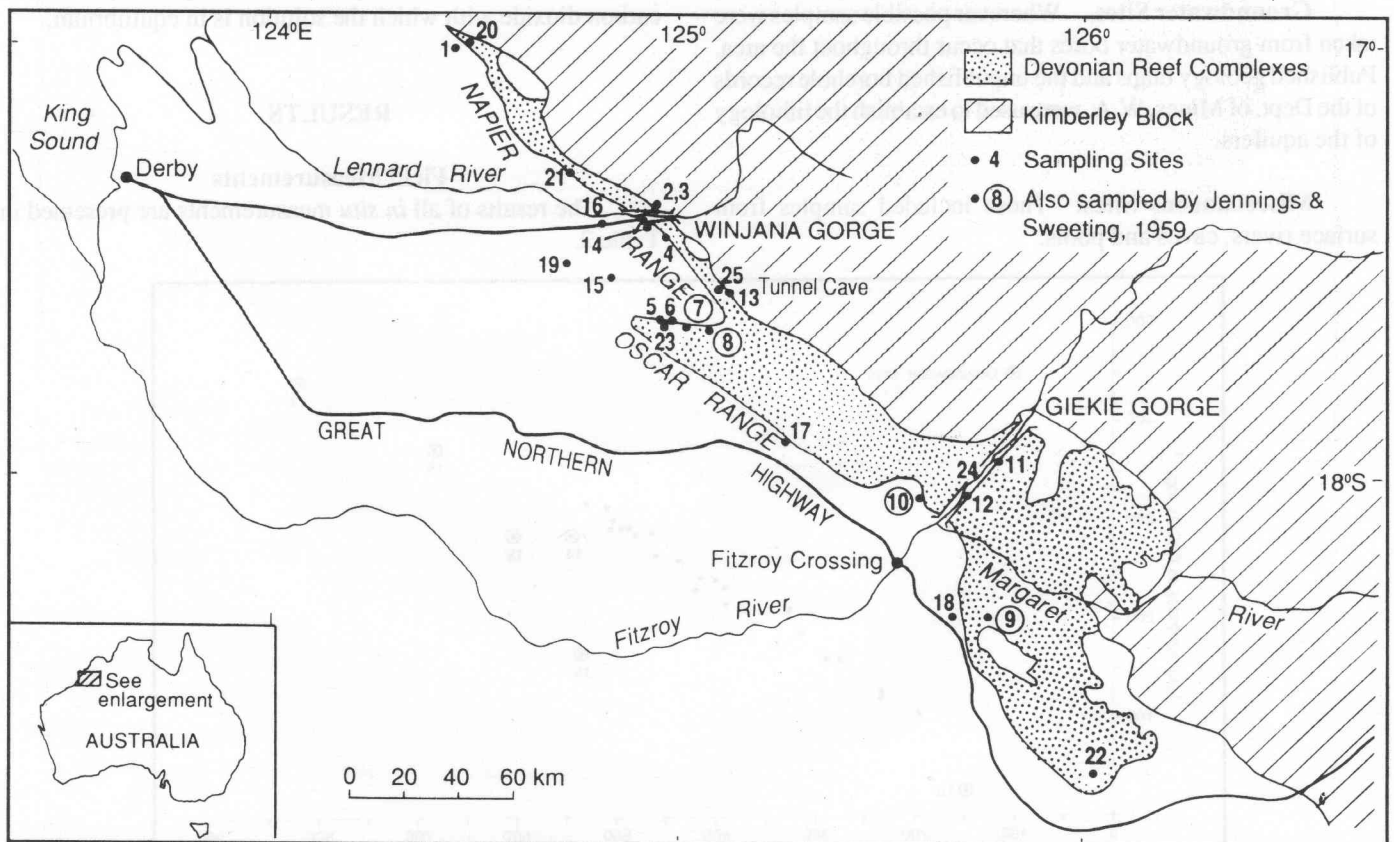


Figure 1. Location of sampling sites

The value of the samples is limited as they were all collected in the period 5-24 May 1988, the beginning of the dry season. They do however, provide reconnaissance values for water quality in a region for which such data are otherwise absent. Collection over a full year, wet and dry, would require considerable expense and organizational effort. The study was part of the Royal Geographical Society/Linnean Society Kimberley Research Project.

SAMPLING PROGRAM

Water samples and *in situ* field data were collected from a variety of sites which can be classified into three categories.

1. Limestone springs
2. Groundwater
3. Miscellaneous

The approximate locations are shown in Figure 1 and the sites described in Table 1; sites also sampled by Jennings and Sweeting are indicated. A striking feature of the limestones of the region is the extensive deposition of tufa. The distribution of tufa and a suggested classification for sites are discussed in Goudie *et al.* (1989).

Limestone Springs. Samples were collected from limestone springs throughout the region, wherever possible at the point at which water issued from the rock. There were large variations in discharge with many springs having minute flows. Thus, qualitative assessments of discharge were made in the field. Additional samples provide a background to the water quality associated with the downstream deposition of tufa at many of springs.

Groundwater Sites. Wherever possible samples were taken from groundwater bores that occur throughout the area. Published geology maps and the unpublished borehole records of the Dept. of Mines, W.A. were used to establish the lithology of the aquifers.

Miscellaneous Sites. These included samples from surface rivers, caves and pools.

COLLECTION AND METHODS OF ANALYSIS

Water and air temperature, conductivity and pH values were measured at each site, the results are presented in Table 2. Temperatures were obtained by the use of calibrated mercury bulb thermometers. Conductivity was measured using a Metrohm model E587 Conductometer and pH with a Metrohm model E606 Portable pH meter.

Two filtered (Whatman GF/C glass fibre filters) water samples (one acidified with concentrated HNO₃) were collected at each site in acid washed polyethylene bottles. One was used for chloride determination and the acidified sample for the ionic analysis described below. A third, unfiltered sample was used for the determination of alkalinity. This was undertaken as soon as possible after collection by titration against standardised 0.02 M HCl to pH 4.5, using BDH pH 4.5 indicator solution. Chloride was determined by titration against standardised 0.0141 M mercuric nitrate (Stainton *et al.*, 1977). Calcium, magnesium, sodium, potassium, sulfur and silicon were determined by ICP analysis. A Perkin Elmer Plasma II Inductively Coupled Plasma Emission Spectrometer was used to determine the trace metals; Fe²⁺, Zn²⁺, Mn²⁺, Pb²⁺, Ni²⁺ and Cu²⁺.

Water samples were rejected, or re-analysed, if the cation-anion balance was greater than $\pm 4.0\%$ i.e. as given by the following equation:

$$(\sum \text{cations} - \sum \text{anions}) / (\sum \text{cations} + \sum \text{anions}) \times 100$$

The results obtained from the chemical analyses were used in the computer program WATSPEC (Wigley, 1977) to compute mineral saturation indices and the partial pressure of carbon dioxide with which the solution is in equilibrium.

RESULTS

Field Measurements

The results of all *in situ* measurements are presented in Table 2.

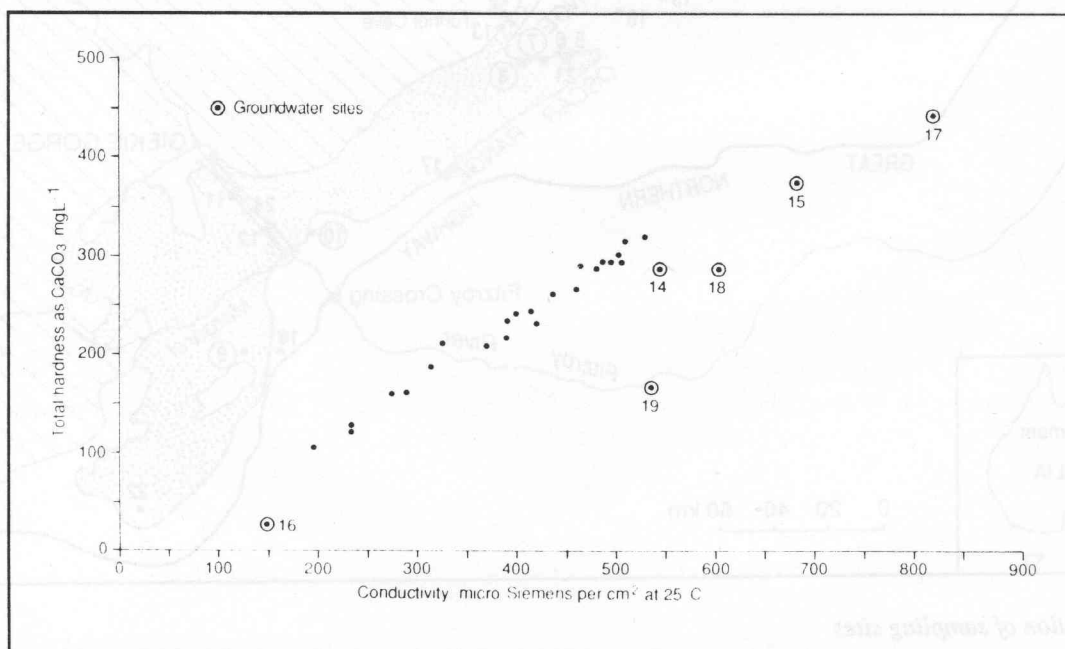


Figure 1

Temperature. Water temperatures varied with time of day and degree of shade. Spring and groundwater temperatures also exhibited a large range due to the difficulty, at some sites, of collecting samples immediately at the point of issue from the rock, i.e., some samples were from small pools with no clearly defined inlet. The range for such sites was 22.5 °C to 34.0 °C. Overall the best estimate of groundwater temperature, an approximation to mean annual air temperature, was 28 °C.

Conductivity. The conductivity of all samples is given in Table 2, and shown graphically in Figure 2. The two extreme values 149 μScm^{-1} for site 16 and 820 μScm^{-1} for site 17, both groundwater samples. As conductivity is a measure of the amount of ions in solution the significance of these results is discussed in relation to the overall ionic composition of the water samples.

pH. These ranged from 6.59 (site 8 iii) to 8.16 (site 13), with the spring sites showing a decrease in pH for samples collected progressively downstream from the risings. This phenomenon is well documented for limestone springs and is associated with CO_2 degassing and tufa deposition (Jacobson and Usdowski, 1975; Usdowski *et al.*, 1979; Dunkerley, 1981; Brook and Ford, 1982; Ellaway and Finlayson, 1984; Dunkerley, 1987). There is little correlation between these pH values and those reported by Jennings and Sweeting at the same sites in 1959. In several cases the differences exceed 1.0 pH unit, this is probably due to the use of a Lovibond Comparator by the earlier workers.

Chemical Analyses

The results of the chemical analyses for the major cations and anions are presented in Table 3. Values for SiO_2 , SO_4^{2-} and total hardness (as mg L⁻¹ CaCO_3) were calculated from the results of the ICP analysis obtained for the elements silicon, sulfur, calcium and magnesium and by multiplying by the appropriate conversion factors. For all the sites, except for 16 and 19, Ca^{2+} and HCO_3^- (bicarbonate obtained from the alkalinity value $\times 1.219$) were the dominant cation and anion and usually account for >90% of the respective cation and anion totals (in terms of epm). For Sites 16 and 19 (both from groundwater bores) Na^+ is the dominant cation with HCO_3^- remaining as the dominant anion although the relative ionic proportions of Cl^- and SO_4^{2-} are much greater than for the other sites sampled.

$\log P_{(\text{CO}_2)}$ values, see Table 4, ranged from -2.69 (Site 4 ib) to -1.01 (Site 8 iii). Four of the six groundwater sites have $\log P_{(\text{CO}_2)}$ values similar to those for many of the spring sites. The two samples collected from the Fitzroy River (Site 24) had $\log P_{(\text{CO}_2)}$ values that correspond to the mid-range of the spring sites; normally higher $\log P_{(\text{CO}_2)}$ values would be expected for a surface stream in contact with the atmosphere. These two sites are about 8-10 km apart and represent the upstream and downstream limits of a long pool of water with no surface outlet.

SI_c values for the majority of the spring sites were >0.0 and indicate supersaturation with respect to calcite, in contrast the saturation index for dolomite (SI_d) was usually negative, indicating undersaturation. The undersaturation for dolomite is not unexpected as the Mg^{2+} values for most of the spring sites

were low. Only two of the six groundwater sites were saturated with respect to calcite, one of these was also saturated in respect of dolomite. Site 20 was the only miscellaneous site that had both positive SI_c and SI_d values.

The results of the trace metal analyses are given in Table 4. The values for the majority of sites were below the level of detection for the methods employed. The majority of the groundwater bores have relatively high Zn^{2+} concentrations and Site 16 has a particularly high Fe^{2+} value. These results could be due to the metal casing used at all the bores. All sites were below the detection limit for Pb^{2+} (1.0 mg L⁻¹) and Ni^{2+} (0.5 mg L⁻¹) which are therefore, omitted from Table 4.

Figure 2 plots conductivity against total hardness. There is a close relationship except for the five groundwater sites. This results from an ionic composition that differs from the other sites, see Tables 3, 4 and 5. Information on the geology and previous water chemistry for these bores is sparse and the limited chemical analyses that are available show little agreement with those presented in this study. The explanatory notes for the Nookanbah and Lennard River 1:250,000 geology maps (Crowe and Towner, 1981 and Derrick and Playford, 1973) provide information on the background geology for the majority of groundwater bores sampled in this study. Site 16 is located in gravels overlying the Grant Formation which is essentially non-calcareous, this accords with the water chemistry. The remainder would appear to be dominantly in strata which are, at least partially, composed of calcareous-rich beds.

The major conclusion is that the spring and miscellaneous sites are all located on, or within, the main karst limestones of the region and that these differ in chemistry from the groundwater sites. This is true even of the Windjana camp ground bore located only 2-300 m from the south facing cliffs of the Napier Range. This bore is, without doubt, drilled into the limestones of the main Devonian reef complex that dominates the karst of the region. Due to the differing chemistry the groundwater sites are omitted from later discussion on the solutional erosion rates of the Limestone Ranges.

Comparisons of spring sites 7,8,9 and 10 (this report) with analyses for the same sites reported by Jennings and Sweeting (1963, p 53) show that the total hardness values for 7 and 10 are within 20 mg L⁻¹ CaCO_3 but the results for 8 and 9 differ markedly.

KARST SIGNIFICANCE

The significance of the results is restricted due to the limited time range represented. This is heightened by the climatic regime of the region which is dominated by the contrast between the wet and dry seasons. On average, 85% of the annual precipitation of some 650 mm falls in the period December-March, for the driest quarter the average is less than 10 mm. The climatic information throughout this account was obtained from a geographical information system (GIS) held at the Centre for Resource and Environmental Studies, Australian National University. This includes weekly rainfall and temperature data for several thousand meteorological station distributed throughout Australia together with information on altitude. From this data base the GIS is able to provide average climatic data for any nominated location, including the appropriate adjustments for elevation. The climate statistics pre-

sented are for longitude 124° 45' E and latitude 17° 20' S, and an elevation of 100 m.

The period of field observation, in May, is at the tail of the discharge peaks for the wet season. Notwithstanding this limitation, the water chemistry will be discussed in relation to tufa deposition and to the overall rate of limestone solutional erosion.

Tufa Deposition. The deposition of tufa is a marked feature of the karst of the Limestone Ranges and is discussed in Jennings and Sweeting (1963) and in Goudie *et al.* (1989). The latter classify the form of tufa deposits into eight types. Several of these are associated with the emergence of groundwater at the surface, at springs or cave entrances. Many of the results reported in this study are from such sites and were collected to investigate the physical and chemical changes of water downstream of their point of emergence.

Sequential samples were collected at three spring locations; namely Site 3 (on two occasions), Site 8 and site 9. The salient analyses are presented in Table 5 and selected parameters shown graphically in Figure 3. For Site 3 (on both sampling occasions) conductivity, Ca^{2+} , alkalinity and $\log P_{(\text{CO}_2)}$ values decreased downstream, whereas pH and SI_c increased. An exception was at station iii on 1.5.88 when SI_c was lower than that at station ii. The decrease in water temperature (6 °C cooler at iii than at ii) could in part explain this lower SI_c value as the solubility of CO_2 is enhanced in colder water. On the second sampling occasion at station iii the SI_c , water temperature and pH values were higher than those recorded on 10.5.88. The Mg^{2+} results are presented in order to investigate possible concentration effects due to evaporation. However, all values are similar and lie within the limits of experimental error. The concentration effects observed by Dunkerley (1987) for Ryans Creek (Chillagoe, North Queensland) are not evident. This is surprising as this site, out of the three studied, has the highest evaporation rates and it would therefore be expected that concentration would be enhanced, particularly at station ii where flow terminates in a large shallow (<10 cm) pool. The long term average monthly open pan evaporation for May is slightly in excess of 170 mm.

Changes at Site 8 between stations i and ii appear as expected in that conductivity, Ca^{2+} , alkalinity and $\log P_{(\text{CO}_2)}$ values decrease and indicate calcite precipitation as the spring water degasses. Site 8 differs from Sites 3 and 9 in that the water disappears near station ii and re-appears about 100 m further downstream, at station iii. The results from station iii show that conductivity, Ca^{2+} , alkalinity and $\log P_{(\text{CO}_2)}$ values are higher than at station ii and in travelling underground the water regains its aggressiveness and increases its concentration of solutes. The Mg^{2+} values for the four stations at Site 8 are similar for stations i and ii, decrease at station iii and double by station iv. There are slight increases in Na^+ , SO_4^{2-} and SiO_2 with Cl⁻ remaining constant. The increase in Mg^{2+} is more difficult to explain but does not appear to be due to the effects of concentration as other ions do not show this effect. A possible explanation is that the water which sinks at Site 8 ii is joined by additional groundwater before it re-emerges at 8 iii.

Site 9 exhibited similar effects to the other two sites, i.e. conductivity, Ca^{2+} , alkalinity and $\log P_{(\text{CO}_2)}$ decreased downstream and water temperature and SI_c also decrease from spring

to downstream sink. As noted by Dunkerley (1987), "... quite complex reactions and localised increases and decreases in the level of supersaturation may occur when water enters a tufa dam and mixes with impounded water".

The role of mosses, algae and other biota in aiding CO_2 degassing and calcite precipitation has been regarded as minimal by a number of authors (Marker, 1973; Dandurand *et al.*, 1982; Herman and Lorah, 1987). They favoured turbulence as the main factor responsible for CO_2 degassing and calcite precipitation in their studies of tufa depositing streams. In contrast Pitty (1971), in a study of Gordale Beck, concluded that biological activity was the main cause of the seasonal fluctuations in tufa deposition.

Whether the presence of floating algal mats and other biogenic sources at Sites 3, 8 and 9 aided in CO_2 degassing and calcite precipitation is hard to say from the water quality data available. Discharge will play a major role in governing such processes and differing hydrological conditions may well result in differing chemical processes. These may aid or hinder CO_2 degassing and chemical precipitation and may also differ along a stream course in response to minor features such as pools and riffles. Dandurand *et al.* (1982) from their studies at La Cascade de la Turossa, France, noted that discharge over a 24 m cascade affected CO_2 degassing and this occurred more readily when stream discharges were lower than normal (<90 L/s). Supersaturation with respect to calcite does not necessarily imply calcite precipitation Suarez (1983) Troester and White (1986) and Barnes (1965) suggested that SI_c should be >0.5 and that vegetation or humic material was needed before CaCO_3 will nucleate. It is clear that only detailed interdisciplinary studies that include water quality, chemistry and biology will provide a better understanding of tufa deposition.

Solutional rates of erosion. Karst geomorphologists are concerned with rates of limestone solutional activity. In order to make comparisons between differing limestone regions the information is presented in terms of rates of lowering, normally expressed in mm per thousand years (mmka^{-1}). Reviews of the methods are widely available - see Atkinson and Smith (1976), Jennings (1985) and Trudgill (1985). Data are available for most of the major limestone regions of the world and for a range of climates and carbonate rock types - see White (1988) and Ford and Williams (1989). There are however, no estimates for the Limestone Ranges and only limited data for semi-arid karst regions elsewhere. Jennings and Sweeting (1963) considered that their analyses were inadequate to estimate the rates of solutional erosion for the Limestone Ranges. The water quality data presented in this study is more detailed but still far from ideal. However, an attempt is made to present a tentative estimate for the rate of solutional erosion.

The procedure for establishing regional rates requires two sets of data. The first is an estimate of the average total hardness of the runoff waters expressed as CaCO_3 mg L⁻¹. The second is an estimate of the run-off, in terms of runoff per unit area. The runoff is the balance between average annual precipitation and evapotranspiration. At first sight analyses for samples collected over a restricted time period would be insufficient to undertake such calculations. However, hardness values for the majority of karst springs throughout the world are frequently constant in terms of concentration regardless of season or

discharge. The estimates that follow are firmly based on this assumption, if subsequent samples collected at other times of the year show this to be incorrect the estimates should be disregarded.

Spring Hardness. Samples were collected from every limestone spring located during the fieldwork; the objective of these observations was to estimate the regional solutional rate. The total hardness information is given in Table 3 and the spring locations in Figure 1. With the exception of Site 5, there is a marked difference in total hardness for the sites in Windjana Gorge and further west compared to those to the east of the gorge. For sites 1-4, to the west, the hardness range is 186-297 $\text{CaCO}_3 \text{ mg L}^{-1}$, with an average of 201 $\text{CaCO}_3 \text{ mg L}^{-1}$. For the eight samples to the east of Windjana Gorge the range is 354-371 $\text{CaCO}_3 \text{ mg L}^{-1}$, with an average of 324 $\text{CaCO}_3 \text{ mg L}^{-1}$. These geographical variations are difficult to explain, since there are no major changes in the lithology of the dominant limestones throughout the area.

The total hardness for both sets of sites is within the range frequently recorded from other temperate and tropical karst locations although the eastern set, with a mean of 324 $\text{CaCO}_3 \text{ mg L}^{-1}$, are at the upper end of the range. Within each group the spread of values is also comparable to karst springs elsewhere. Further, the values within each set show no major variation from springs that are little more than slow seeps to those that have a much larger discharge and are quite likely to have perennial flows. In short, the pattern of hardness values exhibited by the springs of the Limestone Ranges is typical of other temperate or tropical limestone regions. For the purposes of estimating overall solutional erosion two sets of results are presented based on total hardnesses of 201 and 324 $\text{CaCO}_3 \text{ mg L}^{-1}$ for the western and eastern areas respectively.

Runoff. The markedly seasonal precipitation, high evaporation and lack of any observations on transpiration pose difficulties in estimating mean runoff. The best long term average of precipitation is 650 mm, 85% of which occurs in the wet season. Much of the rainfall in the wet occurs as heavy falls, the mean rainfall per rain day in the wet season is in the range 16.8-18.0 mm (Mills and Adam, 1986). The GIS derived average annual open pan evaporation for the region is close to 2500 mm, with the lowest mean monthly estimate (for September) at 160 mm. The crux of the problem is that for long term average weekly data there is no occasion when the precipitation exceeds the open pan evaporation. It is clear that the runoff will be only a small proportion of the annual precipitation.

An alternative approach is to use river discharge records to estimate mean annual runoff. This is discussed in Brown (1983), the approach is to select catchments that have longer runs of discharge records and to compare these to the annual precipitation that falls within the their catchments. Brown includes a map of Australia that presents runoff estimated in this way. The scale is small but the likely values for the Limestone Ranges is an annual average value in the range 70-100 mm. A recent study (Aust. DPIE, 1987) presents runoff data for major catchments in the Kimberley area under study. For the Fitzroy, Lennard and Isdell Rivers this data converts to mean annual runoffs of 62, 80 and 165 mm respectively. For the Limestone Ranges the most appropriate average annual

runoff is about 80 mm. This value will be used to estimate the overall solutional erosion rate. It corresponds to an annual evapotranspiration loss of about 88% of total precipitation. This is broadly the same methodology used to assess solutional losses of limestone in other regions worldwide. They all assume that the 'runoff' in karst areas passes into the groundwater system to reappear at springs normally located at the periphery of the limestone mass.

Thus, the estimation of solutional erosion becomes a calculation that assumes an average annual runoff of 80 mm with a total hardness of 201 $\text{CaCO}_3 \text{ mg L}^{-1}$ for Windjana Gorge and for the area to the west and 324 $\text{CaCO}_3 \text{ mg L}^{-1}$ for the eastern area. These data are substituted into the formula first outlined by Corbel (1959) to obtain an overall estimate for limestone solutional erosion.

$$\text{Limestone solutional erosion in mmka}^{-1} = \frac{E H}{10d}$$

Where d = density in g cm^{-3} , E is average annual runoff in decimetres, and H is the average hardness expressed as $\text{CaCO}_3 \text{ mg L}^{-1}$. If density is assumed to be 2.5 g cm^{-3} then the equation becomes:

$$X = \frac{4EH}{100}$$

Substituting the values for the Limestone Ranges, 0.8 dm for runoff, and 201 and 324 $\text{CaCO}_3 \text{ mg L}^{-1}$ for hardness, X is 6.4 and 10.4 mmka^{-1} .

Estimates of this kind should only be regarded as broad indications of limestone solutional erosion, the value of which is limited to comparative studies from region to region. The problems are outlined in Jennings (1985) and Trudgill (1985) although both give estimates for major world limestone regions. It must be stressed that such estimates give no indication of the source of the erosion, i.e. surface, subsoil or subterranean, or any relationship between rate and landform type. However, it is clear that the overall rate of limestone solution loss in the Limestone Ranges is low. Improved data for spring hardness are more likely to decrease the estimate than to increase it. This is because at times of high discharge the hardness may decrease rather than maintain the constant value for concentration assumed in the calculations. In comparison to other karst regions, lower rates of solution are generally found only in arid regions or in alpine and polar areas where the lack of a soil cover gives low values for biogenic carbon dioxide and lessens the solutional erosion of the underlying carbonates.

During the course of the fieldwork the authors installed a number of micro-erosion meter sites; for a discussion of the technique see Spate *et al.* (1985). The sites will be re-read after a suitable interval in order to obtain estimates of absolute lowering of the bedrock limestone surface. These observations will present an independent estimate of erosion that is site specific.

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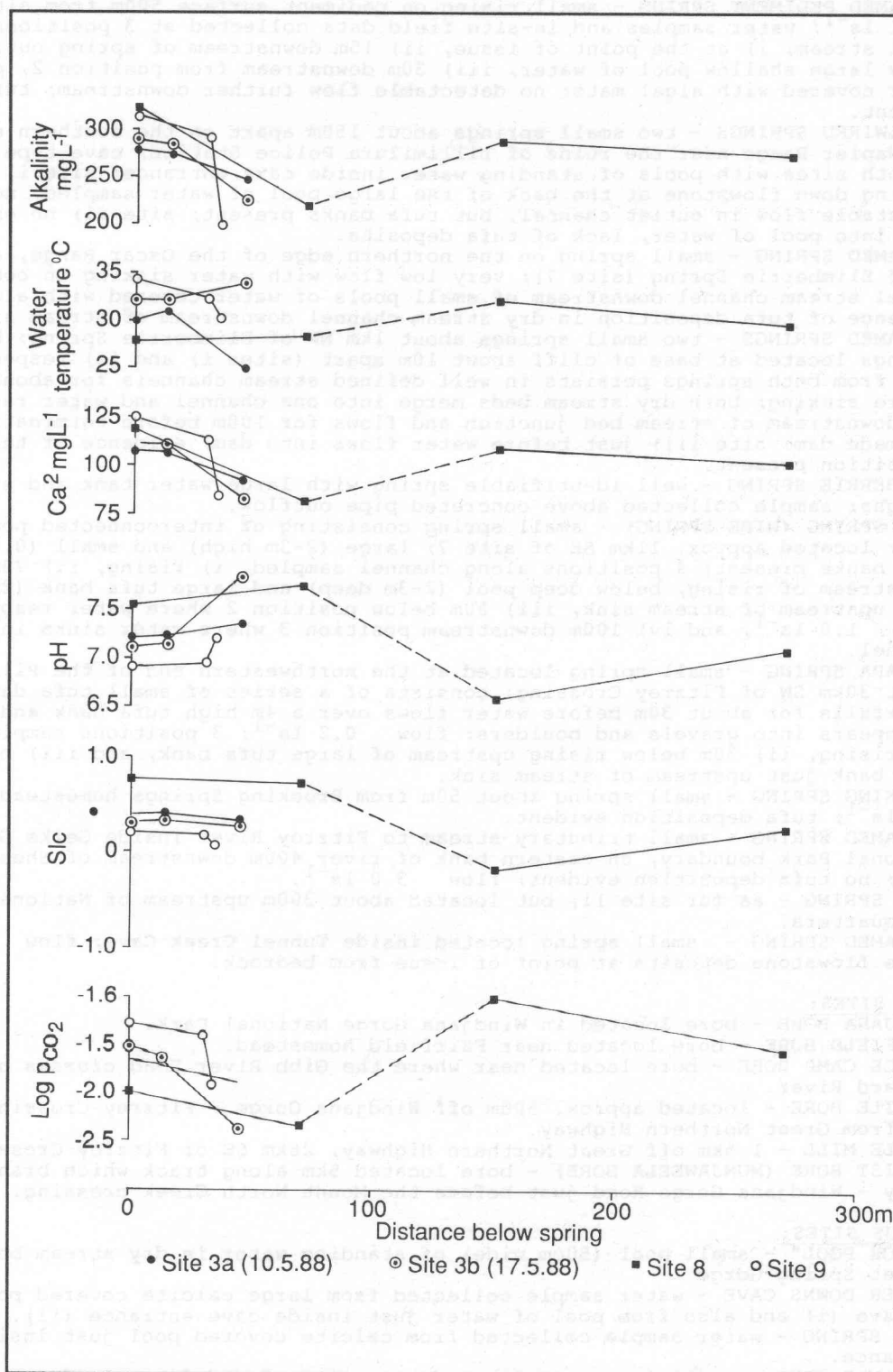


Figure 3 Variations of physical and chemical properties downstream from spring sites

TABLE 1

SITE DESCRIPTIONS

SPRING SITES:

- 1) BARNETT SPRING - small spring at the northwestern end of the Napier Range; no tufa deposition evident in stream channel; flow 0.3 ls^{-1} .
- 2) BARRALUMLA SPRING - large rock pool on the northern edge of the Napier Range near Windjana Gorge; no detectable flow in outlet channel.
- 3) UN-NAMED PEDIMENT SPRING - small rising on pediment surface 500m from site 2, flow 0.1 ls^{-1} ; water samples and in-situ field data collected at 3 positions along small stream, i) at the point of issue, ii) 15m downstream of spring outlet just below large shallow pool of water, iii) 30m downstream from position 2, pool of water covered with algal mats; no detectable flow further downstream; tufa banks present.
- 4) LIMALWIRRU SPRINGS - two small springs about 150m apart on the southern edge of the Napier Range near the ruins of Lillimilura Police Station; cave type entrances at both sites with pools of standing water inside cave entrance; site i) has water flowing down flowstone at the back of the large pool of water sampled, no detectable flow in outlet channel, but tufa banks present; site ii) no obvious flow into pool of water, lack of tufa deposits.
- 5) UN-NAMED SPRING - small spring on the northern edge of the Oscar Range, about 4km NW of Elimberrie Spring (site 7); very low flow with water sinking in cobble and gravel stream channel downstream of small pools of water covered with algal mats; evidence of tufa deposition in dry stream channel downstream of stream sink.
- 6) UN-NAMED SPRINGS - two small springs about 1km NW of Elimberrie Spring; both springs located at base of cliff about 10m apart (sites i) and ii) respectively); flow from both springs persists in well defined stream channels for about 5m before sinking; both dry stream beds merge into one channel and water re-appears 15m downstream of stream bed junction and flows for 100m before terminating in a man-made dam; site iii) just before water flows into dam; evidence of tufa deposition present.
- 7) ELIMBERRIE SPRING - well identifiable spring with large water tank and stock troughs; sample collected above concreted pipe outflow.
- 8) WINE SPRING (WIRE SPRING) - small spring consisting of interconnected pools of water located approx. 11km SE of site 7; large (2-3m high) and small (0.1-1.0m) tufa banks present; 4 positions along channel sampled, i) rising, ii) 70m downstream of rising, below deep pool (2-3m deep) and large tufa bank (2m high) just upstream of stream sink, iii) 80m below position 2 where water reappears, flow 1.0 ls^{-1} , and iv) 100m downstream position 3 where water sinks into stream channel.
- 9) PILLARA SPRING - small spring located at the northwestern end of the Pillara Range about 30km SW of Fitzroy Crossing; consists of a series of small tufa dams and waterfalls for about 30m before water flows over a 4m high tufa bank and disappears into gravels and boulders; flow 0.2 ls^{-1} ; 3 positions sampled, i) at the rising, ii) 30m below rising upstream of large tufa bank, and iii) below large tufa bank just upstream of stream sink.
- 10) BROOKING SPRING - small spring about 50m from Brooking Springs homestead; flow 0.1 ls^{-1} ; tufa deposition evident.
- 11) UN-NAMED SPRING - small tributary stream to Fitzroy River inside Geike Gorge National Park boundary, on eastern bank of river 400m downstream of Sheep Camp Yard; no tufa deposition evident; flow 3.0 ls^{-1} .
- 12) LILY SPRING - as for site 11, but located about 300m upstream of National Park Headquarters.
- 13) UN-NAMED SPRING - small spring located inside Tunnel Creek Cave; flow 3.0 ls^{-1} ; large flowstone deposits at point of issue from bedrock.

GROUNDWATER SITES:

- 14) WINDJANA BORE - bore located in Windjana Gorge National Park.
- 15) FAIRFIELD BORE - bore located near Fairfield homestead.
- 16) POLICE CAMP BORE - bore located near where the Gibb River Road crosses over the Lennard River.
- 17) 12 MILE BORE - located approx. 500m off Windjana Gorge - Fitzroy Crossing Road, 7km from Great Northern Highway.
- 18) 8 MILE MILL - 1.5km off Great Northern Highway, 26km SE of Fitzroy Crossing.
- 19) TOURIST BORE (MUNJAWEELE BORE) - bore located 5km along track which branches off Derby - Windjana Gorge Road just before the Mount North Creek crossing.

MISCELLANEOUS SITES:

- 20) "GORGE POOL" - small pool (50cm wide) of standing water in dry stream bed in Barnett Spring Gorge.
- 21) NAPIER DOWNS CAVE - water sample collected from large calcite covered pool at end of cave (i) and also from pool of water just inside cave entrance (ii).
- 22) CAVE SPRING - water sample collected from calcite covered pool just inside cave entrance.
- 23) UN-NAMED CAVE - small cave near located near sites 5 and 6; pool of standing water inside cave about 10m from entrance; massive tufa banks at cave entrance.
- 24) FITZROY RIVER - two water samples collected from this river, i) upstream of site 11 and ii) 100m upstream of the Margaret River junction.
- 25) TUNNEL CREEK - sample collected at outflow of Tunnel Creek from Tunnel Creek Cave.

TABLE 2 RESULTS OF IN-SITU FIELD MEASUREMENTS AND DATA OF DATA COLLECTION

SITE NO.		WATER (°C)	AIR (°C)	CONDUCTIVITY ($\mu\text{S cm}^{-1}$) (25°C)	pH	DATE
<u>SPRING SITES:</u>						
1)		25.5	30.4	327	7.98	9.5.88
2)	a)	28.0	30.0	391	7.38	10.5.88
	b)	26.0	30.5	372	7.79	17.5.88
3)	ia)	30.0	29.5	488	7.20	10.5.88
	ib)	32.0	34.0	505	7.10	17.5.88
	iaa)	31.0	31.5	483	7.23	10.5.88
	iib)	32.0	36.0	495	7.19	17.5.88
	iiia)	25.0	30.5	439	7.35	10.5.88
	iiib)	34.0	30.5	400	7.80	17.5.88
4)	ia)	26.5	29.0	314	7.96	10.5.88
	ib)	23.6	23.5	323	7.98	18.5.88
	ii)	22.5	23.0	291	7.81	18.5.88
5)		27.0	31.5	460	7.27	11.5.88
6)	i)	27.0	30.5	530	6.80	11.5.88
	ii)	23.5	30.5	510	7.65	11.5.88
	iii)	26.2	30.5	416	7.87	11.5.88
7)		29.0	29.5	569	6.76	18.5.88
8)	i)	28.0	33.0	580	7.55	18.5.88
	ii)	28.5	35.5	407	7.78	18.5.88
	iii)	32.5	33.5	540	6.59	18.5.88
	iv)	30.0	32.0	511	7.12	18.5.88
9)	i)	34.0	34.0	567	6.90	23.5.88
	ii)	32.5	32.5	495	6.96	23.5.88
	iii)	28.5	30.5	353	7.20	23.5.88
10)		29.0	32.5	559	6.82	23.5.88
11)		29.0	25.0	563	6.97	24.5.88
12)		28.0	27.0	618	6.97	24.5.88
13)		29.0	28.0	538	8.16	24.5.88
<u>GROUNDWATER SITES:</u>						
14)		29.0	24.0	543	7.15	18.5.88
15)		31.0	28.0	681	6.73	18.5.88
16)		30.0	35.0	149	6.88	18.5.88
17)		31.5	29.0	820	6.94	24.5.88
18)		29.0	35.5	604	6.86	23.5.88
19)		32.0	31.0	537	6.71	11.5.88
<u>MISCELLANEOUS SITES:</u>						
20)		30.0	37.0	507	7.74	9.5.88
21)	i)	28.0	29.0	466	7.17	9.5.88
	ii)	26.5	31.5	273	7.93	9.5.88
22)		22.5	25.0	421	6.99	23.5.88
23)		25.0	27.5	233	7.17	9.5.88
24)	i)	27.0	26.0	233	6.93	23.5.88
	ii)	26.0	28.0	196	6.87	23.5.88
25)		25.0	26.5	396	7.00	24.5.88

TABLE 3

RESULTS OF CHEMICAL ANALYSES

SITE NO.	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SiO ₂	Cl ⁻	SO ₄ ²⁻	Alkal.	Tot. Hard.
<u>SPRING SITES:</u>									
1)	83.7	0.1	7.9	1.4	10.7	6.7	<3.0	208.2	209.4
2) a)	83.2	1.8	4.3	0.8	14.1	10.8	<3.0	198.7	215.2
b)	80.1	1.8	4.4	0.9	14.4	10.0	<3.0	193.4	207.4
3) ia)	108.0	6.4	3.3	<0.5	12.6	7.8	<3.0	277.4	296.0
ib)	109.0	6.3	3.3	0.6	12.0	7.6	<3.0	289.9	298.1
iiia)	106.0	6.1	3.3	0.6	12.4	7.6	<3.0	274.0	289.8
iib)	108.0	6.3	3.5	0.9	12.4	7.6	<3.0	284.6	295.6
iiia)	94.7	6.0	3.4	<0.5	12.0	7.6	<3.0	247.0	261.2
iiib)	85.9	6.1	3.2	0.7	12.4	7.5	<3.0	224.3	239.6
4) ia)	74.4	0.5	1.1	0.7	10.9	3.2	<3.0	172.7	187.8
ib)	72.9	0.5	0.8	<0.5	10.9	3.3	<3.0	170.3	184.1
ii)	63.4	1.0	0.9	0.9	12.9	3.2	<3.0	155.8	162.4
5)	103.0	1.8	3.0	1.0	16.5	7.2	<3.0	255.7	264.6
6) i)	127.0	0.1	2.3	<0.5	13.7	7.5	3.9	316.0	317.5
ii)	125.0	0.2	2.9	<0.5	13.9	7.3	3.9	303.9	312.9
iii)	96.7	0.3	3.0	<0.5	14.6	7.2	3.3	229.1	242.7
7)	120.0	2.8	4.0	<0.5	13.7	8.4	4.5	306.3	311.2
8) i)	117.0	7.4	3.4	<0.5	15.2	7.9	3.9	320.3	322.6
ii)	82.9	7.1	3.4	<0.5	15.2	7.8	<3.0	220.5	236.2
iii)	114.0	2.3	2.7	<0.5	13.3	7.9	3.3	291.9	294.1
iv)	106.0	4.6	3.3	<0.5	14.1	7.9	4.2	277.9	283.6
9) i)	125.0	<0.1	3.1	<0.5	11.6	3.9	4.5	318.4	312.5
ii)	115.0	<0.1	1.9	<0.5	11.8	4.1	3.6	290.0	287.6
iii)	85.2	<0.1	1.9	<0.5	12.0	4.1	<3.0	199.2	213.2
10)	121.0	4.0	4.0	0.6	15.9	5.7	<3.0	311.1	318.6
11)	125.0	3.7	1.2	<0.5	14.6	5.3	4.2	323.2	327.4
12)	133.0	5.3	2.1	<0.5	18.6	3.6	3.3	351.7	353.9
13)	101.0	18.4	1.4	0.8	16.9	2.7	<3.0	307.3	327.9
<u>GROUNDWATER SITES:</u>									
14)	113.0	0.5	10.9	<0.5	16.7	11.4	6.3	272.6	284.2
15)	87.6	37.1	30.5	1.8	48.6	31.4	4.8	366.6	371.4
16)	6.0	2.5	19.2	<0.5	16.9	20.6	<3.0	30.4	25.3
17)	116.0	36.8	29.5	3.8	21.6	21.1	52.2	401.8	441.1
18)	101.0	7.1	26.4	4.2	29.4	32.4	9.3	270.7	281.4
19)	35.5	18.7	65.4	3.3	38.8	70.4	21.9	121.0	165.6
<u>MISCELLANEOUS SITES:</u>									
20)	113.0	2.6	3.7	4.3	56.4	8.5	<3.0	294.3	292.9
21) i)	114.0	1.2	2.4	<0.5	12.9	5.7	3.3	279.8	289.6
ii)	63.7	<0.1	1.8	<0.5	13.7	5.7	<3.0	150.1	159.5
22)	93.7	1.2	2.5	1.0	22.5	7.6	4.5	223.8	238.9
23)	51.5	<0.1	1.5	1.5	17.4	5.6	5.1	121.1	129.0
24) i)	34.3	9.7	7.6	1.0	18.4	7.2	4.8	122.5	125.6
ii)	28.8	7.9	7.1	1.1	18.4	7.2	5.7	96.5	104.4
25)	70.8	14.2	5.3	2.1	16.7	5.3	<3.0	227.5	235.2

All values mg L⁻¹ except alkalinity and total hardness which are expressed as mg L⁻¹ CaCO₃,

TABLE 4

COMPUTED PARAMETERS AND TRACE METAL RESULTS

SITE NO.		Log P (CO ₂)	SI _C	SI _D	Fe ²⁺	Zn ²⁺	Mn ²⁺	Cu ²⁺
<u>SPRING SITES:</u>								
1)		-2.60	0.85	-0.93	0.3	-	0.1	-
2)	a)	-1.99	0.28	-0.80	-	-	-	-
	b)	-2.43	0.63	-0.09	-	-	-	-
3)	ia)	-1.66	0.35	-0.21	-	-	-	-
	ib)	-1.53	0.31	-0.30	-	-	-	-
	iaa)	-1.69	0.39	-0.14	-	-	-	-
	iib)	-1.63	0.38	-0.14	-	-	-	-
	iiia)	-1.89	0.34	-0.23	-	-	-	-
	iiib)	-2.33	0.83	0.85	-	-	-	-
4)	ia)	-2.65	0.73	-0.40	-	-	-	-
	ib)	-2.69	0.70	-0.49	-	-	-	-
	ii)	-2.56	0.43	-0.68	-	-	-	-
5)		-1.78	0.34	-0.78	0.1	-	0.1	-
6)	i)	-1.22	0.03	-2.75	-	-	-	-
	ii)	-2.12	0.80	-0.92	-	-	-	-
	iii)	-2.44	0.85	-0.52	-	-	-	-
7)		-1.18	-0.01	-1.35	-	-	-	-
8)	i)	-1.97	0.76	0.63	-	-	-	-
	ii)	-2.35	0.71	0.68	-	-	-	-
	iii)	-1.01	-0.17	-1.70	-	-	-	-
	iv)	-1.58	0.27	-0.50	-	-	-	-
9)	i)	-1.28	0.23	-2.32	-	-	-	-
	ii)	-1.38	0.20	-2.34	-	-	-	-
	iii)	-1.81	0.12	-2.38	-	-	-	-
10)		-1.24	0.05	-1.06	-	-	-	-
11)		-1.37	0.23	-0.75	0.2	-	-	-
12)		-1.34	0.27	-0.55	0.3	-	-	-
13)		-2.61	1.28	2.13	-	-	-	-
<u>GROUNDWATER SITES:</u>								
14)		-1.62	0.30	-1.42	-	1.3	-	-
15)		-1.07	-0.10	-0.25	-	-	-	-
16)		-2.27	-2.04	-4.00	2.2	14.4	-	-
17)		-1.24	0.24	0.32	-	-	-	-
18)		-1.34	-0.04	-0.92	-	0.1	-	-
19)		-1.31	-0.74	-1.42	-	2.1	-	0.1
<u>MISCELLANEOUS SITES:</u>								
20)		-2.18	0.93	0.54	0.4	-	0.3	0.1
21)	i)	-1.64	0.33	-1.02	-	-	-	-
	ii)	-2.67	0.59	-1.34	-	-	-	-
22)		-1.58	-0.09	-1.81	-	-	-	-
23)		-2.00	-0.35	-3.36	0.4	-	-	-
24)	i)	-1.75	-0.74	-1.72	-	-	0.1	-
	ii)	-1.89	-0.88	-2.02	-	-	-	-
25)		-1.57	-0.16	-0.73	-	-	-	-

All cation values in mg L⁻¹; - below detection limit of 0.1 mg L⁻¹

TABLE 5

CHANGES IN PHYSICAL, CHEMICAL AND COMPUTED PARAMETERS FOR SITES 3, 8 AND 9

SITE 3:				a) ¹				b) ²			
Position	i)	ii)	iii)	i)	ii)	iii)		i)	ii)	iii)	
WT (°C)	300	→ 31.0	→ 25.0	32.0	→ 32.0	→ 34.0		→ 32.0	→ 34.0		
AT (°C)	29.5	→ 31.5	→ 30.5	34.0	→ 36.0	→ 30.5		→ 36.0	→ 30.5		
Cond. (μS cm ⁻¹) #	488	→ 483	→ 439	505	→ 495	→ 400		→ 495	→ 400		
pH	7.20	→ 7.23	→ 7.35	7.10	→ 7.19	→ 7.80		→ 7.19	→ 7.80		
Ca++ (mgL ⁻¹)	108.0	→ 106.0	→ 94.7	109.0	→ 108.0	→ 85.9		→ 108.0	→ 85.9		
Mg++ (mgL ⁻¹)	6.4	→ 6.1	→ 6.0	6.3	→ 6.3	→ 6.1		→ 6.3	→ 6.1		
Alkal. (mgL ⁻¹) *	277.4	→ 274.0	→ 247.0	289.9	→ 284.6	→ 224.3		→ 284.6	→ 224.3		
Log P (CO ₂)	-1.66	→ -1.69	→ -1.89	-1.53	→ -1.63	→ -2.33		→ -1.63	→ -2.33		
SI _C	0.35	→ 0.39	→ 0.34	0.31	→ 0.38	→ 0.3		→ 0.38	→ 0.3		
SITE 8:											
Position	i)	ii)	iii)	iv)							
WT (°C)	28.0	→ 28.5	→ 32.5	→ 30.0							
AT (°C)	33.0	→ 35.5	→ 33.5	→ 32.0							
Cond. (μS cm ⁻¹) #	580	→ 407	→ 540	→ 511							
pH	7.55	→ 7.78	→ 6.59	→ 7.12							
Ca++ (mgL ⁻¹)	117.0	→ 82.9	→ 114.0	→ 106.0							
Mg++ (mgL ⁻¹)	7.4	→ 7.1	→ 2.3	→ 4.6							
Alkal. (mgL ⁻¹) *	320.3	→ 220.5	→ 291.9	→ 277.9							
Log P (CO ₂)	-1.97	→ -2.35	→ -1.01	→ -1.53							
SI _C	0.76	→ 0.71	→ -0.17	→ 0.27							
SITE 9:											
Position	i)	ii)	iii)								
WT (°C)	34.0	→ 32.5	→ 28.5								
AT (°C)	34.0	→ 32.5	→ 30.5								
Cond. (μS cm ⁻¹) #	567	→ 495	→ 353								
pH	6.90	→ 6.96	→ 7.20								
Ca++ (mgL ⁻¹)	125.0	→ 115.0	→ 85.2								
Mg++ (mgL ⁻¹)	<0.1	→ <0.1	→ <0.1								
Alkal. (mgL ⁻¹) *	318.4	→ 290.0	→ 199.2								
Log P (CO ₂)	-1.28	→ -1.38	→ -1.81								
SI _C	0.23	→ 0.20	→ 0.12								

¹10/5/88 ²17/5/88 ³25.0 °C *as mg L⁻¹ CaCO₃

A PRELIMINARY STUDY OF LEAD IN CAVE SPIDER'S WEBS

Julia M. James, Michael Gray and David J. Newhouse

Abstract

The spider *Badumna socialis* constructs large communal webs on the roof of several caves in New South Wales. Recent observations of the apparent increase in the number of webs falling from the Grand Arch at Jenolan appear to indicate that the number of spiders is declining. One theory is that fumes and in particular lead from the large number of cars driving through the arch is a contributing factor. This paper reports a preliminary study of the lead and insoluble sediments associated with spiders webs from a number of caves.

INTRODUCTION

A colony of spiders dwells in the Grand Arch at Jenolan Caves, New South Wales, Australia. Casual observers have noted masses of their webs falling from the cave roof and the fallen webs contain dead spiders. The fallen webs have been found more frequently over the recent years (E. Holland, pers. comm). It has been suggested that the spiders are being poisoned by lead (Jenolan Caves Reserve, Draft Plan of Management Volume 1, 1988) or toxic fumes. The postulated source of lead is volatile lead compounds produced in the exhaust fumes of cars passing through the Grand Arch.

The spiders in the Grand Arch live approximately 17 m above the roadway and weave enormous web complexes which cover many square metres of the cave roof. This location is ideal for trapping dust, water vapour and, under some circumstances, gaseous fumes. Much smaller webs spun by the same spider can be seen on the walls of the Grand Arch. The roadway provides the main access to the Jenolan Caves Tourist Resort and has been excavated through the Grand Arch. The resort currently receives over 250,000 visitors a year, almost all of whom pass through the Grand Arch in cars or buses.

Maurer (1974) noted a reduction in diversity and abundance of certain invertebrate groups (carabid beetles and spiders) in roadside meadows affected by chemical pollution from motor vehicles. The spider communities studied showed significant reductions in species diversity and individual numbers for those associated with heavy compared to light motor traffic regimes. Lead in the bodies of beetles living in field edges immediately adjacent to heavy traffic roads were significantly high in 2 of 3 species tested compared with control animals living deeper within these fields.

THE SPIDERS

The enormous communal webs spun by the social cave spider *Badumna socialis* are a feature of the entrance regions of several caves in southern New South Wales. These spiders are related to the black house or window spider, *B. insignis*, a

solitary species common in urban areas. The webs of *B. socialis* are built upon the roof of large, protected cave entrance arches. They form continuous silk sheets covering many square metres of roof area. Such 'mega-sheet' webs are made up of hundreds of individual sheet webs (10-20 cm across), each with its own entrance funnel and spider occupant. The spiders tolerate each other to the extent of allowing their small sheet webs to be built so close together that they merge at the margins to form a mega-sheet. Behavioural work is needed to determine if their level of social behaviour extends beyond this, e.g. to communal prey capture and feeding.

Factors limiting the occurrence and size of these spider aggregations would logically seem to be the availability of suitable substrate space and abundant, localised food. Cave entrances may fulfil both of these criteria. Entrance arches, especially the larger examples, can provide the space required. Entrance zones are usually energy rich and often support an abundant invertebrate fauna, including flies, moths and crickets, all potential spider prey.

The best known populations and mega-sheets of *B. socialis* occur at Jenolan, the Grand Arch population being the most notable example, and in the Abercrombie Arch at Abercrombie Caves. Mega-sheets are also associated with other highland cave systems, including Wombeyan and Colong. Chemotaxonomic studies indicate that there is considerable genetic differentiation between the Jenolan, Abercrombie and Wombeyan populations (Gray, in prep.). This suggests that there is little gene flow between these populations and provides the basis for a more detailed study of the relationships and evolutionary history of these spiders.

The mega-sheet web in Abercrombie Arch is noted for the blue-grey sheen of its surface. This colour results from the way that light is reflected from the many fine silk fibrils that make up each of the millions of cribellar catching threads that form the mega-sheet surface. It is a reliable sign of a thriving spider population in a well maintained web. Polluted or abandoned webs soon become dull grey, discoloured and tattered, feature apparent over large parts of the web in the Grand Arch at Jenolan. In addition, almost all of the mega-sheet once covering the west side of the Grand Arch has now disappeared.

In this initial study webs were chosen for analysis because they were readily obtained. The lead associated with the web is likely to be proportional to the lead within the spider's body because as the spider moves about its web it picks up contaminants caught in the web, especially on its legs. Spiders regularly groom their limbs, drawing them through their jaws to remove foreign material. It is during this process that chemical contaminants such as lead could be ingested by the spider. Similarly, if the lead is entering the spiders' bodies through prey ingestion, air intake or body covering, lead deposited in the web by the spider or caught in it as dust will still be proportional to that found in the spiders' bodies.

METHODS

Several kilograms of fallen web material were available for analysis from the Grand Arch and as a result none of the *in situ* web silk was collected. The number of spider colonies that could be used as controls for this study were limited as web silk could only be collected from large thriving colonies of the spiders. It was possible to collect suitable quantities of web from three other caves.

- i) The Abercrombie Arch: a tourist cave within hundreds of metres of a parking area.
- ii) The Entrance Chamber at Colong Caves: a wild cave, three to four kilometres from the nearest road.
- iii) Paradox Cave in the Southern Limestone at Jenolan: a wild cave remote from the road.

The spider's webs were collected from the roof of Abercrombie Arch and Paradox Cave and from the floor of the Grand Arch and the Entrance Chamber of Colong Caves. The webs were stored in clean plastic bags. The web from Paradox Cave, Jenolan was collected when results of the lead analyses from the first three caves were inconsistent. Table 1 contains descriptions of the webs from the four caves.

TABLE 1 DESCRIPTION OF THE SPIDER WEB SAMPLES AND THEIR PROPERTIES ON DIGESTION

<p>Abercrombie Arch live healthy spiders pale grey silk web web easily digested - slight effervescence small amount of pale pink residue easy to filter clear colourless solution</p> <p>Colong Caves no spiders in web sample dark brown web web difficult to digest - effervescence large amounts of yellow brown residue difficult to filter clear deep orange solution</p> <p>The Grand Arch dead spiders dark grey web web difficult to digest - considerable effervescence large amounts of pink-brown residue difficult to filter clear deep orange solution</p> <p>Paradox Cave live healthy spiders pale grey web web easily digested - slight effervescence small amount of grey residue easy to filter clear colourless solution</p>	
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The methods used for the lead analyses were adapted from those developed for human blood, urine and scalp hair (Kopito *et al.* 1972 and Weiss *et al.* 1972) and are similar to those used for the analysis of cave sediments by Stenner, 1978.

The damp web samples were digested in 5 mL of Merck suprapur concentrated nitric acid and then heated to dryness. This procedure was repeated four times. The blanks were prepared by evaporating 4 x 5 mL of the suprapur concentrated nitric acid.

The digested samples were dissolved in 15 mL of 0.1 M HCl and filtered through 0.4 mm Nucleopore filters, the filtrate was made up to 25.0 mL with 0.1 M HCl for measurement on a Varian Techtron AA6 - Atomic Absorption Spectrometer. The residue and Nucleopore filter were dried at 70 °C and weighed.

Standards were prepared as follows: A 1000 mL of a stock solution containing 1000 mg L⁻¹ of Pb(NO₃)₂ was prepared by dissolving 1.5982 g of Merck Pb(NO₃)₂ 99.5% purity, in 1000 mL of 0.1 M HCl. From this stock solution 100 mL standards of 2, 4, 6, 8, 10, 14 and 20 mg L⁻¹ were prepared in 0.1 M HCl.

In the first series of analyses two samples of webs from three caves were analysed and the results were inconsistent. In the second set of analyses, two more samples from the previously analysed webs from the first three caves were repeated together with four samples of the web from Paradox cave.

A description of how the samples behaved during digestion, the ease with which they could be filtered and the colour of the filtrate can be found in Table 1. The % residue insoluble on digestion with concentrated nitric acid and the results of the lead analyses in mg g⁻¹ of lead in the damp web and any material soluble in concentrated nitric acid are given in Table 2.

RESULTS

The results of this survey (Table 2) show that there is a considerable amount of lead associated with the spider's webs from the Grand Arch at Jenolan Caves. The control web from Paradox Cave shows minimal amounts of lead. The Abercrombie webs have effectively no lead. The consistent high lead values (four samples; one web) for Colong Caves are unexpectedly high.

At first contamination of the Colong Caves web was suspected, however, Stenner (1978), reports enhancement of lead analyses in the presence of calcium when the chosen method of analysis for lead is atomic absorption spectrometry. Stenner (1978), did not correct his results for calcium enhancement but states that it lies between 30 - 50 mg kg⁻¹ for the samples he was analysing. The effervescence of the Colong Caves samples indicates that they contain a significant amount of calcium carbonate dust. Thus the high Colong results may be an analytical artifact and if this is the case then it follows that the Grand Arch results are also enhanced. As all of the webs contain an unknown amount of detrital calcium carbonate; more accurate lead values can only be obtained using the technique of standard addition (Skoog & West, 1986); this technique compensates for interference by other ions present in the analyte solution.

Lead poisoning in humans manifests itself after prolonged exposure by chronic symptoms and rarely by death (Scientific American, 1971). A study by Turner (1980), con-

TABLE 2 RESULTS OF LEAD ANALYSES

Sample #	Weight of sample g	Weight of residue g	% Insoluble residue	Weight of digested sample g	Pb in digested sample mg kg ⁻¹
B1	-	-	-	-	-
B2	-	-	-	-	-
B3*	-	-	-	-	-
B4*	-	-	-	-	-
A1	0.2105	0.0238	11.3	0.1867	0.0
A2	0.2347	0.0266	11.3	0.2081	48.1
A3*	0.2256	0.0276	12.2	0.1980	0.0
A4*	0.2421	0.0289	11.9	0.2132	0.0
C1	2.0511	0.3655	17.8	1.6856	109.8
C2	1.0747	0.1729	16.1	0.9018	105.3
C3*	2.2701	0.4023	17.7	1.6518	107.6
C4*	1.8064	0.3212	17.8	1.5843	103.2
J1	1.5646	0.4206	26.9	1.1440	297.2
J2	1.0070	0.2177	21.6	0.7893	133.0
J3*	1.6855	0.5130	30.4	1.1725	304.6
J4*	1.4786	0.3615	24.4	1.1171	290.2
P1*	0.2164	0.0315	14.5	0.1849	13.5
P2*	0.2208	0.0346	15.7	0.1862	13.3
P3*	0.2268	0.0382	16.8	0.1886	26.5
P4*	0.2010	0.0298	14.8	0.1712	0.0

B Blanks

* samples analysed in the second set

A Abercrombie Arch, Abercrombie Caves

C The Entrance Chamber, Colong Caves

J The Grand Arch, Jenolan Caves

P Paradox Cave, Jenolan Caves

cluded that lead in petrol did not constitute a significant source of lead poisoning for humans. There have been no studies published on the toxicity of lead to fragile cave fauna. Stenner's 1978 study of the sediments in the caves of Mendip found hundreds of thousands of mg kg⁻¹ of lead in the cave sediments and these were attributed to lead mining in the vicinity of the caves. The lead mining commenced nearly 2000 years ago in Roman times and continued to the early this century yet it is in these caves that a number of rare fragile aquatic troglobitic species of cave fauna exist (Hazelton, 1975). Bosnak and Morgan, 1981 in their study of toxicity of cadmium and zinc in cave and surface isopods demonstrated that the aquatic cave fauna were less susceptible to heavy metal poisoning. This sparse evidence seems to indicate that lead poisoning of the spiders is unlikely and another reason for the webs falling is required.

The water vapour and dust that is soluble in nitric acid were not quantified in this study. The majority of the soluble dust will be calcium carbonate derived from the limestone both inside and outside the caves. An optical microscopic examination of the insoluble material in the control caves and the Grand Arch webs showed that it is aeolian dust. The dust from the control caves consists largely of breakdown products of the rocks and the soils close to the caves. A minuscule amount of this insoluble material will have been derived from the weath-

ering of calcite decorations and limestone bedrock. The Grand Arch insoluble sediments are more complex indicating other sources, such as concrete and road surface materials. The difficulty experienced when filtering the digested samples from the Grand Arch and Colong Caves indicates the presence of colloidal materials. The colloids are most likely to be derived from aeolian clay materials. The deep orange colour of the filtrates from these caves indicates the presence of soluble iron compounds.

The Grand Arch web contains more insoluble residue than the others (Table 2). Assuming that it also had correspondingly more limestone dust it would have been heavily weighted. The web from Paradox Cave shows that the webs naturally support considerable amounts of dust. Thus it is postulated extra dust created by traffic passing through the Grand Arch could be the sole cause of the webs falling to the floor. The web complex becomes so filled with dust that the spiders can no longer maintain it and its points of attachment fail. This needs to be confirmed by experiments on *in situ* webs and freshly fallen webs. Dead spiders are found in the web but some may escape and commence web building again either in the same or another location.

The lead poisoning hypothesis and the dust contamination of the webs are both compatible with the observation that the webs have fallen more frequently in recent years. The

increase in traffic through the Grand Arch will have definitely increased the amount of dust. It is not possible to predict the variation in lead levels. Increased lead levels are possible due to an increase in traffic, however, the lead levels will be decreasing due to the introduction of lead free petrol. This is the first set of lead measurements in the Grand Arch and other measurements are required to demonstrate how lead levels are varying with time.

It should not be forgotten that motor vehicle exhaust fumes contain other volatile toxic materials such as nitrogen oxides and carbon monoxide both of which are expected to be fatal to the spiders if present in sufficient quantities. Cars using lead free petrol also produce fumes that are harmful to the spiders because reactions in catalytic converters produce toxic sulfur compounds. At most times it is expected that gaseous fumes are not likely to accumulate to hazardous amounts in the well ventilated areas where webs are found. However, in the Grand Arch it is possible that gaseous fumes may accumulate within the upper arch air space during periods of still weather. Such conditions could last for many hours or even days; long enough to cause the death by suffocation of spiders. A gas monitoring program in the Grand Arch concentrating on the toxic oxide gases of carbon, nitrogen and sulfur would be useful in testing this hypothesis.

This preliminary study started with the hypothesis that lead poisoning of the spiders was the cause of the increase in the number of spider's webs falling. The presence of lead in the webs does not confirm this hypothesis. This investigation has produced an alternative hypothesis which can be validated by experiments using material readily available in the Grand Arch. It is intended to focus further studies on the second hypothesis at the same time improving the analytical methods for lead in spiders' webs, spiders, the dust and the cavern air in order to confirm that the initial hypothesis is invalid.

ACKNOWLEDGEMENTS

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- Julia M. James - School of Chemistry, Sydney University
Mike Gray - The Australian Museum, Sydney
David J. Newhouse - Sydney Grammar School

A COMPUTER PROGRAM FOR 3D CAVE MAPS

Alan Warild

In early 1990 a computer program called DeltaGraph appeared which, when, coupled with other Macintosh software, goes a long way to doing everything a cave surveyor could want while still being easy to use. DeltaGraph is designed for graphing but has a reasonable drawing capability so that simple plots can be touched up with extra labels, north arrows etc. For more complex drawing, DeltaGraph readily exports files which can then be worked on in more detail by a dedicated drawing program.

The necessary data to be collected in the cave is -

station distance compass clino left, right, up, down

STATION	TAPE	COM-PASS	CLINO	←	→	↑	↓
N2701	5.7	250	20	1.2	1	0	1.5
2	9.8	0	90	0	4	1.5	10
3	6.4	330	-15	0	4	11.5	0
4				1.4	0	3	2.5

Useful conventions to be observed are -

- * take all bearings in the same sense (i.e. all forward or all back bearings), so as to avoid confusion and extra calculations.
- * left and right are estimated or measured for each station while facing in the direction which the survey is running, usually into the cave. The left and right distances should be taken on a bearing which bisects the angle between the survey legs either side of the station.
- * Up and down are taken as verticals and like left and right are estimates or measurements of the average passage size.

Calculations

The data are then run through a program such as the spreadsheet Excel to give the following output data -

stn	X	Y	Z	left X	left Y	right X	right Y	up	down
1	0	0	0	2	-3.464	-4	6.9282	3	-1.1
2	1.670	-2.894	2.706	2.1590	-3.002	-3.210	-1.811	3.7060	1.6060
3	0.261	-19.006	4.4402	-1.236	-18.91	1.7583	-19.09	7.2402	5.3402
4	-0.05	-27.98	5.0167	0.4202	-28.15	-0.998	-27.66	6.5167	3.9167
5	1.536	-29.88	4.2132	3.4443	-30.48	1.1554	-29.76	5.7132	3.1132
6	1.136	-34.45	4.4540	3.0891	-34.89	0.1602	-34.24	5.9540	3.3540
7	2.628	-37.04	6.4671	3.0273	-37.07	1.1345	-36.91	7.4671	5.3671

This data can then be put into DeltaGraph (DG) for plotting. A simple line plot can be made by plotting XYZ, then rotating it to give views from plan to elevation and any range of 3D views in between. For fancy effects, the perspective can also be changed.

"3D" with passage dimensions

To show passage dimensions takes somewhat more manipulation of the data. It is organised to give a series of boxes around each station, joined at the top left corner and the 3 lines for each of top right, bottom right and bottom left. In order to get reasonable boxed in cave plots, a complete set of LRUD data is required otherwise pitches (the usual place where such data are neglected) may appear as thin spindly lines. Steeply angled sights give a much better 'picture' of the pitch than using vertical sights, which only serve to superimpose two boxes on each other.

DG has a capability for simple data sorting so it is arranged in five blocks 1-top left, 2-lower left, 3-lower right, 4-top right, 5-top left, thus-

stn	left X	left Y	down	stn	right X	right Y	down
1	2			1	3		
2	2	2.1590	-2.785	2	3	-3.210	-3.976
3	2	1.7583	-19.09	3	3	-1.236	-18.91
4	2	0.4202	-27.82	4	3	-0.998	-28.31
5	2	3.4443	-29.28	5	3	1.1554	-30.00
6	2	3.0891	-34.02	6	3	0.1602	-34.67
7	2	3.0273	-37.00	7	3	1.1345	-37.17

The blocks are then stacked vertically -

- 1-top left
- 2-lower left
- 3-lower right
- 4-top right
- 5-top left

2-lower left

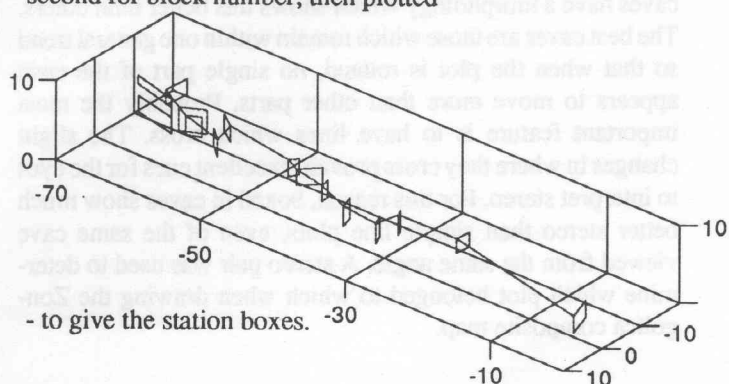
3-lower right

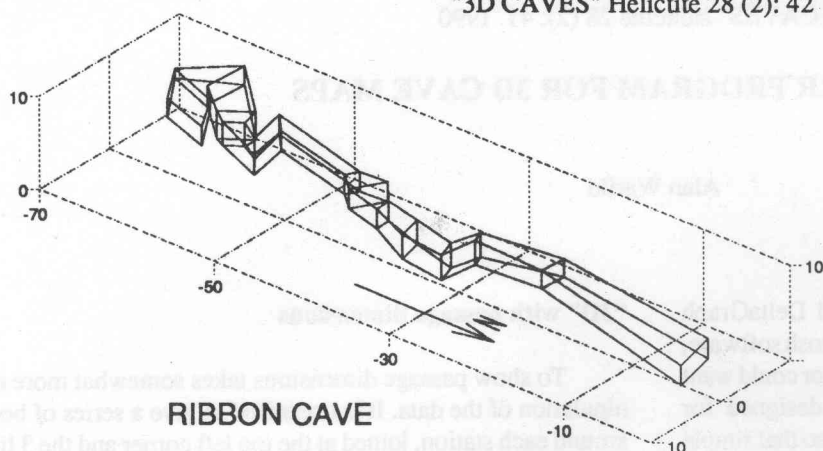
4-top right

station	position	X	Y	Z
2	1	2.1590	-2.785	3.7060
2	2	2.1590	-2.785	1.6060
2	3	-3.210	-3.976	1.6060
2	4	-3.210	-3.976	3.7060
2	5	2.1590	-2.785	3.7060
3	1	1.7583	-19.09	7.2402
3	2	1.7583	-19.09	5.3402
3	3	-1.236	-18.91	5.3402
3	4	-1.236	-18.91	7.2402
3	5	1.7583	-19.09	7.2402
4	1	0.4202	-27.82	6.5167
4	2	0.4202	-27.82	3.9167
4	3	-0.998	-28.31	3.9167
4	4	-0.998	-28.31	6.5167
4	5	0.4202	-27.82	6.5167
5	1	3.4443	-29.28	7.132

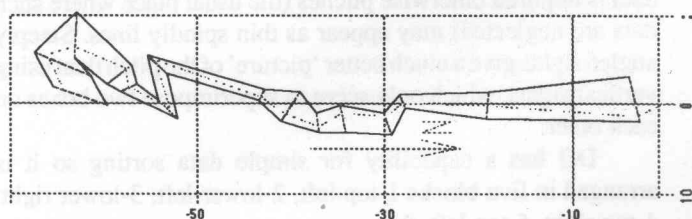
- with a gap between any two stations which do not connect.

The lower five blocks are sorted first for station and second for block number, then plotted

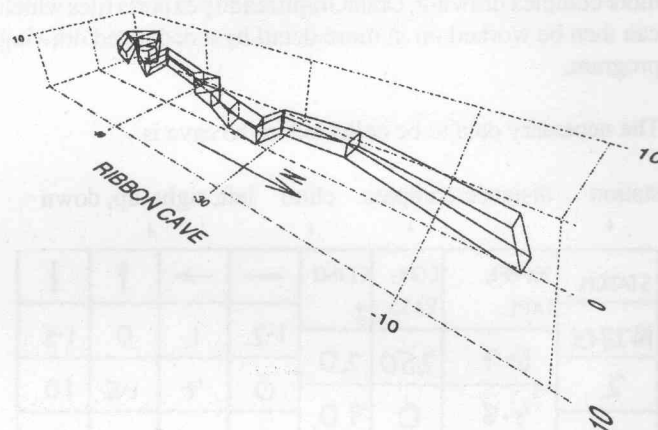




RIBBON CAVE



RIBBON CAVE -PLAN



Surface features

Surface features can be plotted by covering a contour map of the area with a grid and entering the altitude data. The data may need to be manipulated to obtain the desired view and vertical exaggeration keeping in mind that caves and surface must be kept on the same grid, orientation and scale to fit together or mean anything.

Composite Underground and Surface

The Zongolica area map is a composite of 27 caves plotted simultaneously (3,300 stations) some of which are shaded differently so they can be identified. Three surface plots are used- a partial one in black over the caves, another partial one in white, with thicker lines between the black surface and the caves to make the surface appear to cross over the caves, and a third surface to fill the caps, make the edges tidy and carry the fills and grid. Finally the labels were added.

Stereo Pairs

Rotation of plots is very easy and can be finely adjusted to give the most suitable view. By plotting two views of the cave from angles about 5° apart, DG can produce stereo pairs. Some caves have a morphology which shows this better than others. The best caves are those which remain within one general trend so that when the plot is rotated, no single part of the cave appears to move more than other parts. Probably the most important feature is to have lines which cross. The slight changes in where they cross provide excellent cues for the eyes to interpret stereo. For this reason, boxed in caves show much better stereo than simple line plots, even of the same cave viewed from the same angle. A stereo pair was used to determine which plot belonged to which when drawing the Zongolica composite map.

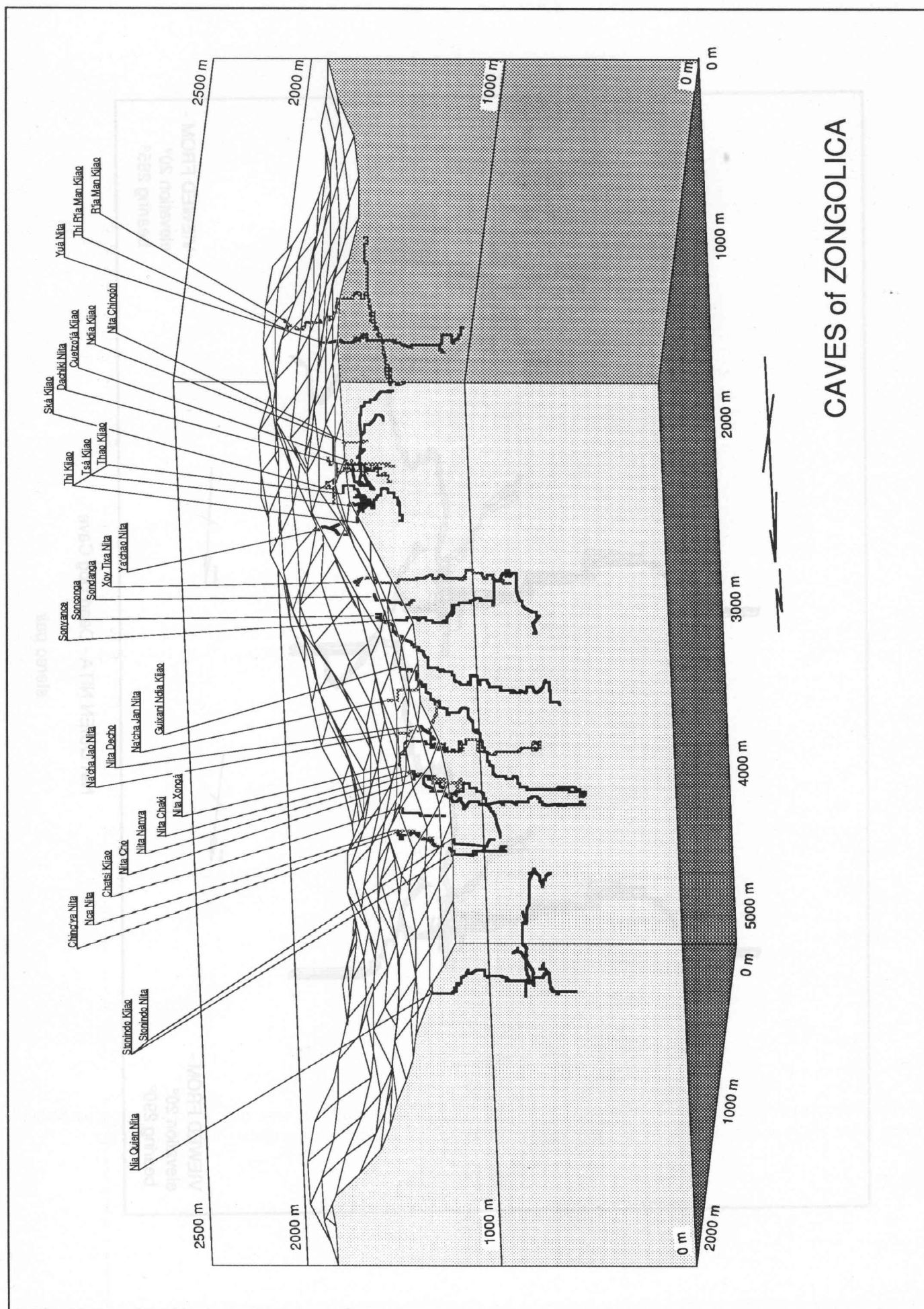
Limitations

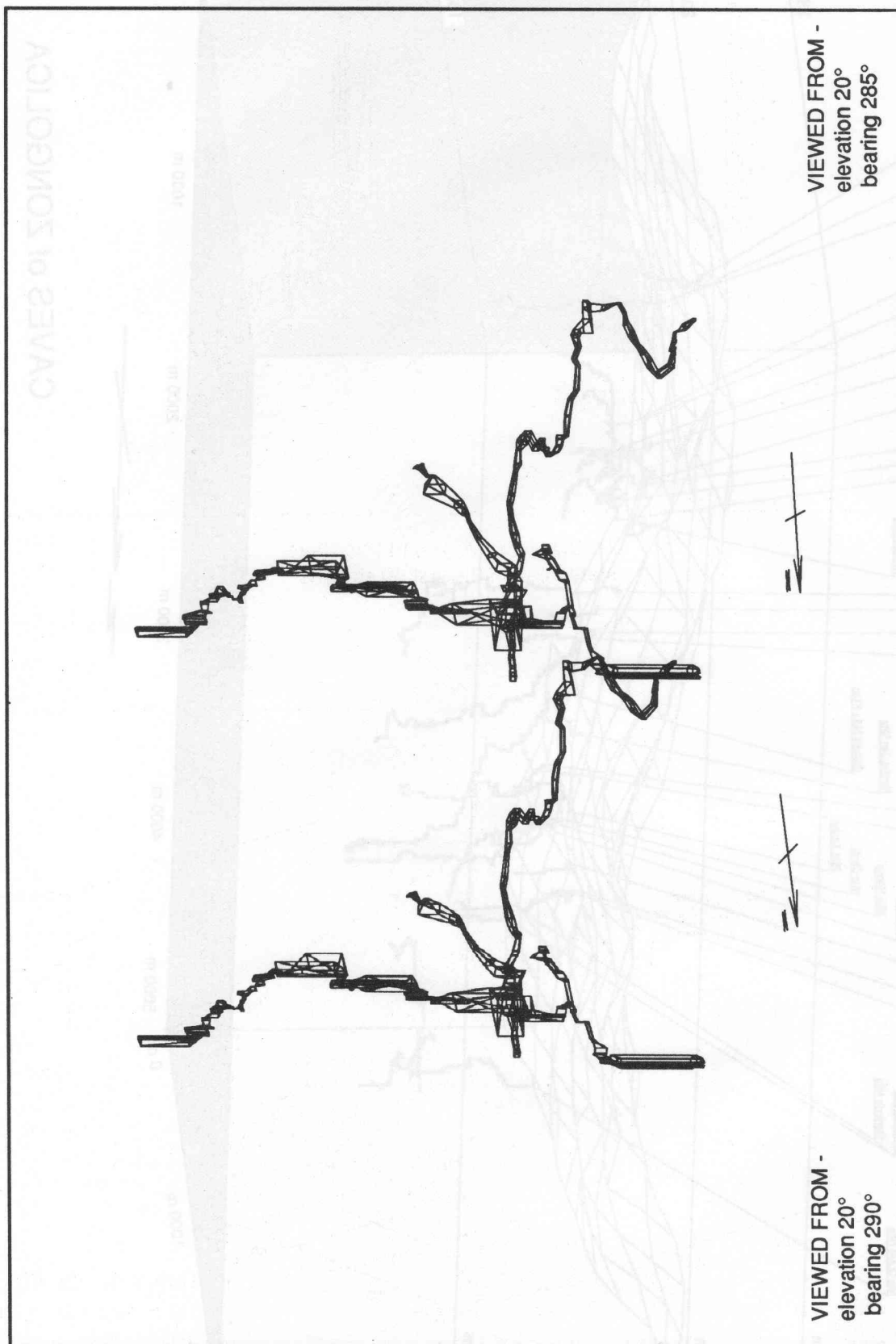
DG is a big step forward for cave plotting but it is not without its limitations.

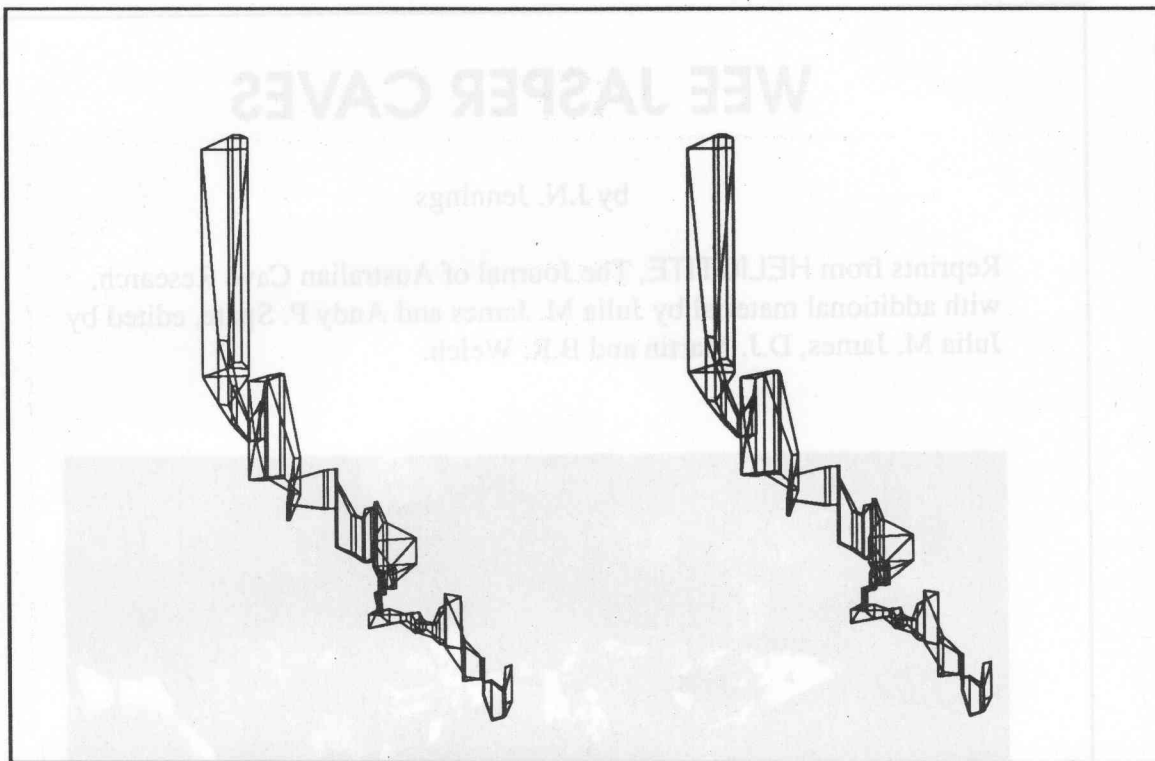
- * The plot can only be rotated through a range of 90° vertically (from plan to elevation) and 90° horizontally (say north to east). To obtain other views the sign must be changed on some or all of the X, Y or Z data.
- * DG can't label points. This makes it difficult to track down errors and correct them. Possible solutions are to make very large blowups of the area where the error is in order to discover exactly where things went wrong or to make plots of just the suspect area. A common problem is joining points which do not in reality join.
- * Every time the plot is changed DG must recalculate the entire plot. On large complicated plots this can be quite time consuming. A fast computer helps, as does a lot of memory.
- * If several separate caves are plotted at the same time they are regarded as the same plot, hence they all must be the same colour (or grey shade), line thickness etc.

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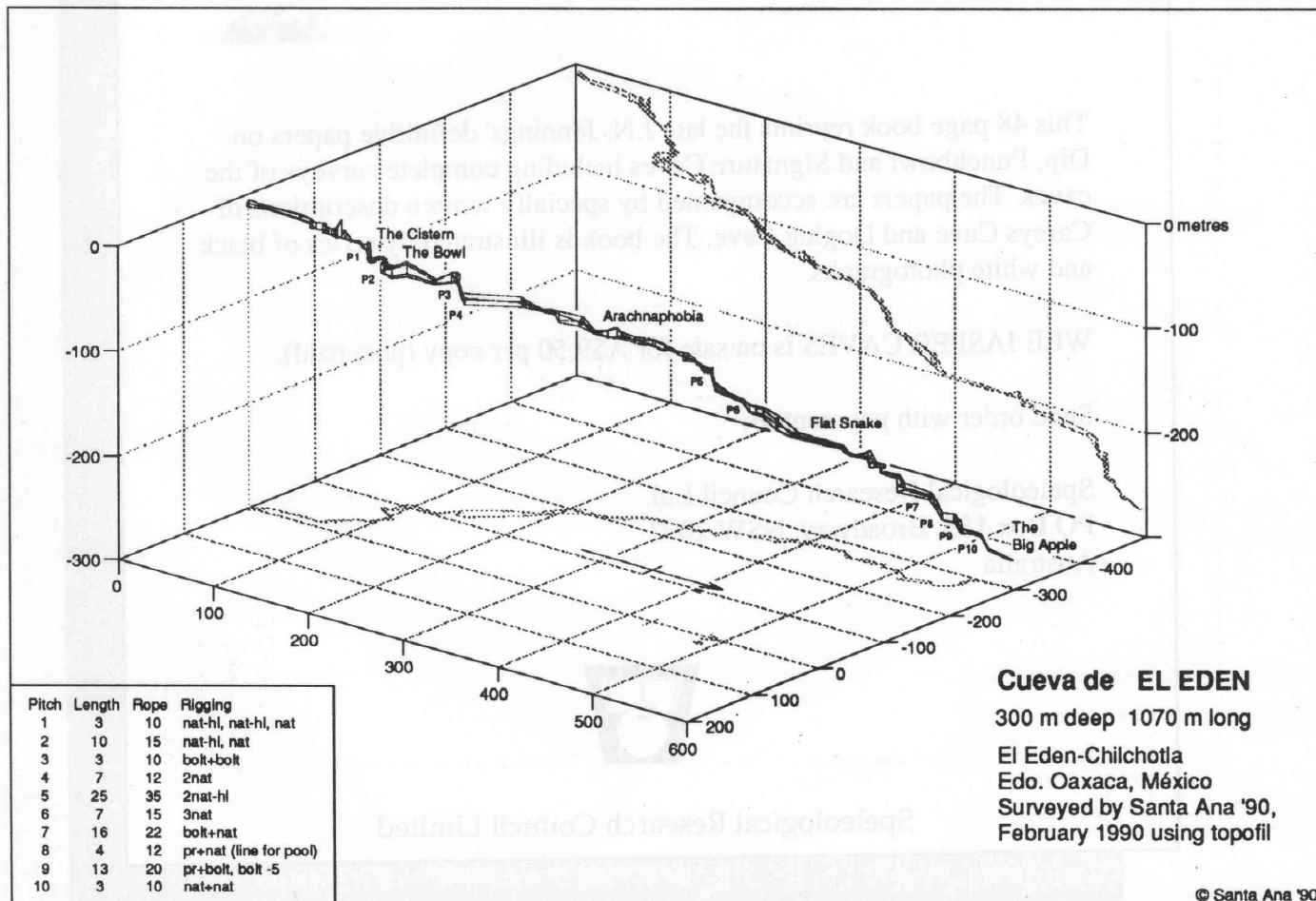
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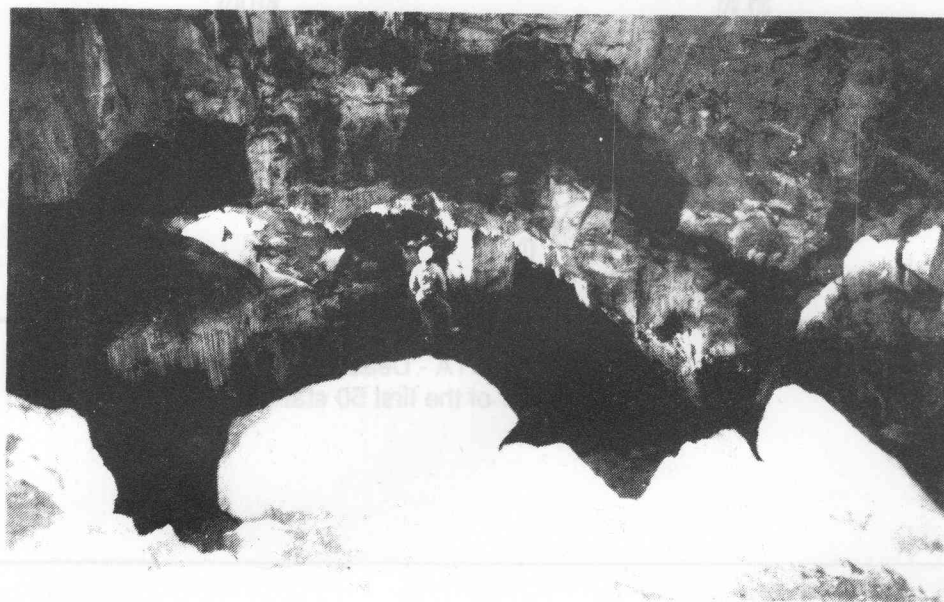
NIA QUIEN NITA - Dead Dog Cave
stereo pair of the first 50 stations



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References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication (e.g. "(Grey, 1973)"). Where there is more than one reference to the same author in one year the letters a, b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by 'et al.' should be used in subsequent citations. References should be checked particularly carefully for accuracy. Journal titles should be abbreviated following the "World List of Scientific Periodicals", which is available in most large libraries. The following examples illustrate the style:

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

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

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

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Figures and photographs should be kept to a minimum and generally should not duplicate information in tables or other material. Photographs should be clear black and white prints with sharp focus. Where several photographs are to form one plate they should be mounted together on white card. Any lettering required on photographs should be applied with 'Letraset'. Figures should be drawn in Indian ink on white card, heavy paper or tracing material and lettered using stencils or 'Letraset'.

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