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TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 5 Number 2 June 1978

Aboriginal snake painting, Chillagoe
(T. D. Ford)

Chillagoe Karst
Survey Instrument Calibration
Uranium Series dating
Metals in Cave Sediments
Network models

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A very short summary of the principal conclusions should accompany every contribution.

References to other published work should be cited in the text thus . . . (Bloggs, 1999, p.66) . . . and the full reference with date, publishers, journal, volume number and page numbers, given in alphabetical order of authors at the end, thus . . .
Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

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CONTENTS

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Bryan Ellis,
30 Main Road,
Westonzoyland,
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Somerset TA7 OEB

CHILLAGOE - A TOWER KARST IN DECAY

by Trevor D. Ford

SUMMARY

A belt of tower karst in N.E. Australia enjoys a strongly seasonal climate of hot wet summers and long dry winters. Vertically bedded Siluro-Devonian limestones occur in fault blocks with intervening shales. Following early peneplanation phreatic solution has developed complex joint-controlled cave systems at the same time as pedimentation has trimmed the limestone into towers up to 100m high. Intense karren development is partly controlled by lithology, but little vadose modification of the caves is seen. Partial collapse leads to the formation of daylight holes with "skylights" in the roofs of large chambers, decorated with tufa and stalactites. The sequence of events suggests a climatic oscillation in the Pleistocene but does not prove it.

Lying in northern Queensland in the wide southern foot of the great Cape York peninsula Chillagoe's karst is probably closest to that recently described in New Guinea (Brook et al., 1976), but it presents major contrasts and throws a little light on the evolutionary processes of tower karst regions.

The karst belt of Chillagoe is some 60 km long from northwest to southeast with a maximum width of 8 km; the settlement of Chillagoe (population 120) lies roughly in the centre, at an altitude of some 390m above sea level. The karst takes the form of an aligned series of towers rising up to 100m within a moderate, rolling topography of volcanic and granitic rocks. Drainage is by a network of shallow stream courses, many of them dry for much of the year, focussing on the Walsh river and its tributary Chillagoe Creek, which discharge into the Gulf of Carpentaria some 700 km to the west, rather than to the coast 130 km to the east. In fact the divide is only some 20 km inland from the port of Cairns.

The limestone towers of Chillagoe carry a locally dense vegetation of figs and evergreen vines, while the intervening grasslands have gum trees so closely packed that visibility is often limited to 100 metres; together these form a marked contrast to the barren Limestone Ranges of Northwest Australia illustrated by Jennings and Sweeting (1963); there, however, the relative lack of other rocks and the wider expanses of limestone pediments may contribute more to the sparsity of vegetation than the lower rainfall.

The climate is highly seasonal of alternating humid or arid tropical type (Köppen AW climatic type) with the highest temperatures occurring at the period of greatest rainfall in January and February (mid-summer) whilst from April to October very little rain falls, and many winters are totally dry. Mid-summer temperature maxima are over 120^{O}F while mid-winter temperatures reach daily maxima of around 80-90^{O}F, with night-time minima down to 40^{O}F. The quantity of precipitation is not high, the annual average being about 750mm but most of this falls in summer, with rapid run-off accompanied by very high humidity. Exceptionally high rainfall in 1973-4 gave nearly 2000mm in three months (Wilson, 1974).

PREVIOUS RESEARCH

The tower karst of Chillagoe attracted early scientific attention for the Czech geographer Jiří V. Daneš studied much of Australia's karst and referred to Chillagoe in papers published in 1910, 1917 and 1924. A valuable summary of Daneš' work has been provided by Jennings (1966). In Daneš' time it was a declining copper-lead-silver mining area. Mining ceased around 1926 with resultant depopulation; the towns of Mungana, Redcap and Zillmanton are now totally abandoned and largely obliterated. Postwar investigations brought in the Queensland Geological Survey and two memoirs cover the essentials of the regional geology (De Keyser et al., 1964, 1968). They include reconnaissance geological maps but no detailed map has yet been prepared. The map presented herein has been compiled by the writer from the above and various other sources as well as his own observations.

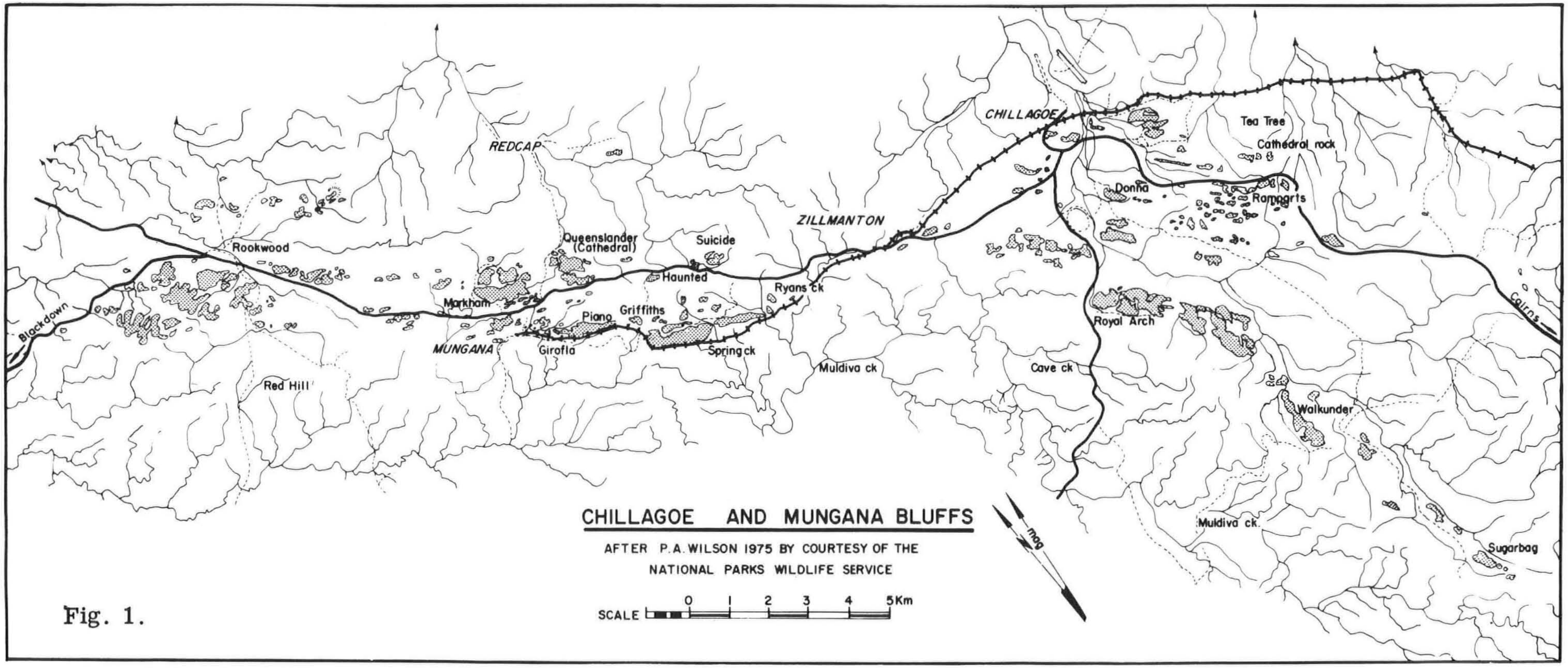

CHILLAGOE AND MUNGANA BLUFFS
AFTER P.A. WILSON 1975 BY COURTESY OF THE
NATIONAL PARKS WILDLIFE SERVICE
SCALE 0 1 2 3 4 5Km
mag
Blackdown
Rookwood
Red Hill
REDCAP
Queenslander (Cathedral)
Suicide
Haunted
Markham
Piano
Griffiths
MUNGANA
Girofla
Spring ck
Ryans ck
ZILLMANTON
Muldiva ck
CHILLAGOE
Cave ck
Royal Arch
Donna
Ramparts
Tea Tree
Cathedral rock
Walkunder
Muldiva ck.
Sugarbag
Cairns

Fig. 1.

Speleological studies culminated in the preparation of the comprehensive "Communications" by Sydney Speleological Society (1969) wherein some 50 caves are listed and a number of surveys presented. This also includes reproductions of a number of the early reports by Danes and others. Subsequent SSS journals have added notes on new discoveries and notes on drastic flooding effects (Wilson, 1974). Some 80 cave systems with over 160 entrances are now listed.

Geomorphological researches have been conducted by Jennings (1969, 1971, 1975) who outlined the processes operating. Subsequently Lundberg (1977a & b) and Marker (1977) have carried out morphometric studies in which they noted the geomorphological processes responsible for the towers and their detailed features, and drew comparisons with other areas. However, they said relatively little about the evolutionary processes operating in the caves or the chronology involved. Shrewd aside remarks are, however, present in their works.

Marker's (1977) morphometric analysis showed a consistent bevel at pediment level throughout the area, but a distinct lack of summit accordance on the towers emphasized the advanced state of dissection. The pediment is at 360m altitude west of Chillagoe but rises to over 400m southwards.

Few of the speleological and geomorphological reports except Jennings seem to recognize that most of the limestone beds exhibit vertical (or nearly so) inclination, and there is virtually no discussion of the significance of this fact in the geomorphological and speleological processes.

GEOLOGY

The Chillagoe Formation limestones are of Siluro-Devonian age (De Keyser et al., 1960, 1964, 1968); no detailed palaeontological study has been made and it is not yet possible to assign individual beds to any particular division of the Upper Silurian or Lower Devonian.

The Chillagoe limestones strike northwest to southeast; to the southwest is an intermittent belt of coarse sandstones and breccias cut off by the Palmerville Fault from high grade metamorphic rocks of the Precambrian shield (Fig. 2). To the northeast of the limestone belt is a large area of Devonian greywackes and slates covered by Permian volcanic rocks; both these and the limestones were intruded by a number of Permo-Carboniferous granites. Within the limestone belt are low hills of argillaceous rocks variously referred to as shales or slates, often highly siliceous, and bedded cherts of uncertain but not volcanic origin as suggested by Broadhurst (1952, 1953). Rarely seen in fresh outcrops, these appear to lie on the strike of the limestones in several places and as they are not present within the towers an explanation of the discrepancy must be sought. Previous suggestions of deposition in the channels of a river system flowing between the Siluro-Devonian reefs (De Keyser et al., 1964, 1968) cannot be supported owing to lack of evidence in the sedimentology, and it seems much more likely that there is a complex system of faults trending at an acute angle to the strike, and probably splaying off the Palmerville Fault. The isoclinal folding claimed by a few previous writers has not been seen in the present study. Thus the isolated towers are surrounded by discrete slices of shale, slate or chert. Some of the faults are mineralized and in the Girofla Mine cavernous ground with oxidized ores was found to a depth of over 150m (Broadhurst & Edwards, 1953).

The disposition of the fossil bands shows clearly that the beds are nearly vertical and projection along strike from one tower to another across a shale outcrop confirms that there is fault displacement though the amount and sense of movement usually cannot be made out.

The ore deposits of copper, lead and silver are mainly confined to the contacts of the limestones with other rocks, generally along faults and with more or less vertical disposition. A few deposits however, are within the limestone outcrops, though there is little sign of ores within the towers or caves.

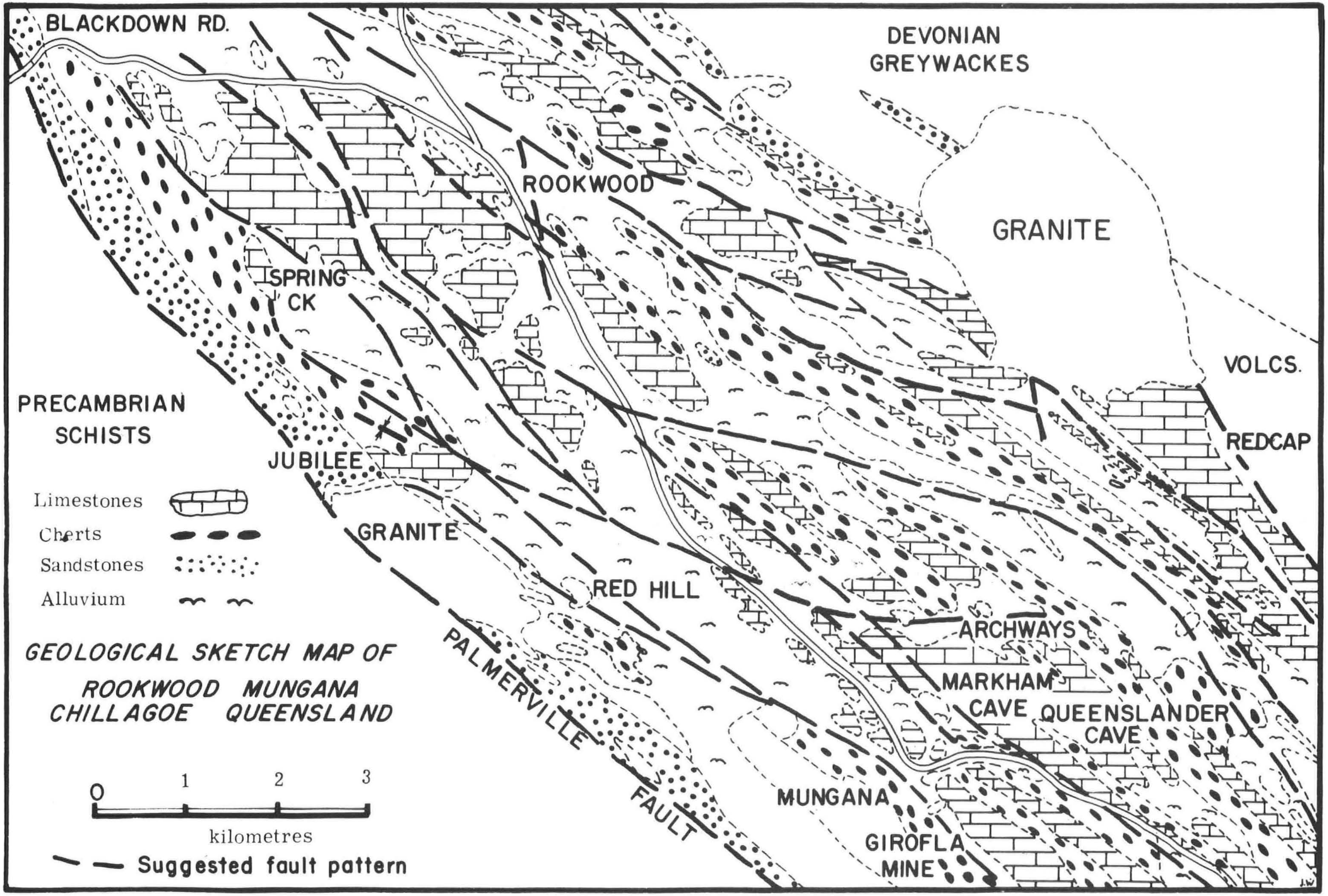

BLACKDOWN RD.
DEVONIAN GREYWACKES
ROOKWOOD
GRANITE
SPRING CK
VOLCS.
PRECAMBRIAN SCHISTS
REDCAP
JUBILEE
Limestones
Cherts
Sandstones
Alluvium
GRANITE
RED HILL
ARCHWAYS
GEOLOGICAL SKETCH MAP OF
ROOKWOOD MUNGANA
CHILLAGOE QUEENSLAND
PALMERVILLE FAULT
MARKHAM CAVE
QUEENSLANDER CAVE
0 1 2 3
kilometres
MUNGANA
GIROFLA MINE
Suggested fault pattern

Fig. 2.

On the erroneous assumption that the cherts were of volcanic origin, Broadhurst (1952, 1953) argued that the ore-bodies were diatremes, representing crypto-volcanic vents, wherein explosions of gas-laden ash clouds had prepared the ground for ore deposition. De Keyser et al. (1964, 1968) disputed this explanation and regarded the ore breccias as due to solution collapse, indeed open cavities were found at considerable depth at Girofla. Although no comparable ore body was seen to be present in a tower or in a cave system it does demonstrate the presence of deep phreatic circulation.

A reconstruction of the geological history suggests that the Precambrian gneiss shield was transgressed by the sea in Siluro-Devonian times. After an initial fluvial and beach phase of sedimentation a shallow shelf sea ensued with a shore at an unknown distance to the southwest and a deeper ocean to the east. A reef belt might be expected along the seaward margin of the shelf but, in spite of some general comments on the whole area being a series of reefs (De Keyser et al. 1964, 1968), the only evidence of reef-like limestones is in some small outcrops close to the old Mungana railway station, where fossil corals and stromatoporoids are common. In later Devonian times deeper water sedimentation resulted in greywackes of the Mount Garnet and Hodgkinson formations and in Carboniferous times an orogenic episode affecting most of eastern Australia resulted in faulting, folding and granite intrusion, followed by Permian vulcanicity (Fig. 3). The limestones were caught in a monoclinal flexure of perhaps 1500-2000 metres amplitude, of which the present outcrops mark the vertical limb. The upper limb has been eroded away and the lower limb of the monocline is still concealed at depth. The tower karst as seen today may well be unique in being developed in vertical limestones. Limestones in the vicinity of the granites were thermally metamorphosed to marble, with textures varying from compact and sugary to coarsely crystalline calcite.

There are no rocks younger than the Permian in the Chillagoe area, but regional evidence suggests that there has been renewed movement on the Palmerville and other faults together with upwarping in Tertiary times.

THE LIMESTONES

The Chillagoe Formation limestones have often been regarded as reef limestones (e.g. De Keyser & Wolff 1964) or as representing an ancient reef complex, but collectively they are best called "Shelf" limestones. Wilson (1975) noted four main types of limestones and others, notably Lundberg (1977a) and Marker (1977), have broadly followed his grouping:

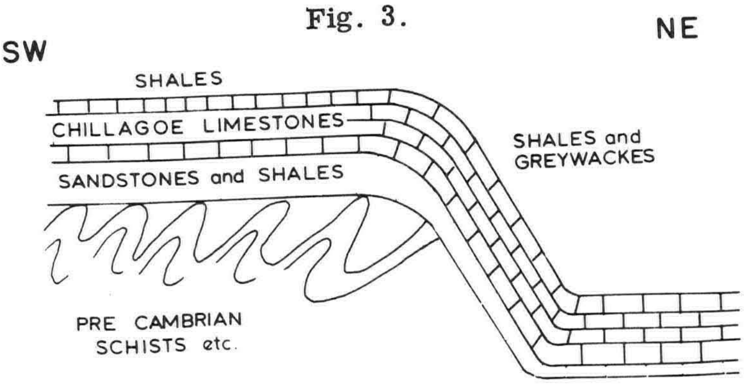
(a) sparite, dark grey compact and crystalline, forming many of the towers.
(b) banded pale blue-grey limestone, less common, forming lower towers, and sometimes with chert.
(c) sugarstone, granular white limestone usually with easily disagregated calcite crystals.
(d) breccias: (1) cave breccias or relatively recent origin; and angular grey limestone clasts in a pinkish matrix.

The present study has shown that this is something of an over generalization and a fuller description can now be given, as below, with some environmental indications.

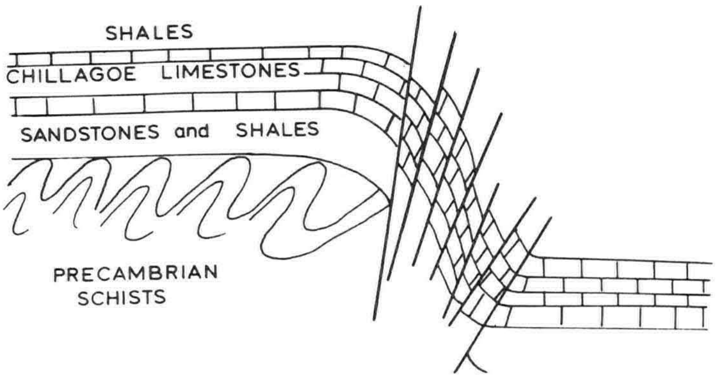
i) Dark grey limestone forms a large part of the towers where the karren weathering obscures almost all fossils and textures. Beds with scattered large brachiopods and coral colonies indicate that the beds are vertical or nearly so.

ii) Shelly limestones were packed with large brachiopods up to 10 cm wide. Best seen in the pediment fringes of the towers, bands could be followed, though obscured by weathering, right across some towers, indicating the strike of the beds. The brachiopods are either *Conchidium* or *Stringocephalus*. These beds were often interlayered with beds packed with smaller brachiopods of the Pentamerid type usually about 3 cm wide with the weathered sections giving a characteristic "Broad arrow" appearance. Near the Blackdown Road, the brachiopod bands showed some displacement from

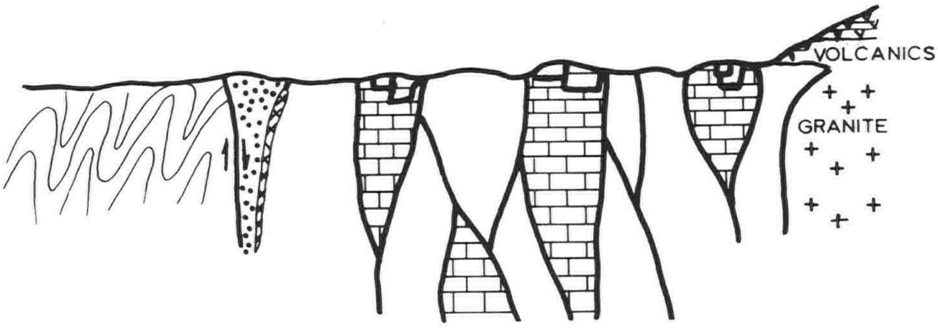
Fig. 3.



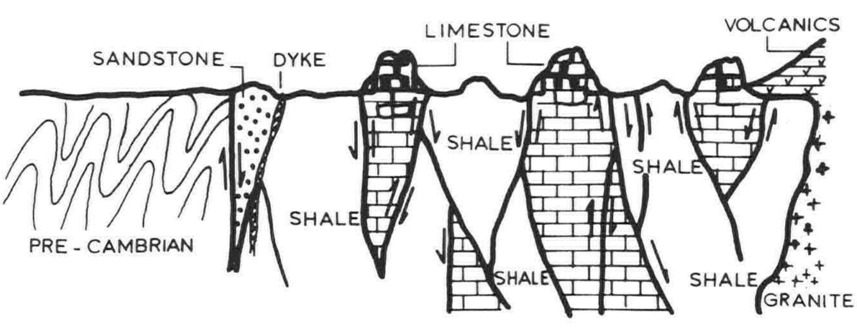
1. A monocline develops along the site of the Palmerville Fault in early to middle Carboniferous times as the initial phase of the Palmerville - Chillagoe structure.



2. Intense faulting of the middle vertical limb of the monocline causes differential movement of fault-blocks containing nearly vertical Chillagoe limestones.



3. After the block-faulting the Chillagoe area was intruded by granites and partly covered by volcanic rocks in Permo-Carboniferous times. Subsequent erosion in Tertiary times has removed the upper limb of the monocline and phreatic solution has initiated speleogensis in the limestones.



4. Repeated cycles of pedimental trimming of the limestone blocks has resulted in karst tower formation with drained phreatic caves left high and dry.

tower to tower indicating the presence of faulting in the alluvial areas.

iii) Coral limestones were found in the pediment areas of a number of towers, and they could occasionally be traced through the obscuring karren on to the tops of towers. The coral bands were less distinct and merged with other fossil faunas, particularly stromatoporoids. The corals were dominated by colonies of *Favosites* type, with *Heliolites* and *Halysites* less common. Small Rugose corals were locally common.

iv) Stromatoporoid limestones, seen in low outcrops close to Mungana railway station, were packed with colonies of the extinct colonial hydrozoan coelenterates.

v) Crinoidal limestones: a single bed with abundant crinoid ossicles occurs immediately overlying the stromatoporoid limestones at Mungana railway station. In the low outcrops the contact is variable from sharp in places to interlayered on a scale of a few centimetres each in others, so that there is no unconformity or other discordance. The crinoidal bed has a maximum visible thickness of around 4 m being lost in alluvium to the north-east. It can be traced intermittently along the strike for about a kilometre to the south-east.

vi) Thin-bedded banded limestones were seen to be well-developed 100 metres or so north of the road, some ½ km east of Rookwood turnoff. With dips of 60-70° to the north-east, the beds were platy in appearance with individual plates 2-5 cm thick, separated by 1 cm layers which weathered black. Both types of bed are an opaque micrite, or fine calcisiltite to calcilutite. At this locality the thin-bedded limestones are visible to a thickness of perhaps 20 m and pass upwards without obvious break into the uniform dark grey limestones. East of Rookwood these limestones were involved in a number of small folds of submarine slumping type. Karren were developed across uniform, banded and folded limestones alike. Small areas of thinly bedded limestone are occasionally seen in caves, as in Disney Cave in Royal Arch Bluff.

vii) Bioclastic limestones: a number of localities showed patches of a more granular limestone, in which surface weathering gives a spurious impression of oolitic texture. Thin sections showed these to be calcarenites with numerous clasts of most elements of the fauna, mixed with faecal pellets, but no ooliths.

viii) Burrowed limestones: limestones with elongate to ramifying mottled structures were common interlayered with the brachiopod beds near the Archways, and with shelly and coral limestones elsewhere. The mottlings were burrowing traces believed to have been made by marine worms.

ix) Breccias and conglomerates: coarse boulder beds were a distinctive feature of many karst towers, where they seemed to have the effect of a more rounded morphology with the karren very much interrupted on them. Boulders were often 30 cm or more in diameter, though 15-20 cm was probably average. They varied from angular to well-rounded, and appeared to be all limestone. In traverses made west of Rookwood on the Blackdown road, the breccia was seen to form a vertical band varying from 10-20 metres in thickness. Contacts appeared to be sharp both top and bottom, and De Keyser et al.'s interpretation of the boulders on a wave-cut platform is probably not far from the truth. In a few voids a geopetal texture gave a useful way-up criterion confirming the vertical bedding. On no traverse was more than one bed of breccia-conglomerate seen and it is possible that only one such layer is present in the area.

No evidence was seen to support Broadhurst's (1953) concept of reef-front breccias.

x) Pseudobreccias: many of the outcrops in the Archways-Aboriginal Painting Cave area had a brecciated appearance on weathered surfaces, though the clasts were small (10 cm maximum) and showed little contrast with the matrix. Sufficient examples were found with clasts that fitted together to suggest that this was brecciation in situ and not the wave-breccia. This lithofacies seems to be a pseudobreccia, produced either by burrows penetrating the whole rock, or by partial dolomitization.

xi) Volcanoclastic limestone was seen only in one thin section from near Girofla Mine, and not recognised until after the visit; it is a calcarenitic limestone containing numerous rounded semi-opaque grains with abundant lath-shaped feldspar crystals. The opaque matrix is thought to be volcanic glass with crystallites. The source, and hence the significance of these pyroclasts, is unknown.

xii) Fragmental limestones: some small crags at the extreme north-western end of the limestone belt (immediately north of a bend in the Blackdown Road, and apparently the lowest limestones in the succession) consisted of a calcareous mud-flake breccia. These flake limestones were interlayered with conglomerates containing pebbles of granitic and volcanic material, as well as a few limestones.

xiii) Diagenetic textures: apart from the pseudobreccia dolomitization noted above only limited diagenetic textures were seen. A few limestones have scattered micro-blebs of silica, probably of authigenic origin. Chert, however, within the limestone is uncommon and many outcrops were seen without chert. Near the Donna Cave, south of Chillagoe town, thin-bedded limestones had bands and nodules of chert which occasionally coalesced into masses a metre or so in thickness. Similar occurrences were seen on a smaller scale elsewhere but no evidence of widespread chert formation was seen.

xiv) Dolomite was not recognised as such in the field but the matrix of the pseudobreccia contains a little dolomite.

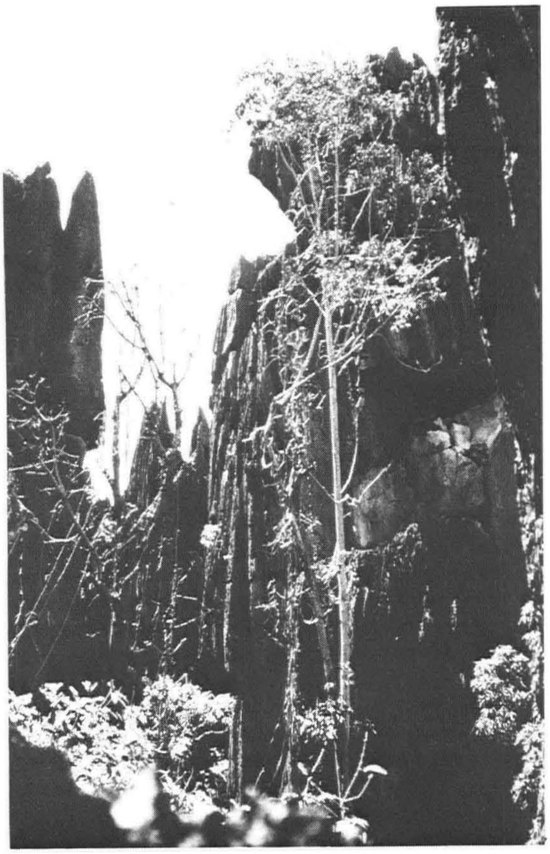
xv) Marble and Calc-silicate rock were seen in a number of outcrops. Both result from the thermal metamorphism of limestone by the heat of a nearby intrusion. The closeness of outcrops near Redcap suggests that the conversion of limestone to marble and calc-silicate is a critical reaction. Outcrops no more than a few metres apart were distinctly either limestone or marble though a gradation was seen near Zillmanton. An apparent transition showed a pseudo-nodular texture in one outcrop.

Lundberg's (1977a) chemical analyses of the limestones showed generally less than 1% Mg, insoluble residues variable but generally less than 2%, and very low SiO_2 and FeO. The analyses showed little correlation with lithological characters or with weathering features.

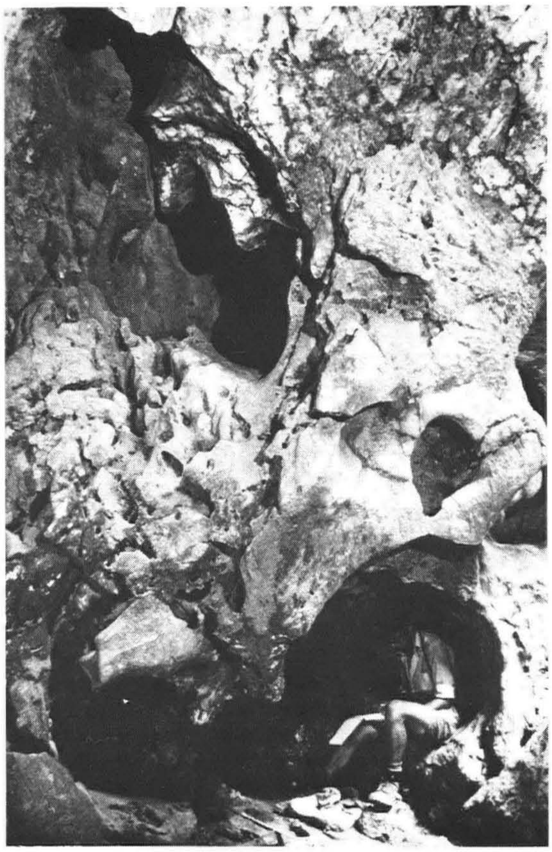
THE TOWERS

The isolated towers of limestone, locally called bluffs, rise up to 100 m above the general topographic level which is characterized by pediments cut across limestones and shales. Individual towers may be anything up to a kilometre in length, though a few hundred metres is more usual (Plate 2, figs. 1 & 3). Small towers are no more than 10 m high and wide and sometimes give the impression of large wild animals hiding in the trees, as in the Elephant Rock near Archways (Plate 3, fig. 1). The towers often have vertical walls with indentations along joints or bedding planes (Plate 1, fig. 3) but steps or terraces are present on many and provide rugged routes for climbing to the tops.

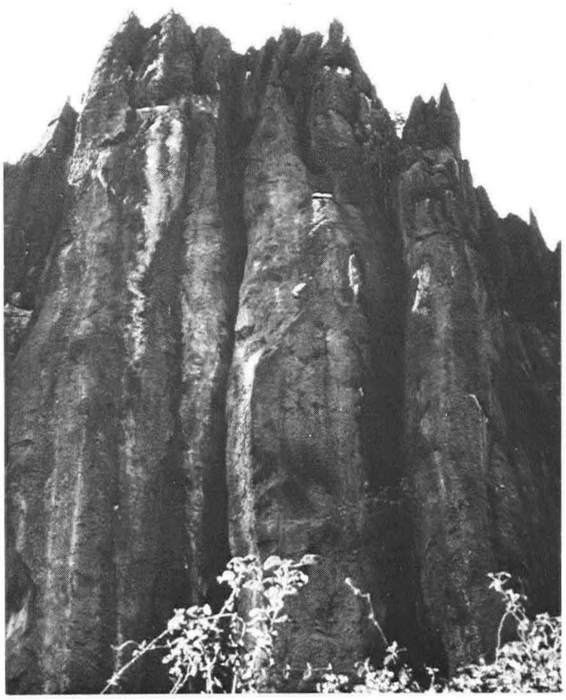
The upper surfaces of the towers are cut with intense karren development, with razor-sharp ridges averaging some 7 cm apart (Plate 2, fig. 2). These funnel rainwater down the walls or into joints; crevices a few cm wide may be tens of metres in depth. On flatter areas there are scattered shallow saucer-like depressions or Kamenitza, up to 30 cm in diameter and 10 cm deep (Plate 2, fig. 4). Sloping surfaces generally have parallel karren but occasionally these are broken by shelf-like kamenitza. Also on the tops of towers are scattered skylights into large caverns beneath, dangerous for the unwary climber and the occasional rock wallaby!



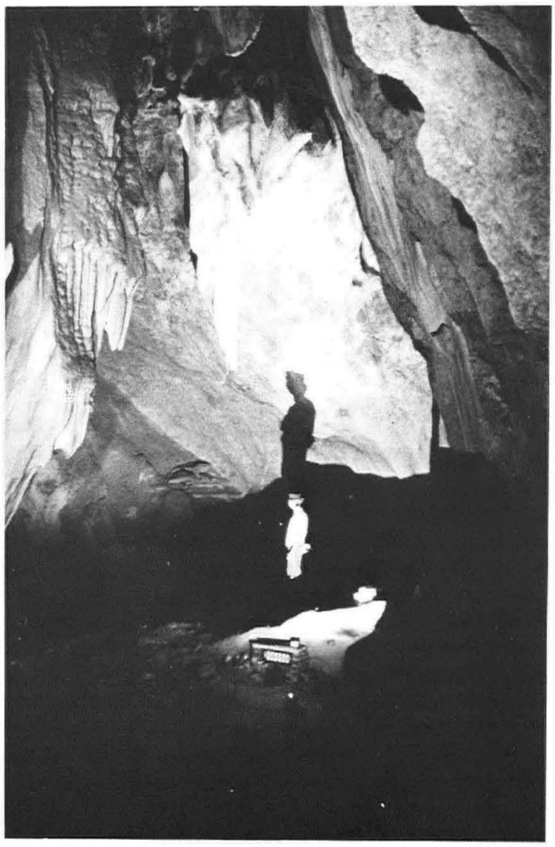
1. Supergrikeland, Queenslander Bluff. (photo Joyce Lundberg)



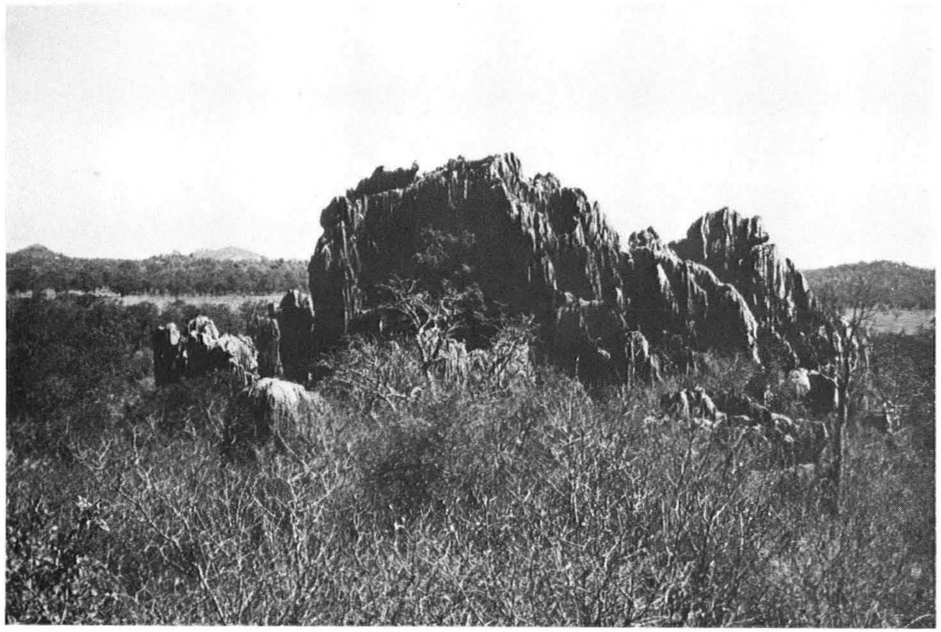
2. Phreatic spongework in Moss Road, Supergrikeland (photo Joyce Lundberg)



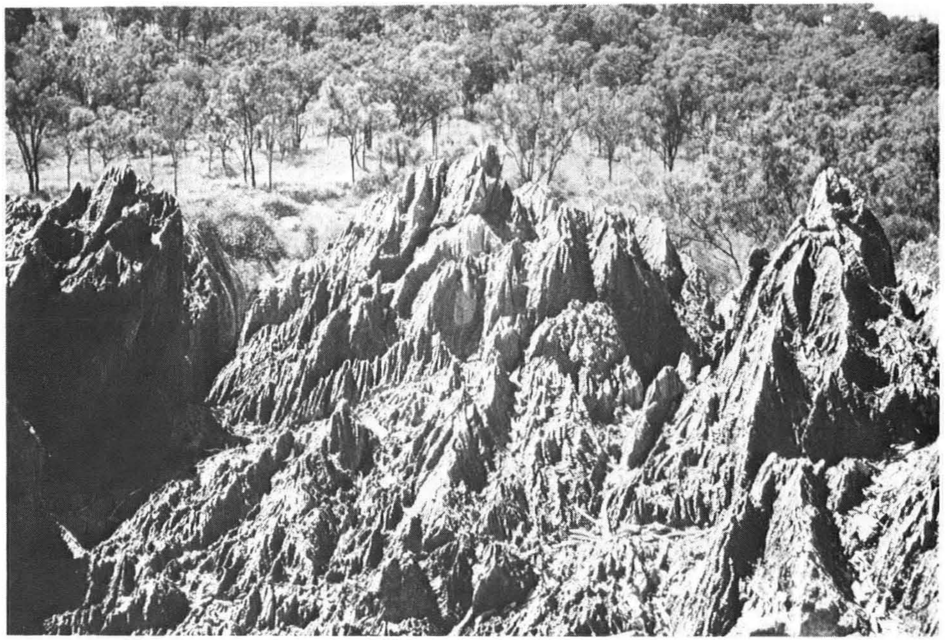
3. Open joints high above Royal Archways.



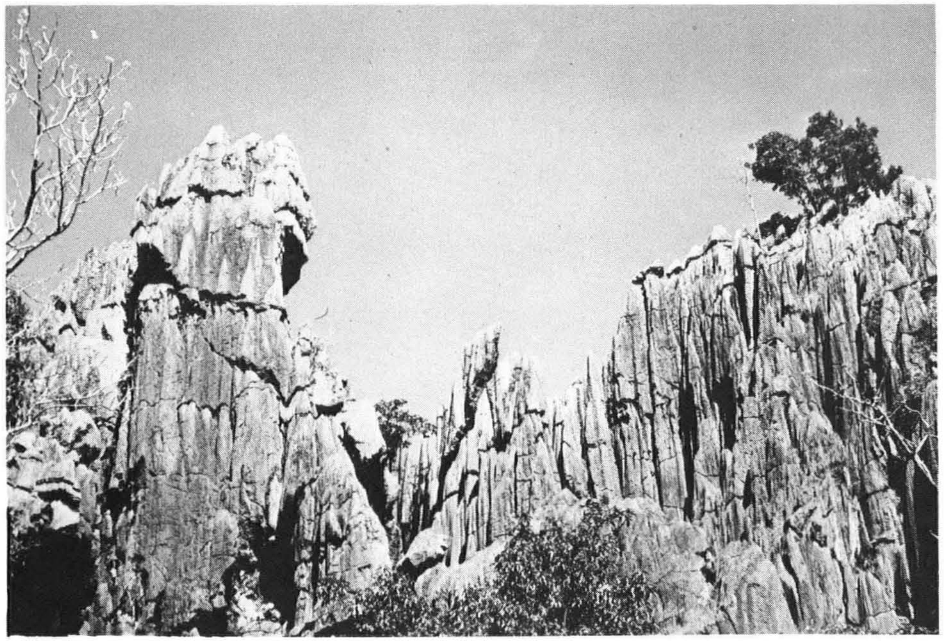
4. The Main Chamber of Donna Cave. (photo Joyce Lundberg).



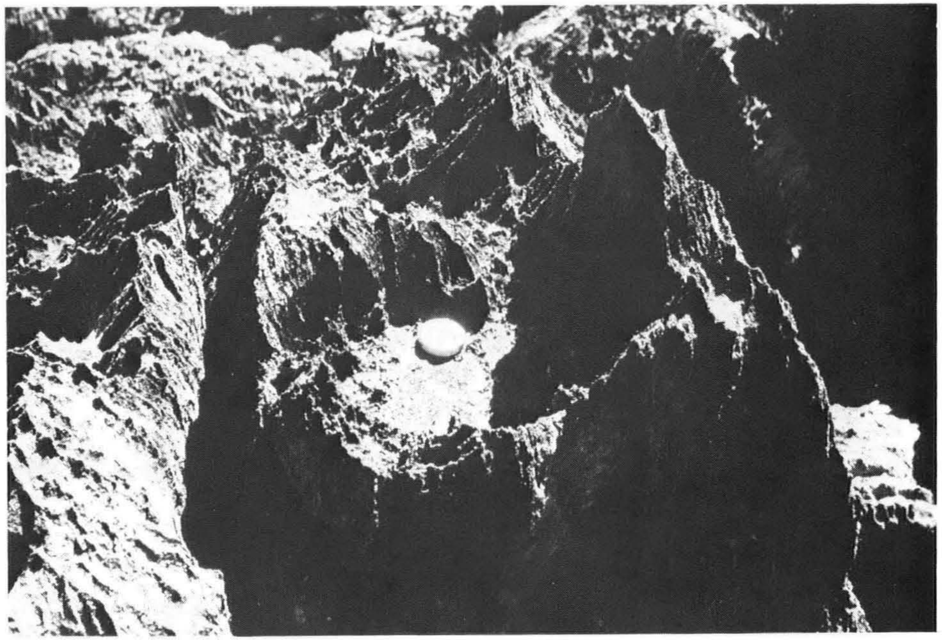
1. Bluff southwest of Rookwood.



2. Jagged karren on a bluff near Rookwood.



3. Karren walls on Markham Bluff.



4. A kamenitza hollow on top of a bluff. (Scale 5cm diameter).

The jagged karren of the towers is best developed on the fine dark grey limestones (Plate 2, fig. 2). The lack of crusts in the grooves and the sharp ridges clearly indicate that active solution is still taking place and that karren development is relatively fast. Both rundkarren and rillenkarren are present. Lundberg's (1977a and b) studies have shown that the karren are not so sharp or deep on the "Sugary limestones" but otherwise the different lithologies seem to have little effect. Fossils sometimes cause irregularities, but in many cases the grooves cut across fossils and matrix alike.

A few of the wider towers have amphitheatre-like depressions on the tops, filled with jumbled masses of enormous blocks: these appear to represent collapsed caverns; a rim of jagged pinnacles surrounds them. They were referred to as collapse dolines by Jennings (1966).

Narrow corridors, up to 30 m deep, cut through some towers though they are often obstructed by fallen blocks. They are often aligned along joints (Hamilton-Smith, 1966). In the Queenslander Bluff the frequency of such corridors is such that they have been named "super-grikeland" (Plate 1, figs. 1 & 2); they are predominantly oriented in the north to north-east sector, roughly at right angles to the strike of the bedding (Robinson, 1976). Some of the corridors lead into caves via daylight holes, and in some bluffs the combination of corridors and caves has led to wholesale collapse.

Marker's (1977) analysis of a sample of 89 towers near Chillagoe showed a slight tendency for higher towers where pedimentation was least, south of Chillagoe, and this in turn tended to correlate with the size of the towers.

Only a few of the towers show much evidence of chert in the limestone, but on Donna Bluff chert nodule bands were to be found on surfaces ranging from horizontal to vertical. They projected from the limestones by no more than a few millimetres.

A few of the towers show masses of cemented chert gravel high on the walls, generally in widened joints: these suggest the former presence of high level pediment gravels though whether they have survived from the Tertiary is debatable (Daneš, 1917; Jennings, 1966). Some such masses on bluffs south-west of Rookwood were in limestones apparently without chert nodules in them, indicating the transported nature of some of the chert gravel masses.

Some towers had relics of old stalagmite deposits high on them, suggesting the former presence of caves now destroyed.

Towers developed on the marbles and sugary limestones are generally more rounded, with poorly formed karren. Exfoliation sheets are present and the walls are usually more gentle slopes, grading down to the pediment with only a minor break of slope.

LIMESTONE PEDIMENTS

The towers are generally surrounded by pediments, more or less flat surfaces eroded across bed-rock, whether limestone or intervening shales. The pediments are usually composed of patches of bare rock showing rounded solutional forms protruding through a veneer of alluvium of terra rossa soil, with developments of calcareous tufa, interspersed by shallow stream channels, e.g. Ryan's Creek. The latter may be cut through to bed-rock but more commonly they are gravel-floored, and low (one metre) terraces of cemented gravel flank a few. At the foot of the towers the pediment may spread right to the vertical rock face but often there is a mass of tumbled boulders. In a few cases where the pediment spreads to the rock foot the cliff-foot is undercut with shallow solutional caves and these are sometimes decorated by aboriginal paintings as at Markham Bluff. Some pediments, as at Zillmanton, carry griked surfaces.

The pediments have been cut by a combination of processes with both solution and abrasion by migrating sediment. The pediments pass without any distinctive break into alluvial fans flanking the stream courses.

The limestone pediments seem to be more extensive than those described in the Limestone Ranges of northwest Australia by Jennings and Sweeting (1963). This may be due to wetter climates in the past with greater run-off, but alternatively it may be due to the fact that the limestones are in discrete fault blocks, with impervious rocks between so that pedimentation could cut in from all sides as streams meandered from shales on to limestones and back, (Jennings, 1969).

Former pediment surfaces are represented by patches of cemented gravel high on the towers, occasionally with tufa, and probably by the steps or terraces on some towers, though no consistency of altitude has been detected.

THE CAVES

Some 160 caves have been catalogued in the Chillagoe area, and have been assigned numbers (tagged on the rock at the entrances) in accordance with Australian Speleological Foundation recommendations. Fifty of them have been described briefly in the Sydney Speleological Society's Communications No. 3 (1969) and more in the Chillagoe Caving Club's "Tower Karst" (1976), but other descriptions and discoveries are scattered in various journals, e.g. Holt (1974). Detailed descriptions need not be given here, and the following comments are concerned with general deductions on speleomorphology and speleogenesis. Four caves are open to tourists as part of the Queensland National Park system. Development of a fifth for tourists had commenced when a sudden collapse of part of the entrance arch discouraged further work.

The larger cave systems, Royal Arch, Queenslander and Markham, are clearly phreatic networks of great complexity. Some of the others, such as Donna and Ryan Imperial, are clearly in the same category, but less complex. Other large systems have recently been found around Rookwood, e.g. Caviare Cavern. Most of the smaller caves seen by the writer are of the same type but of considerably less extent being clocked by stalagmite fill, roof falls, etc.

The plan of the *Queenslander System* (Fig. 4 after Robinson et al., 1976) shows some 6 km of passages which now link several caves formerly thought to be separate; these include Queenslander itself, Cathedral, New Southlander, Epi-Frenetic and others. Together they comprise what is probably the third longest cave system in Australia. The system occupies a considerable proportion of the Cathedral Bluff, the rest of which is separated off by deep corridors and the small detached bluffs contain isolated caves as remnants of an even more extensive cave system. Development has been strongly joint-controlled with many chambers oriented north-south or north-east to south-west transecting strike of the nearly vertical limestone beds. Numerous oblique and inclined joints are also present and the large chambers have generally been developed by phreatic solution at joint intersections. Daylight holes perforate many of the larger chamber roofs.

Though less extensive, *Markham Cave* is a similar cave system with 1200 m of passages (Fig. 5). The entrance is at the back of a low step at the foot of the tower; it was an arch some 20 m wide which partly collapsed as a jumble of house size blocks during the cutting of a footpath into the cave. Local stories varied as to whether it was a lightning strike or inadvertent use of explosives which brought the roof down, but the blocks were mostly bounded by karren-ribbed joints and instability was obvious by hindsight. From the back of the arch joint-controlled "rift" passages of varying height lead into the daylit Main Chamber, some 30 m across and 20 m wide, with masses of tufa and stalactites (Plate 4, fig. 1). Beyond, a return to joint-controlled rifts leads to an even larger daylight chamber: some 50 m in diameter and 30 m high, again with enormous stalactites all round, and boulder piles on the floor covered with tufa stalagmite domes 5-10 m wide and high. In the roof there is a circular hole some 5 m in diameter, which admits enough daylight to make lamps unnecessary. The rest of the system is a similar network of phreatic rifts and daylight chambers.

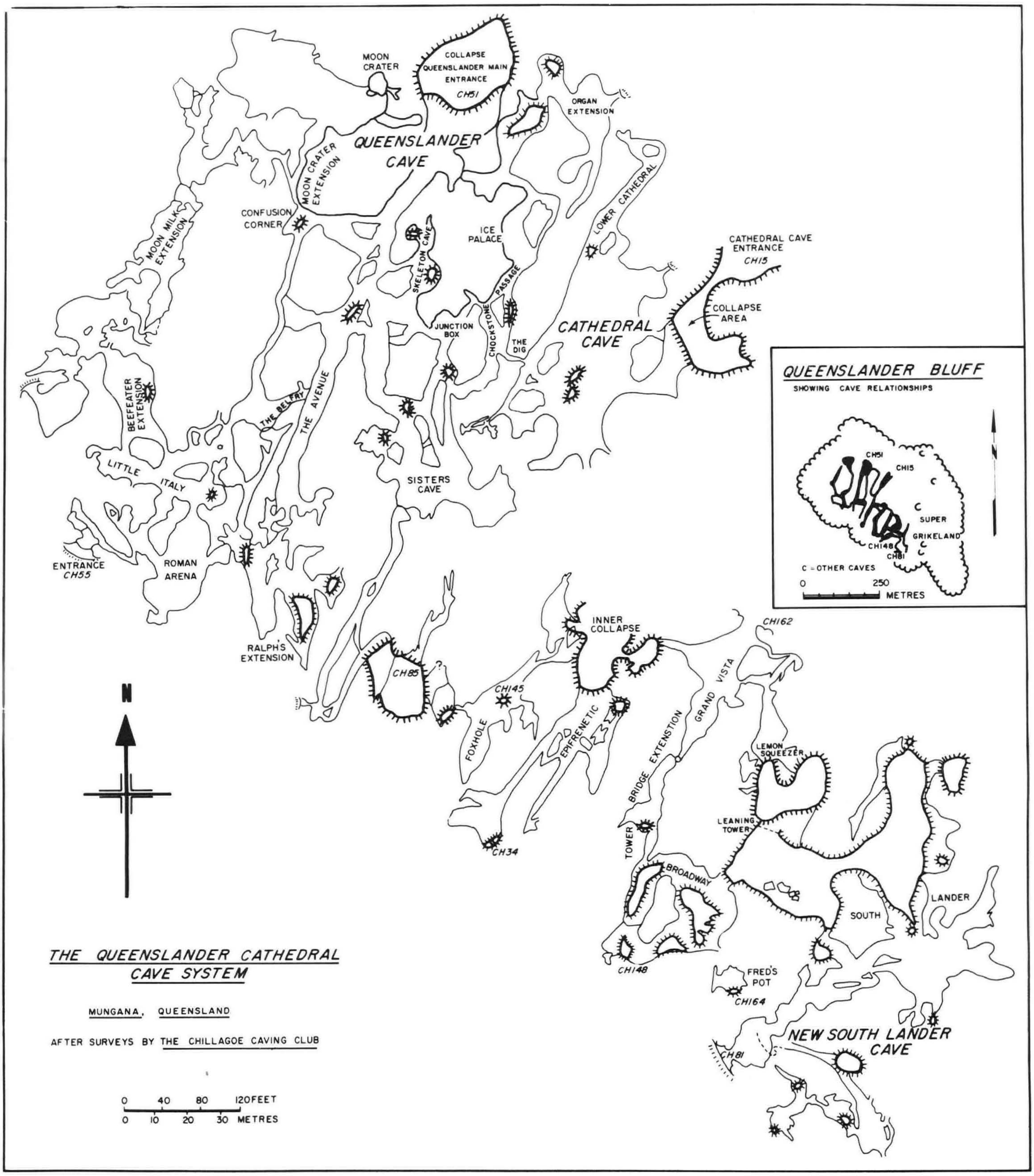

THE QUEENSLANDER CATHEDRAL CAVE SYSTEM
MUNGANA, QUEENSLAND
AFTER SURVEYS BY THE CHILLAGOE CAVING CLUB
0 40 80 120 FEET
0 10 20 30 METRES
N
MOON CRATER
COLLAPSE QUEENSLANDER MAIN ENTRANCE CH51
ORGAN EXTENSION
QUEENSLANDER CAVE
MOON CRATER EXTENSION
CONFUSION CORNER
MOON MILK EXTENSION
ICE PALACE
SKELETON CAVE
LOWER CATHEDRAL
CATHEDRAL CAVE ENTRANCE CH15
COLLAPSE AREA
CATHEDRAL CAVE
JUNCTION BOX
CHOCKSTONE PASSAGE
THE DIG
BEEFEATER EXTENSION
THE BELFRY
THE AVENUE
LITTLE ITALY
SISTERS CAVE
ENTRANCE CH55
ROMAN ARENA
RALPH'S EXTENSION
INNER COLLAPSE
CH162
CH85
CH145
FOXHOLE
EPIFRENETIC
GRAND VISTA
BRIDGE EXTENSION
TOWER
CH34
LEMON SQUEEZER
LEANING TOWER
BROADWAY
LANDER
SOUTH
CH148
FRED'S POT
CH164
NEW SOUTH LANDER CAVE
CH81
QUEENSLANDER BLUFF
SHOWING CAVE RELATIONSHIPS
CH51
CH15
SUPER GRIKELAND
CH148
CH81
C = OTHER CAVES
0 250 METRES

Fig. 4.

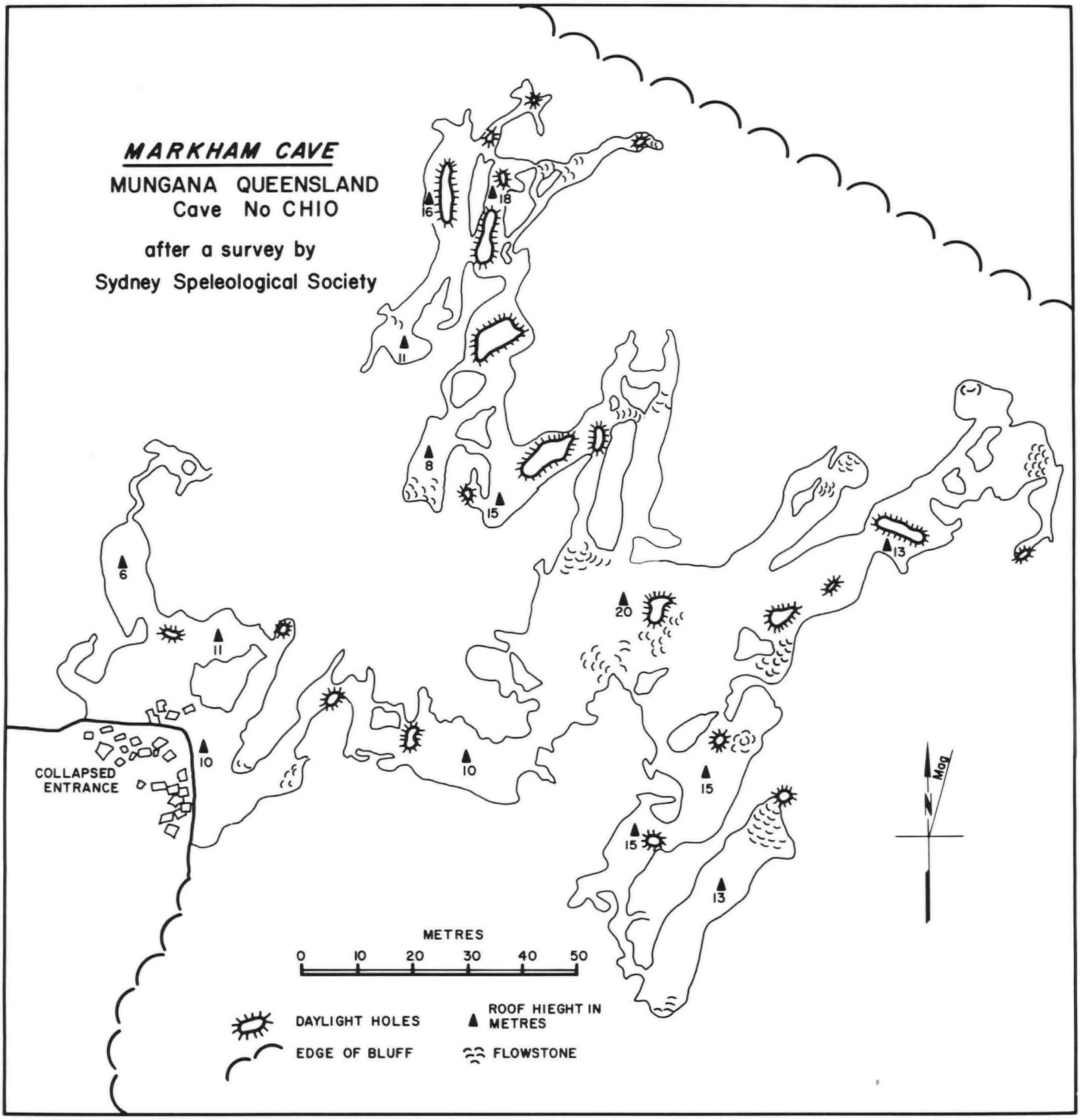

MARKHAM CAVE
MUNGANA QUEENSLAND
Cave No CHIO
after a survey by
Sydney Speleological Society
COLLAPSED ENTRANCE
METRES
0 10 20 30 40 50
DAYLIGHT HOLES
EDGE OF BLUFF
ROOF HIEGHT IN METRES
FLOWSTONE
Mag

Fig. 5.

Royal Arch Cave has been developed for tourists; more than one kilometre of trail has been laid out through the larger chambers of this 3 km long complex of joint-controlled caverns with massive speleothems (Fig. 6 and Plate 3, fig. 2). Several of the 21 caverns are daylight holes with collapses having stoped their way up to daylight. Particularly notable are the fig trees which have rooted in the chambers with trunks growing up and out into daylight. On one occasion at least the fig tree trunk provided a means of escape for a lost group of explorers. The adjacent Disney Cave was probably part of the same system once (Plate 3, fig. 4).

Donna Cave has been developed for tourists although it is formed mostly in two main joints at right angles (Plate 1, fig. 4). Electric lighting has been installed along 600 m of trail which doubles back and forth at different levels (Fig. 7) as there is sufficient stalactite fill to have formed partial false floors and sediments washed in from outside have piled up on these giving the impression of separate chambers stacked one above the other. Bridges and ladderways have allowed a route to be developed on four levels, so that one has a complete loss of sense of direction after doubling back and forth on different routes. Donna Cave is particularly liable to flooding in the wet season (Wilson, 1974) as its floor is below pediment level and a pile of breakdown obstructs the entrance. In early 1974 exceptional floods caused water to rise 5 m above the pathway (more than 9 m above the lowest point in the cave).

Adjacent to Donna Cave, in the same bluff, is *Pompey Cave*, a single large chamber illuminated by a daylight hole in the roof. Some 30 m wide it has a large collapsed block pile in the centre while the walls are thickly decorated with tufa stalactites.

Ryan Imperial Cave at Mungana has also been developed for tourists though it is little more than a single large joint chamber. It is of interest in that its entrance is at pediment level and descends steeply below this. A tight passage links it with the nearby *Keefs Cavern*, a joint complex which gives a combined length approaching a kilometre.

Royal Archways (or simply "Archways", not be be confused with Royal Arch Cave) is close to Markham Bluff north of Mungana. It is mainly a series of deep clefts going back into the almost vertical wall of the bluff for some 50 metres (Plate 1, fig. 3). The clefts are linked by low phreatic passages, and there is some tufa. Daylight holes at the back of one cleft and dense overhanging fig tree foliage make this an attractive though short cave system. A spur from the bluff has an isolated chamber with three entrances and several windows to daylight high up.

Sycamore's Cave, northwest of Mungana, is a single large chamber with a talus slope extending down to a cracked mud sump well below pediment level. Phreatic solution pockets in the walls suggest that solution is still active during the flood season.

Among the other caves visited by the writer was an un-named one south of the Blackwood road where a small tower was completely hollow, with a chamber some 8 by 5 m having four entrances from the four sides. Other caves had all the promise of complex systems riddling a bluff but were blocked by breakdown or fill after a short distance.

The *Aboriginal Painted Cave* at the west end of Markham Bluff is a shallow undercut cliff-foot cave, apparently like those described in Malaya by Jennings (1976). The smooth solutional contours attracted the aboriginals who have decorated the walls with serpents, anthropomorphic figures and miscellaneous dots and lines of ochre and lime. According to Jennings these cliff-foot caves are developed by solution beneath a soil cover but little evidence of this could be seen, and no other examples at Chillagoe provided any clear evidence.

The generalizations which may be deduced from the caves seen are:

1. No sign was found of vadose modification by running streams, apart from runnels extending down through joints from the karren on the tower tops which indicated periodic inflow. Royal Arch Cave has a roof which leaks like a sieve in storms (Wilson, 1974) and presumably so do other daylight chamber complexes. Water sometimes flows into entrances from pediments during the wet season.

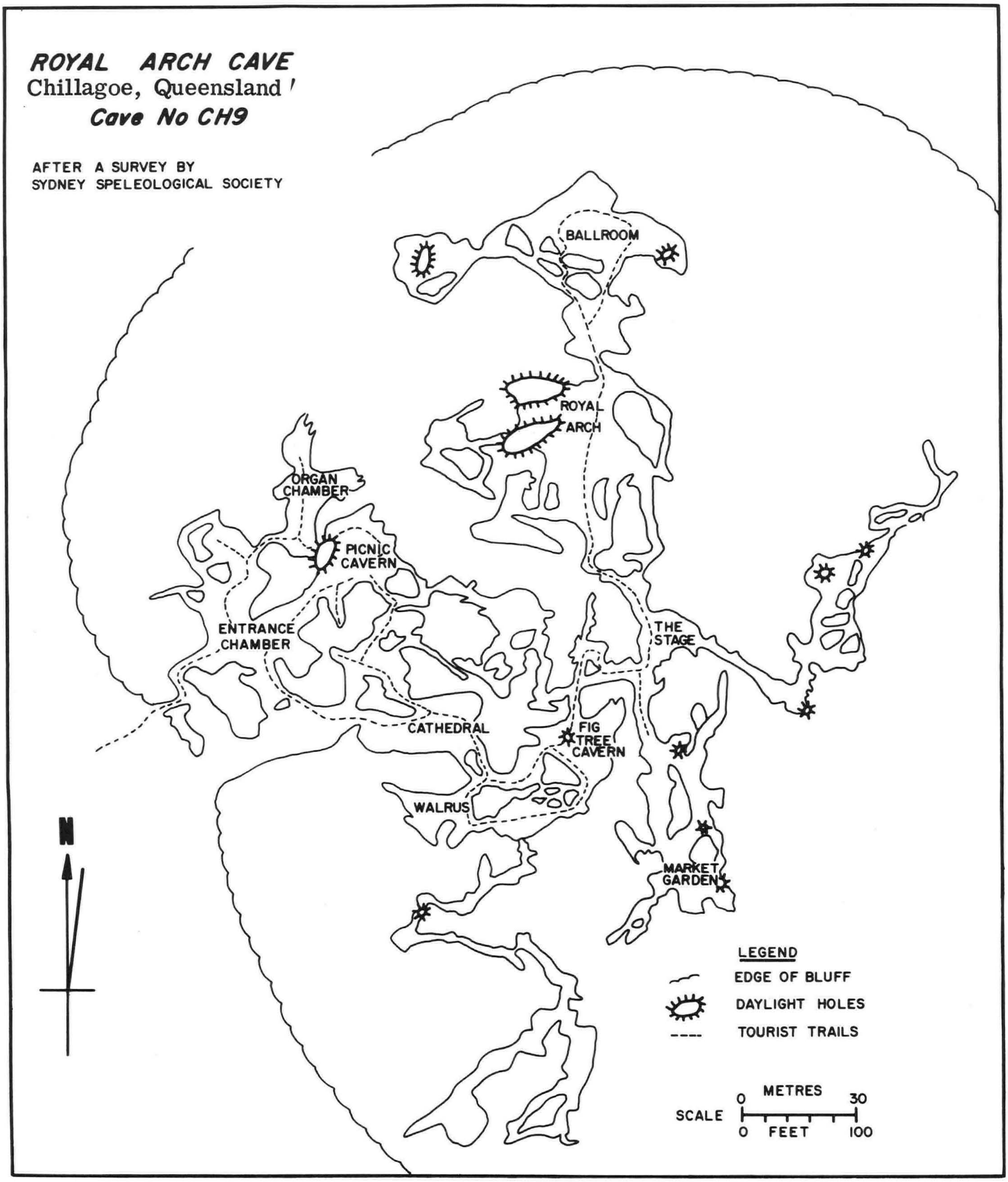

ROYAL ARCH CAVE
Chillagoe, Queensland
Cave No CH9
AFTER A SURVEY BY
SYDNEY SPELEOLOGICAL SOCIETY
BALLROOM
ROYAL
ARCH
ORGAN
CHAMBER
PICNIC
CAVERN
ENTRANCE
CHAMBER
THE
STAGE
CATHEDRAL
FIG
TREE
CAVERN
WALRUS
MARKET
GARDEN
N
LEGEND
EDGE OF BLUFF
DAYLIGHT HOLES
TOURIST TRAILS
SCALE
METRES
0
30
0
FEET
100

Fig. 6.

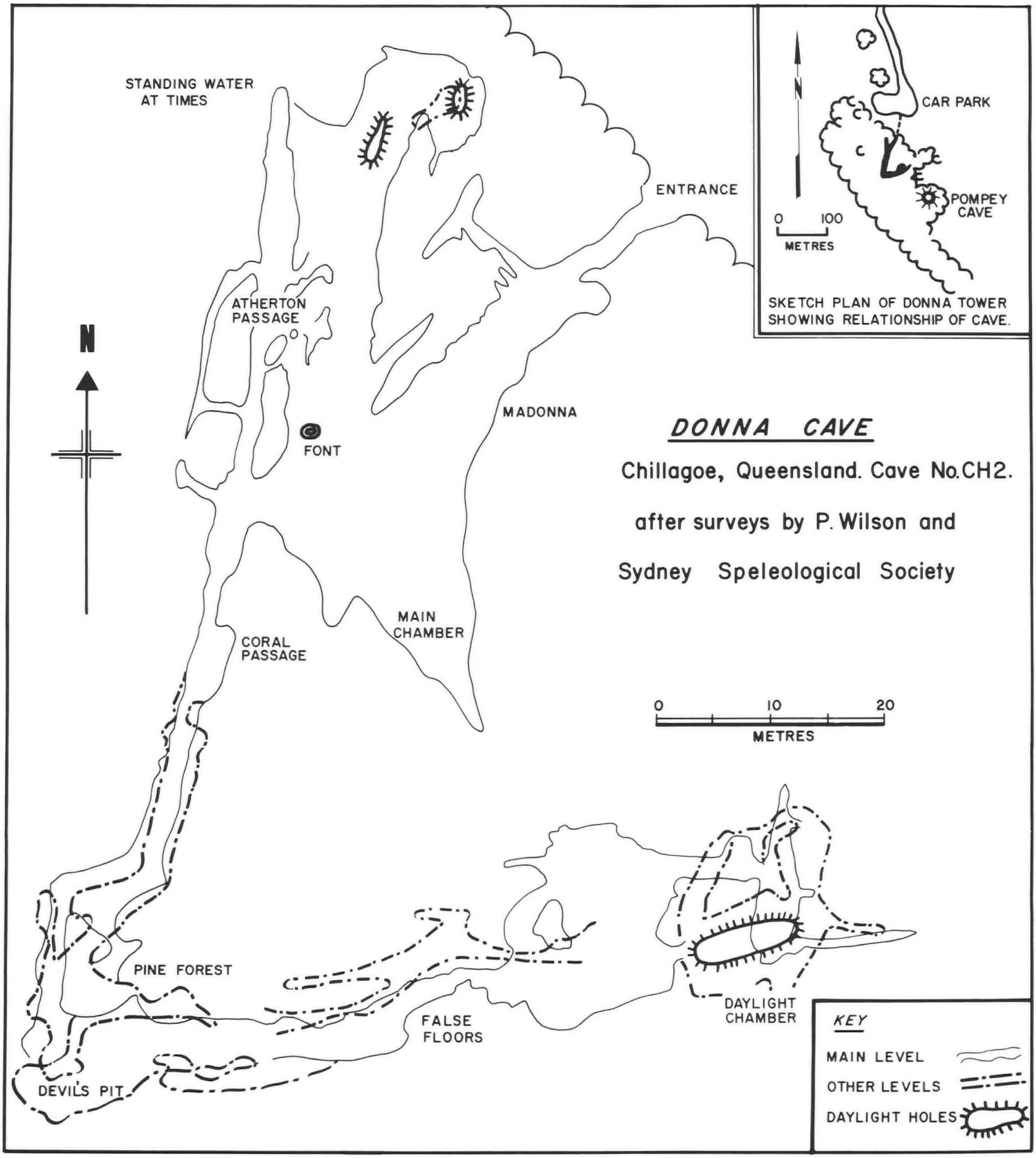
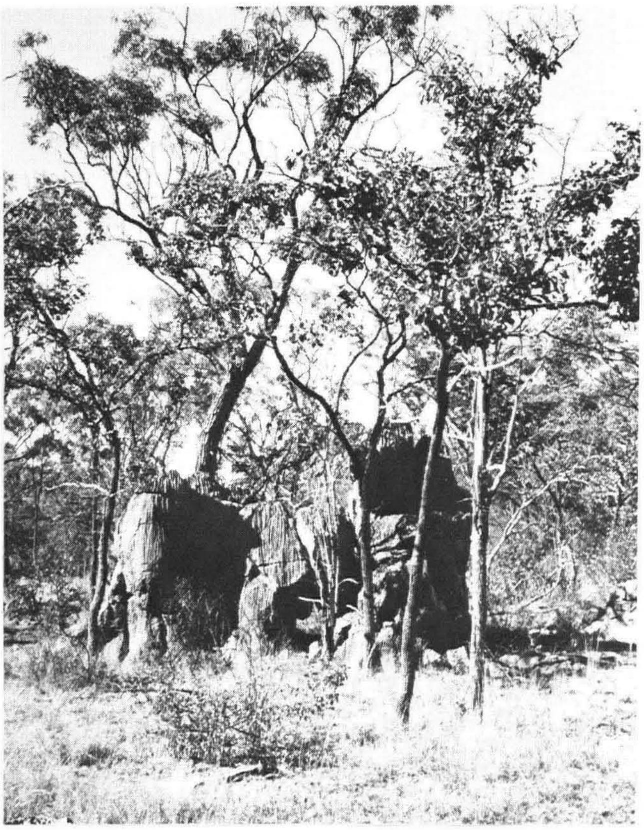

STANDING WATER AT TIMES
ENTRANCE
ATHERTON PASSAGE
N
FONT
MADONNA
DONNA CAVE
Chillagoe, Queensland. Cave No.CH2.
after surveys by P. Wilson and
Sydney Speleological Society
MAIN CHAMBER
CORAL PASSAGE
0 10 20
METRES
PINE FOREST
FALSE FLOORS
DAYLIGHT CHAMBER
DEVILS PIT
N
0 100
METRES
CAR PARK
POMPEY CAVE
SKETCH PLAN OF DONNA TOWER SHOWING RELATIONSHIP OF CAVE.
KEY
MAIN LEVEL
OTHER LEVELS
DAYLIGHT HOLES

Fig. 7.

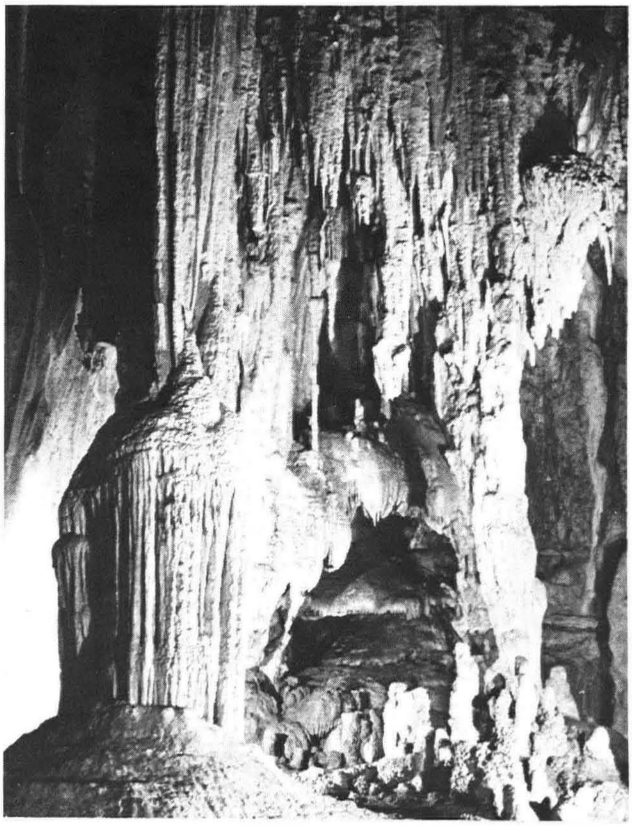
2. The plan of the cave systems was clearly that of solutional development along joints (and bedding planes).
3. Intersections of joints were marked by large chambers or irregular shape, often daylight holes in the roof: such chambers usually had massive breakdown block piles, though typical roof pendants and spongework could be seen in alcoves and the more remote parts of large chambers
4. The walls in the joint passages were usually smooth and without facets, indicating little directional movement of water. Calcite-cemented breccia in a few places such as the Corridor in Ryan Imperial Cave suggested the presence of faults.
5. Some of the larger chambers showed evidence of solutional features on the lowest 2 or 3 metres of the walls which appeared to be fairly fresh, though some may have been due to speleothems falling off. However, some are probably still being developed by the wet season rise in the water table. The temporary pools so formed may explain the undercutting seen in some chambers, which can lead to further collapse.
6. Most of the caves were decorated with large stalactitic masses of tufa (Plate 3, figs. 2 & 4) with relatively few crystalline stalactites. Donna Cave was well decorated and Disney Cave had numerous straws, some helictites, and many cave pearls. Tufa stalactites often had a core of a tree root, sometimes as much as 10 m long. "Cave coral" marked a temporary pool in Ryan Imperial Cave.
7. There was a considerable amount of inwashed sediment, like that of the pediments in some caves, with chert gravels although there was little or no chert in the limestone walls of the cave. Some of the sediment fills were well above the level of the pediment outside. Calcite-cemented fills occasionally showed later corrosion features. In a few cases channels had been cut into the sediment by local inflows, though the sediment was then redeposited lower in the same cave.
8. Most of the caves had floors at the general pediment level, often with entrances slightly higher owing to fallen debris; a few caves not only extended as much as 20 m below pediment level, but also occasionally extended out beneath the pediment.
9. The caves were almost all bone-dry though a few showed evidence of intermittent standing water at the bottom, with cracked mud surfaces and dirty "tide" marks. The solution features noted in 5 above indicate that the standing water is sometimes aggressive. In the wet season the water-table rises by as much as 10 m and, after lingering for some weeks, the excess water gradually drains away into the phreatic zone or seeps out through the block piles at entrances. Conditions at such times may be described as epi-phreatic. Ti-Tree and Narahdran Caves have perennial water in pools at the bottom. Flood marks were present in some caves, e.g. Simpson Pot (Plate 4, fig. 2).
10. Bone deposits in caves are little known. An occasional rock wallaby skeleton is found where is has dropped in through a daylight hole. Jensen (1909) noted a bone deposit several feet thick in an unspecified cave near Chillagoe. It is not known whether this is the same deposit as the bone-breccia seen by Robinson (1975) in Ti-Tree Cave which yielded the extinct *Diprotodon*.

From these observations a sequence of speleogenetic events can be deduced:

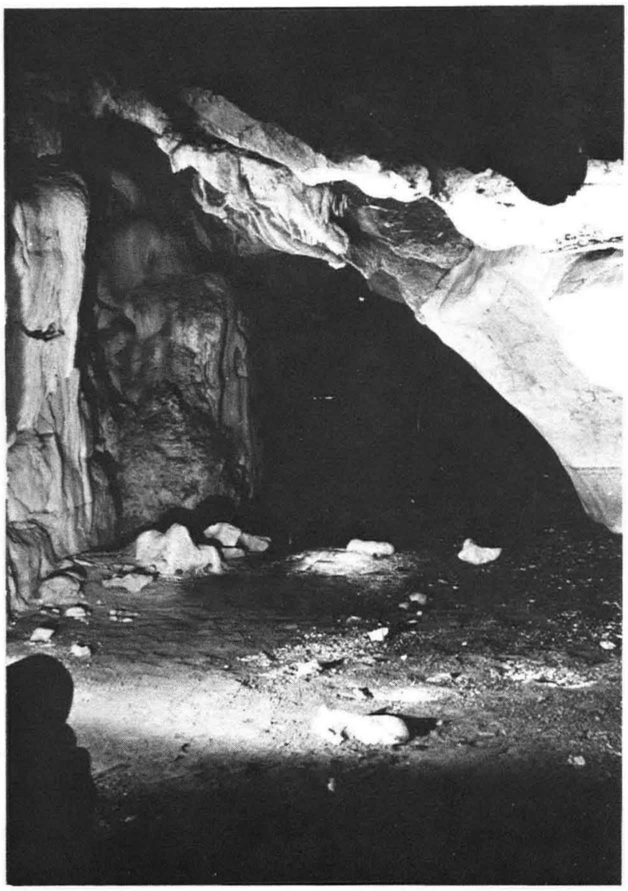
a) Phreatic solution when the water-table was as high as the highest parts of the present cave systems, i.e. as high as the top of the present towers, or even higher. The corollary of this observation is that some parts of the caves are probably older than the enclosing towers which have been trimmed by pedimentation to their present form.
b) Falling water-tables consonant with falling base level and of pediment level outside allowed progressive drying out of the caves at the same time as tower development and modification. Both the falling pediment levels and the drying out of the caves was probably an intermittent process but the only evidence seen was in the steps on the flanks of some towers. Uniform cave levels from tower to tower have not been recognized and do not show up on the surveys. However, the sediment fills now seen as false floors must at least in some cases



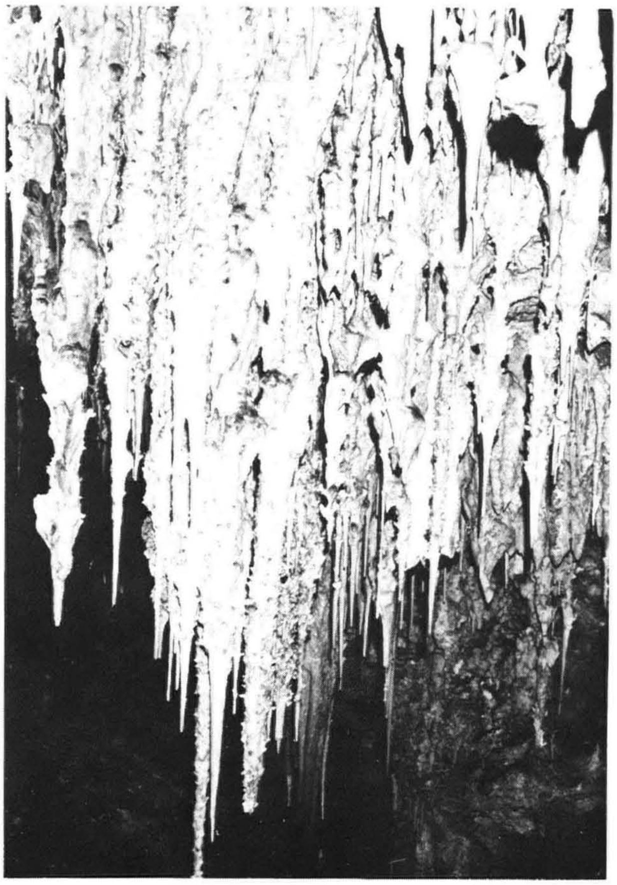
1. A small bluff "Elephant Rock" near Royal Archways.



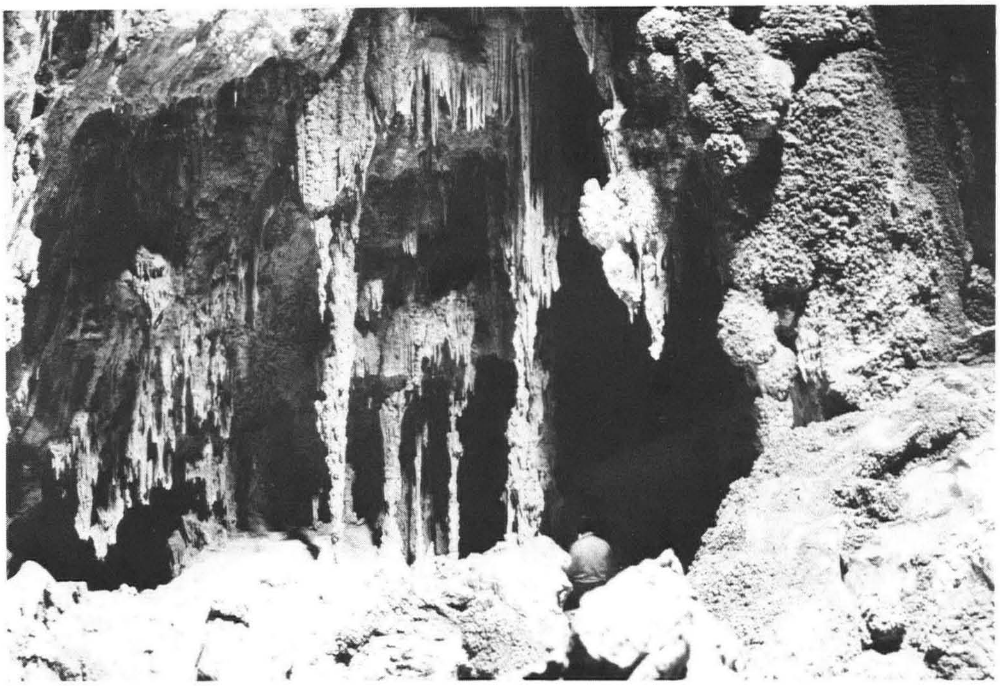
2. Massive speleothems in Royal Arch Cave.



3. Angled Chamber in Ti-Tree Cave (photo Joyce Lundberg).

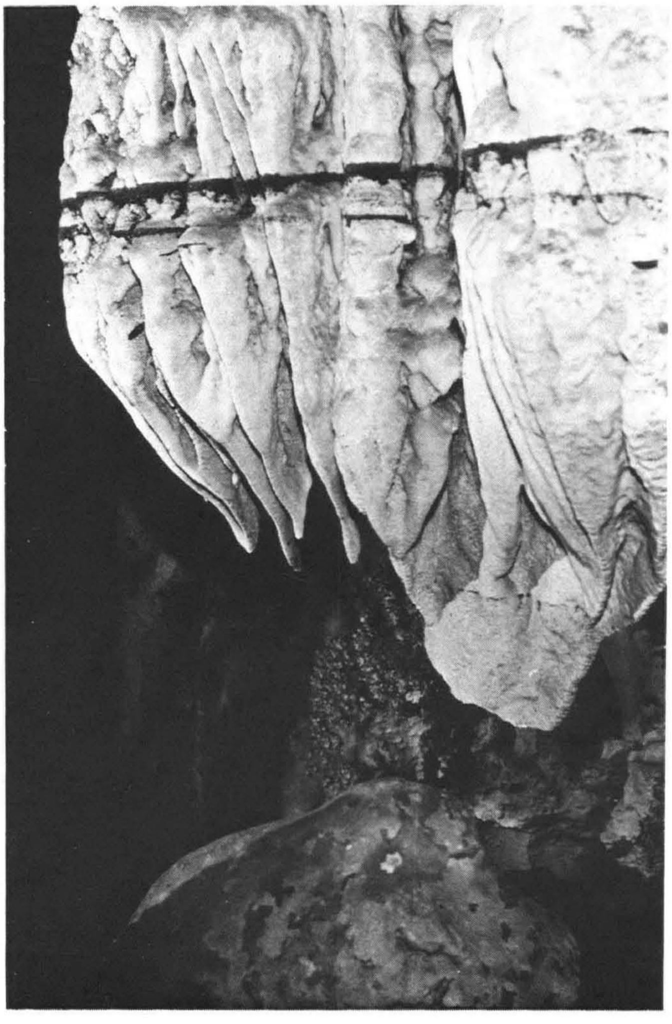


4. Stalactites with secondary overgrowths in Disney Cave (photo Joyce Lundberg).



1. Massive speleothems with tufa encrustations in daylight hole Main Chamber, Markham Cave.

2. Stalactite showing evidence of re-solution in Royal Arch Cave (photo Joyce Lundberg).



3. Stalactites in Simpson Pot showing flood levels (photo Joyce Lundberg).

represent old pediment surfaces, from which the occasional storms washed sediment into the caves, perhaps within a few hours.

c) Breakdown of caves' roofs appears to be largely the result of progressively increasing instability due to solution by rapidly percolating rainwater, though another factor may have been the removal of hydraulic support as the water-table fell.

d) Speleothem deposition started as soon as the water-table fell and resulted in massive tufa-like deposits in the large chambers, particularly those with daylight holes wherein evaporation was high. True stalactites grew in some caves, generally those at least partly sealed from external temperatures. As most speleothems today are dead, and even occasionally subject to re-solution during floods (Plate 4, fig. 2) the former presence of a wetter climate is implied, perhaps indeed an oscillation of wet and dry climates during the Pleistocene.

HYDROLOGY AND WATER-TABLE

Few of the caves normally have standing water, except in the wet season when, as noted by Wilson (1974), water-levels may rise by as much as 10 m. Only three caves seem to have perennial standing water (Wilson, 1975) and in one of these, Narahdran Cave, diving to 15 m depth failed to reach the bottom. The flood water-level usually drops within a few weeks though it may not drain away entirely for three months in some years. Outside, the pediment is devoid of water but shallow stream gullies head on the margins of the pediments and springs discharge water through the wet season. Further away where pediment has given way to alluvial fans, springs discharge small streams through much of the year. The springs sometimes can be seen to rise from limestone hidden beneath the alluvial fan sediments. The perennial creeks, such as Chillagoe Creek, contain tufa dams suggesting that the water is saturated with $CaCO_3$, but precipitation may be partly an effect of high evaporation after resurgence.

It seems that a rise in water-levels is rapid after storm rains, but slow to return to normal. The whole area seems to respond at the same time and no distinct cave-to-resurgence systems have been detected. Further evidence of this general water-level is that mining trial sites in both pediment and alluvium often reached static water a few metres down, and levels in such holes reacted according to rapid storm percolation and slow drain-away processes. In extreme floods the whole pediment may be awash and water sometimes drains into cave mouths. Some writers have argued that this is the cause of flood water standing at a high level for weeks or months after flooding; standing levels are, however, generally well below the pediments.

The mining evidence (Broadhurst and Edwards, 1953) demonstrates that there is deep if slow circulation of groundwater capable of oxidising sulphides to depths of over 150 m. Bore holes drilled by mineral exploration crews have not infrequently penetrated open cavities, wherein the drilling fluid has been lost to the groundwater.

The evidence suggests that there is a widespread and relatively flat water-table under much of the Chillagoe area (from which water-supplies are pumped); presumably solution is still taking place in the phreatic zone beneath this though few analyses have been done to determine the $CaCO_3$ content. Lundberg (1977a) listed a few analyses which showed that though the $CaCO_3$ content was variable, the waters were nearly all saturated. As a corollary it can be argued that there must have been widespread and uniform water-tables in the past, when both caves and towers were evolving. Solution is presumably still taking place at depth and intermittent solution of epi-phreatic type may occur in some caves at times of high water level, though lack of notches at flood water levels suggested a lack of aggressivity, and Lundberg (1977a) noted a film of crystals on the sump in Ti-Tree Cave in the dry season.

There are apparent anomalies in that there is evidence for solution in some caves during the flood season, but a lack of it in others; flood waters do not appear to deposit tufa in the lower parts of caves, yet the emergent streams outside are saturated and deposit tufa.

Solution is occurring at depth in mineralized areas but the saturated nature of overspill from the water-table suggests that it should not occur. These anomalies are probably best explained as local variations in aggressivity, perhaps due to oxidation of sulphides providing acids, in the mineralized areas, or to different residence times in the non-mineralized areas. The water-table throughout the tower area is basically controlled by the level of springs at the outer margins of the pediments.

SPELEOTHEMS

As already noted above, stalactites or impressive proportions and many hues decorate many caves. Those in entrances or in daylight chambers are of a porous tufa-like composition while those in fully underground passages are more solid and crystalline. Broken tufa in daylight chambers sometimes shows a core of old crystalline calcite, but commonly there was a core of tree root instead. Indeed masses some 10 m in length showed roots if their tips were broken off. While no detailed chemistry has been done, it can be suggested that the metabolic removal of CO_2 from percolating water running down the roots had caused the precipitation of $CaCO_3$ as a coating thereon. Masses of tufa stalagmites cover the floors and fallen block piles in many daylight chambers. Some of the speleothems in the lower parts of chambers show evidence of corrosion, suggesting a local temporary change in regime from deposition to solution. This could have been caused by local damming by collapse so that flood-waters stood long enough to cause solution or it could indicate a climatic change. Only studies of the water chemistry during flood periods can solve this problem.

In the daylight chambers much of the tufa has a growth of moss or algae and earlier growths have resulted in sporadic development of cave "popcorn".

Gypsum anthodites are occasionally present, indicating the availability of sulphur from oxidizing minerals or from pyrite in shales.

GEOMORPHOLOGICAL EVOLUTION

Relatively little is known of the detailed erosional history of Tertiary and Pleistocene times. De Keyser et al. (1964, 1968) have outlined a succession of erosion surfaces for the North Queensland region but have discussed relatively little of the detailed story. They argued that the form of the peneplains suggested that upwarping and faulting continued through part of the Tertiary era possibly into the Pleistocene with consequent rejuvenation of the river systems. To what extent the upwarping and faulting affected the Chillagoe area is not known, but intermittent downcutting and pedimentation can be inferred to have occurred in late Tertiary and Pleistocene times, as diagrammatically shown in Fig. 3.

Apart from the immediate processes of tower formation, the chief process in the Tertiary and still operating today is of sheet wash during torrential downpours of summer rain. These have resulted in an alluvial sheet of gravels and sands merging with the pediment around the hills of igneous and crystalline rocks. Soil profiles have developed at intervals (probably under more consistently wet conditions) but under the intense seasonal regimes sheetwash and gullying have gradually lowered the alluvial sheet and pediment. An alternation of wetter (and cooler?) and drier climates during the Pleistocene may well have been responsible for the lowering of the topographic surface head in or adjacent to the limestone towers, so that the deduction may be made that they were relatively resistent to erosion.

As noted by Marker (1977) it is evident that both towers and caves have to some extent evolved synchronously, during lowering of the pediment surface. At the start of the present cycle (possibly mid-Tertiary according to De Keyser and Wolff, 1964) the topographical surface was at or above the tops of the present towers. There may well have been an earlier generation of towers, but what is more significant is that there must then have been a limestone pediment cut across more or less vertical beds, in a series of fault-blocks associated with the Palmerville Fault. As the Walsh River and other main drainage systems cut down so the base level was lowered and pediments were cut back into the emergent towers. Meanwhile solution had been progressing underground opening up the phreatic systems. Doubtless this general process went on throughout the Pleistocene with climatic oscillations between perenially wet and warm on the one hand, and the much more arid seasonal hot climate of today. However, as Jennings and Sweeting pointed out (1963) there is a problem of deciding the extent to which Pleistocene climatic changes have controlled the morphological evolution in contrast to the effects of the present seasonal regime. No unequivocal evidence for past wet climates can yet be demonstrated (Marker, 1977), but the usual occurrence of tower karst in the humid tropics makes it difficult to conclude other than that the climate was once much wetter than at present.

Indeed, it may be that the geological structure of vertically oriented fault blocks will offer little constraint to the downward movement of water, and is conducive to tower formation regardless of climatic effects.

As the pediments were cut back, the erosional residuals took on a tower form rather than cone karst owing to the undercutting by pediment wash. The deep karren development led to rapid run-off with consequent trimming of the tower bases at the inner margins of the pediments. But at the same time the phreatic caves became subject to removal of hydraulic support, and to brief but rapid inflow of rainwater from the karren. The latter was probably not very aggressive owing to the lack of a soil cover, and it is the periodic fluctuations in the water-table which accomplished renewed solution at greater depths. Intermittent breaching of cave roofs allowed the washing in of sediments from the pediment area, indicating that at the time of inwash at least part of the cave system and the associated water-table were below pediment level.

Separation of the towers into the existing bluffs was controlled by two factors: the discontinuous nature of the limestone outcrop which is a series of fault slices with shales, etc. between them; and the rate of pedimental trimming. Some of the towers may be inherited from earlier cycles.

Progressive solution in the upper parts of towers, above cave roofs, is at present accomplished by run-off from karren entering the joint system with at least mild aggressiveness (Lundberg, 1977a); the fluctuating water-table means that some solution is probably still being accomplished by impounded flood waters, particularly at the bottoms of accessible caves where undermining of the walls decreases stability. The presence of tufa in the outflowing stream gullies suggests that solution today may not be as effective as in past wetter climatic phases. Wholesale collapse of cave-riddled towers is the ultimate stage, and evidence of this in the past is seen in the form of jumbled masses of collapsed blocks occupying the central regions of some towers.

With its array of towers riddled with caves, some partly collapsed and others showing instability, the Chillagoe karst can truly be summarized as a karst in decay! Indeed Jennings (1969) suggested that the Chillagoe karst presents a more advanced stage of erosion than the Limestone Ranges of N.W. Australia.

ACKNOWLEDGEMENTS

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T.D. Ford,
Geology Dept.,
University of Leicester,
Leicester. LE1 7RH

CALIBRATION OF CAVE SURVEY INSTRUMENTS

by P.R. Cousins

Summary

For accuracy of calibration for a B.C.R.A. Grade 5 survey it is necessary to provide at least six bearings between surface features over 1½ kilometres apart on every survey trip. The use of reference bearings within the cave is recommended as an alternative for long survey projects.

The limiting accuracy of current cave survey techniques is discussed, and found to be dependant on the Diurnal Variation of the magnetic field.

"If a measurement is duplicated, and the two results do not agree, either result may be correct, but their mean is likely to be incorrect".

Dennis Warburton, circa 1966

One of the requirements of a B.C.R.A. Grade 5 or Grade 6 survey is that the instruments used shall be 'properly' calibrated. This was also a requirement of many previous survey grading schemes. Whilst several authors have stressed the need for calibration, few have given details of the techniques that should be used. A summary was given in *Surveying Caves* (Ellis, 1976). Two further aspects will be covered here: how accurately need the compass be calibrated, and how is this to be achieved?

Regardless of the intended grade of survey the essential fact to remember in all angular measurements is that the ultimate errors are proportional to distance. Just as long survey legs potentially introduce large errors, so large surveys (i.e. large cave systems) can have large errors in plan due to inadequate calibration.

An error of 1 degree in calibration appears on the finished survey as an error of 17.5 metres per kilometre of cave.

Put into perspective this is similar to the random error inherent in a Grade 5 survey. Thus we may conclude that, in all but the smallest surveys, the calibration should be more accurate than the general survey measurements if the resulting error is not unduly to affect the accuracy of the finished survey.

CALIBRATING A MAGNETIC COMPASS

The calibration of a compass for cave surveying consists of two distinct stages:

a) Setting up reference bearings of suitable accuracy.

b) Comparing compass readings to reference bearings with suitable precision.

In the United Kingdom every part of the country has been mapped to at least 1:10,000 scale (formerly 6 inches to the mile). Any identifiable feature can be given, with care, an eight figure Grid Reference from these maps, and this will define its location to the nearest 10 metres (strictly: -½m, +9½m). The Ordnance Survey intend that the 1:10,000 maps will have an error for features of at most 3 metres R.M.S. (root mean square), sic. (Harley, 1975). This can be equated to a standard deviation (s.d*) of 3 metres for the purpose of this paper. We can

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* Note on statistics: throughout this paper a confidence limit of ± 2½ standard deviations will be used. The probability of an error falling into this range is 0.99 (or 99%) for a Mean derived from over 100 readings. However, where only a small number of readings are used the probability of an error falling within these limits is reduced, being 0.95 (95%) if only 5 readings are used to derive the mean. Intermediate values can be obtained from tables of 'Students t' but their use would not significantly alter the conclusions of this paper.

therefore be 95% confident that the features will lie within a circle of radius 6 metres (2 x s.d.) centred on their mapped locations and relative to other features.

Consider the calculation of a bearing between two features such as those described above, using eight figure grid references for both. The error will be 12 metres ($\pm$ 6m) at most. But it is equally likely that the error in mapping is along the line of our bearing, or at any angle between this and the worst case - perpendicular to the line of bearing. Thus the error due to feature mapping will lie between 0 and 12 metres, and it can be shown that the mean error is 7½ metres. Allowing for the precision of the grid references (10 metres) at both ends, we find that the total position error in a bearing between two mapped features is approximately 27.5 metres.

Only over a distance of 1500 metres will a bearing calculated between two such features be correct to the nearest degree.

Let us assume that we require the calibration to be twice as precise as the general survey readings; we obtain the following:

Survey - Grade 5, readings to $\pm$ ½ degree, calibration to nearest degree,
Minimum calibration distance - 1½ kilometres
Survey - Grade 6, readings to $\pm$ ½ degree, calibration to nearest ½ degree,
Minimum calibration distance - 3 kilometres

As an extension of the above it can be stated that features for which only a six figure grid reference (100 metre reference) is available, can only be used for calibration over distances of 15 kilometres.

It has been stated elsewhere (Ellis, 1976; Irwin and Stenner, 1975) that, for calibration, compass bearings must be taken from more than one point to avoid gross local anomalies. Generally it is good practice to take more than one bearing from each location, and it is essential to take some bearings before and after the survey trip to confirm that no damage to the instruments has occurred - this is particularly necessary with a survey unit.

However, if all the bearings give essentially similar calibration corrections the results can of course be averaged; and such an average is potentially more accurate than any individual bearing. In general if a mean calibration correction is derived by averaging 'n' separate readings, an estimate of its precision is given by:

Standard Error of Mean = $s/\sqrt{n}$, where s is the standard deviation of the readings.

If the standard error of such a mean is 0.2 degrees (or less) we can be 99% confident that the mean will lie in the range $\pm$ 2½ x 0.2; i.e. that the mean is correct to the nearest degree, which is the requirement for a Grade 5 survey suggested above. Writing these figures as an equation, we can say that for a grade 5 survey we need sufficient calibration readings for: $5 \times S/\sqrt{n} < 1$, where s is the standard deviation of these n readings. In practice this requirement will usually be achieved with 6 - 8 reasonably close bearing corrections. To achieve the accuracy required of calibration for a Grade 6 survey, 12 - 16 readings will need to be averaged, and whilst these can include duplicates, the use of bearings at more than two locations may be desirable. It should be noted that the mean of a number of results can be more accurate than the measurements themselves - achieving this is part of the surveyor's art.

Finally, if a large cave system is being surveyed, calibration data for the same instruments, taken several months apart, can be aggregated. The annual drift of the magnetic meridian is approximately 0.1 degree within the U.K. and can be ignored over a period of six months or more. Where bad weather, or perhaps darkness, has limited calibration readings on a particular trip this action can be used to salvage the situation. A better procedure is outlined in the next section.

It should be stressed that throughout this section the discussion has been limited to surveying in the U.K.. Not only will the standards and precision of mapping vary overseas, but the annual drift and diurnal variation of the magnetic meridian may be greater.

CALIBRATION UNDERGROUND

In contrast to the restrictions on location of calibration sights on the surface, calibration underground is surprisingly easy. A set of permanent marks or features, suitably chosen in a dry part of the cave, can be used as a local reference frame to calibrate the compass on every survey trip - regardless of weather conditions outside. To relate these underground calibrations to the surface geography, one special trip must be made to take multiple calibration readings at both surface and underground sites.

As before, we require bearings for calibration correct to 1 degree (Grade 5) or correct to ½ degree (Grade 6) - that is twice as precise as the survey readings. But now our stations are not extracted from surface maps, but are point locations within the cave, perhaps averaging 10 metres from our instruments. For such a bearing the station position error is at most ± 1 cm at the target, and perhaps ± 4 cm at the instruments. This gives a total position error of 10 cm, and bearings correct to ½ degree at a distance of 11 metres or over. Thus a set of underground calibration sights provide a potentially very precise means of calibrating the compass on every survey trip, regardless of the time of day, or weather outside.

The common practice of using field junctions on the surface for calibration can also conveniently be examined here. In terms of length of sight lines, and positional accuracy these will provide a set of reference bearings similar to the underground calibration set discussed above. The common pitfall of buried steelwork (see Irwin & Stenner, 1975), or pipes must of course be guarded against. However, a set of field junction bearings will not provide accurate orientation of the finished survey relative to surface map data because, as discussed above (see Calibrating a Magnetic Compass), the bearings are too short. It will thus be necessary at some stage to relate the local reference set of field junctions etc. to proper long distance surface bearings, just as was necessary for the underground reference bearings. In the past this has frequently not been done, and the value of the survey to later workers, perhaps wishing to made additions, is much reduced.

THE LIMITS OF ACCURACY

A discussion of the limiting accuracy of conventional cave surveying is included here because of its dependance on magnetic calibration problems.

The apparent reading limits of the usual cave surveying instruments are probably as follows:

Tape:	Accurate to 10 mm	Clinometer:	Accurate to 0.2 deg.*
Compass:	Accurate to 0.5 deg.*	Station Position:	Accurate to 10 mm

* = with magnification

It is easy to show that on the average 10 metre survey leg the dominant error comes from the angular measurements, and it is doubtful if these can be improved: c.f. Sin 0.5 deg. = .0087, or 8.7 cm per 10 metres. If for instance the compass could be read to 0.2 deg. such readings would be of little value; firstly because readings on currently available instruments are not reproducible to better than 0.2 deg., if that, and secondly because the diurnal variation of the magnetic declination averages 8 min. or 0.15 deg. in the south of England (Leaton, Malin & Finch, 1962). The precise range varies seasonally, and will be greater in more northerly latitudes (fig. 1).

Whilst careful attention to calibration might give a mean correction apparently accurate to 0.2 deg., this will be illusory since the underground survey is likely to have been made at a time of day when the general magnetic field was 0.1 deg. different from that at the time of calibration. Local magnetic anomalies within and around the cave will also be present, and cannot usually be allowed for: hopefully their cumulative effect will be small. Surveying techniques do exist

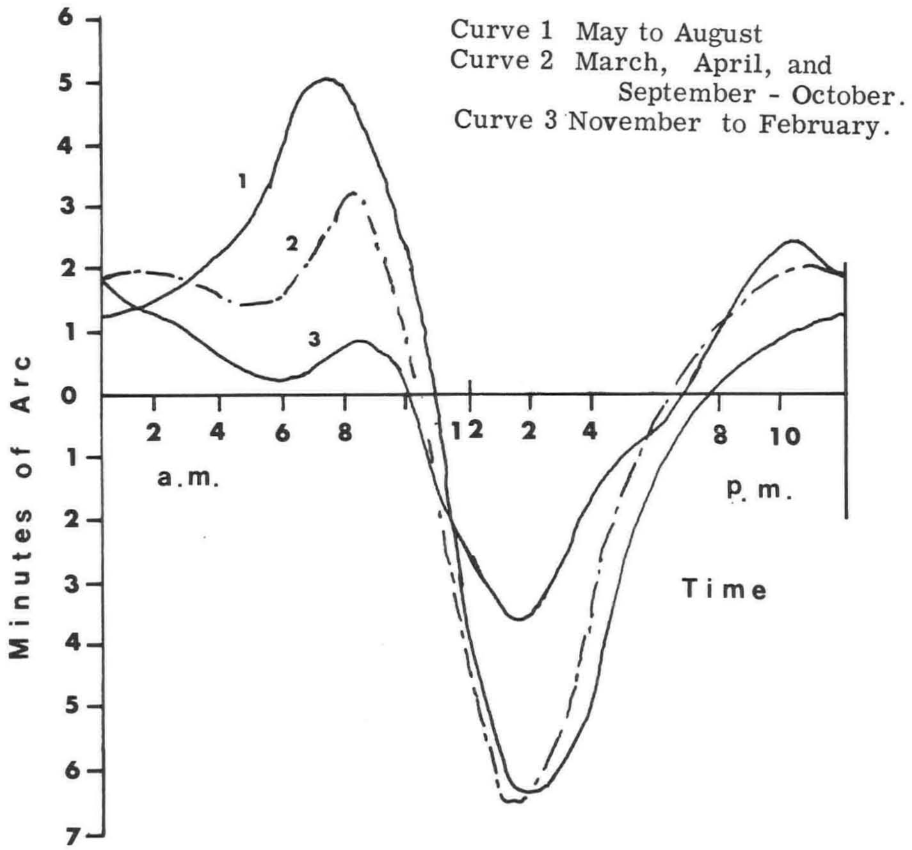

Fig. 1. Diurnal variation of magnetic declination - typical data for southern England (adapted from Leaton, Malin and Finch (1962) by courtesy of the Director, Royal Greenwich Observatory).

to cope with this difficulty, and have been practised by mining surveyors using the Dial (Norman Thomas, 1961).

In summary; any improvement in compass readings beyond ½ deg. is difficult, and beyond ¼ deg. is illusory. The limit set to cave survey accuracy by the Earth's magnetic field has already been reached by B.C.R.A. Grade 6, and no further improvement is likely to be practical in caves.

CONCLUSION

The discussion above has assumed a requirement for the compass to be calibrated correct to one degree for B.C.R.A. Grade 5, and correct to half-degree for B.C.R.A. Grade 6. No such requirements appear in the definitive B.C.R.A. grading scheme (Ellis, 1976), it being assumed that calibration bearings will be read with the same precision as the normal survey bearings. In the present author's opinion this is unfortunate as in all but the smallest cave systems the errors which may arise from inadequate calibration are significant, and, as outlined above, can readily be minimised.

To summarise, the optimum procedure for calibrating a magnetic compass for a B.C.R.A. Grade 5 survey appears to be:

a) Choose reference bearings whose location is known by an 8 figure grid reference, and which are at least 1½ kilometres apart.

b) When working in a large cave system, underground calibration is desirable since adequate surface calibration is dependant on fine weather and daylight.

c) For surface calibration, at least three bearings should be attempted from each of two locations before and after each survey trip.

d) The compass bearings are compared to the calculated Grid bearings, and a mean of results taken. Where no gross changes have occurred, data taken several months apart can be aggregated for a mean.

e) Where the terrain is not adequately mapped, easily identifiable permanent features may be used in a similar manner to derive a local frame of reference. Such features should be recorded to allow later workers to continue the survey.

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P.R. Cousins,
8 Giffords Croft,
Lichfield.

N O W   A V A I L A B L E

L I M E S T O N E S   A N D   C A V E S   O F   . . . . .

URANIUM SERIES DATING AND STABLE ISOTOPE STUDIES OF SPELEOTHEMS: PART I THEORY AND TECHNIQUES

by M. Gascoyne, H.P. Schwarcz and D.C. Ford

Summary

Uranium series dating of speleothems and the application of stable isotope (^{18}O and ^{13}C) fractionation in speleothem growth to paleotemperature measurement are described in detail in this paper. For precise, reproducible results, by the $^{230}Th/^{234}U$ method, only impervious speleothems free of detritus and containing >0.05 ppm uranium can be used. For uranium-rich samples $^{231}Pa/^{230}Th$ dating shows reasonable agreement with $^{230}Th/^{234}U$ ages, but the $^{234}U/^{238}U$ method is found to be unreliable due to the difficulty of estimating initial activity ratio. Speleothem ages are generally found to be clustered within certain periods which correlate to known warm events during the Late Pleistocene. Stable isotope analyses have shown the ^{18}O content of speleothems to increase during colder periods. Analyses of fluid inclusions and associated calcite has shown that temperatures in N. American caves during glacial times were up to 12°C less than at present. Variation in ^{13}C content of speleothems is suggested as an additional paleoclimatic indicator.

Since the discovery of radioactivity in 1896, a number of radioactive decay schemes (uranium - lead, rubidium - strontium, potassium - argon) have been developed for dating rocks. These were successfully applied to rocks and minerals for ages ranging from 10^6 to 10^9 years old. Shortly after the war, Libby (1965) observed the presence of ^{14}C in the environment and showed that many fossil, carbon-containing compounds could be dated providing that the ^{14}C content at the time of growth or deposition were known. Other short-period dating methods were soon to follow: tritium (^3H) in oceanographic and groundwater studies, ^{226}Ra in estuarine sediment studies, ^{32}Si and ^{210}Pb in dating polar ice, ^{234}U and ^{230}Th in carbonate dating, etc.

During the last twenty years much attention has been focussed on short-period dating techniques particularly in archeology, Quaternary geology and geomorphology. By dating ice cores, deep-sea carbonate cores, recent volcanic events and fossil organic remains, and combining these with paleoclimatic inferences, a detailed picture has been constructed of the timing and intensity of Late Pleistocene climatic events. By some quirk of nature it has been possible to date both old (>1 million years) and young (<300,000 years) materials by a number of methods, but in general, very few radiometric techniques are known which cover the period inbetween.

The main requirements for most forms of dating are:

i) knowledge of initial conditions, i.e. the amount of radionuclide (or its ratio relative to some other isotope),

ii) absence of daughter product at time of formation (or possibility of estimating amount initially present),

iii) precise knowledge of decay scheme and relevant nuclide half-lives,

iv) ability to determine precisely concentrations (or more commonly radioactivities) of nuclides,

v) requirement of 'closed system' conditions since formation or emplacement, i.e. no migration or addition of parent and daughter nuclides.

Paleothermal information from certain types of deposit became available when Urey (1947) showed that fractionation of stable isotopes of light elements between co-existing phases occurs predictably under equilibrium conditions and is a function only of the temperature of formation. This temperature can be determined by measuring relative isotopic contents of the same element in two components that are in isotopic equilibrium (e.g. ^{34}S, ^{18}O and ^{13}C in quartz-magnetite, calcite-water, pyrite-galena systems, etc.). Variations in isotopic ratios can then be converted directly to temperature of formation by comparison with results from either experimental calibrations or theoretical calculations.

A number of stable isotope methods now exist to obtain paleoclimatic information from radiometrically datable deposits, e.g. tree rings (Gray and Thompson, 1976; Yapp and Epstein, 1977), deep-sea cores (Emiliani, 1966 & 1971; Broecker and Ku, 1969; Shackleton and Opdyke, 1973) and polar ice-cores (Johnsen et al., 1972). Recently cave travertine formations have also been recognised as a potential source of both a time scale and paleoclimatic information (Hendy and Wilson, 1968).

This paper describes the theory and analytical techniques used in obtaining age and temperature information and briefly reviews previous work on speleothems. A following companion paper will describe results of these techniques applied to speleothems collected from caves in the Craven area of Northern England.

RADIOMETRIC DATING

Decay Theory

In a given decay series:

$$N_1 \xrightarrow{\lambda_1} N_2 \xrightarrow{\lambda_2} N_3 \xrightarrow{\lambda_3} \text{etc.}$$

N_1 is the number of atoms of parent nuclide at one instant in time, N_2, N_3 etc. are those of the daughters of N_1, and λ_i is the decay constant of nuclide i (the probability of decay of nuclide i in unit time, where i = 1, 2, 3 etc.). The rate of formation of any daughter is a function of the rate of its own decay and the concentration and decay constant of its parent. It can be shown that the general law:

$$N_2 = \frac{\lambda_1 N_1^o}{\lambda_1 - \lambda_2} \cdot (e^{-\lambda_1 t} - e^{-\lambda_2 t}) + N_2^o e^{-\lambda_2 t} \qquad 1)$$

applies in this case, where N_1^o and N_2^o are the number of atoms of parent and daughter initially present, and t is the time elapsed since deposition.

This equation can be simplified in the case when a short-lived daughter is accumulating from a long-lived parent (i.e. $\lambda_2 >> \lambda_1$):

$$\frac{N_2}{N_1^o} = \frac{\lambda_1}{\lambda_2} (1 - e^{-\lambda_2 t}) \qquad 2)$$

When a sample such as a speleothem behaves as a closed system, then N_1^o is fixed at the time of deposition and the ratio N_2/N_1^o tends to unity in a time period determined by the rate of decay of the daughter. At unity, 'secular equilibrium' is reached and the method can no longer be used for radiometric dating. Of the decay schemes of the naturally-occurring actinides (Fig. 1), the ^{238}U and ^{235}U series can be used in dating carbonates which have been formed by deposition from solution.

GEOCHEMICAL CYCLE OF URANIUM

The primary source of uranium and thorium in the geochemical cycle is the weathering of felsic igneous rocks. Because of their age, these rocks are in secular radioactive equilibrium with respect to uranium and thorium (i.e. radioactivity ratios $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ = 1.0). Thorium (Th^{IV}) is almost completely excluded from the groundwater cycle owing to its very low solubility and is easily removed on clay minerals and sediment particles. Uranium, however, is readily oxidised from the +4 to the +6 state to form the soluble UO_2^{2+} ion which can be transported in solution, often as an anion complex with carbon dioxide or phosphate (Langmuir and Applin, 1977):

$[UO_2(CO_3)_3]^{4-}$, $[UO_2(CO_3)_2]^{2-}$, $[UO_2(HPO_4)_2]^{2-}$

Subsequent loss of CO_2 and co-precipitation with calcium carbonate in the marine environment forms carbonate sediments which contain 2 - 4 ppm U but less than 0.1 ppm Th (Adams et al., 1959). Clastic sediments, however, are enriched in thorium and also contain some uranium and so may contaminate carbonate deposits. Organic deposits are often enriched in uranium due to the high solubility of uranium in an acid environment and the tendency for U^{VI} to be adsorbed by humic substances.

On subsequent uplift and erosion of these sedimentary rocks, uranium is again mobilized by weathering and taken up in groundwater. In limestone regions a second depositional cycle may occur when the water enters a cave and degasses, causing calcite to precipitate. It is in this water and the associated calcite that one characteristic feature of uranium geochemistry can be seen: fractionation of the isotopes ^{238}U and ^{234}U. Normally a chemical impossibility, this process takes place because ^{234}U occupies a lattice site which has been damaged by radiation emitted in the decay of ^{238}U (Fig. 1). In freshwater systems the activity ratio $^{234}U/^{238}U$ has been found to vary between about 1.0 and 12 (Cherdyntsev, 1955; Kronfeld, 1974; P. Thompson et al., 1975). Ocean water, however, is remarkably constant at 1.14 ± 0.02 (Ku et al., 1974).

The uranium concentration of a speleothem is dependant on U content of the overlying bedrock, presence of organic (black) shale partings, residence time of groundwater, availability of CO_2, rate of degassing in the cave, etc. Work done so far has shown uranium content of speleothems to vary both spatially and temporally. Concentrations of less than 0.01 ppm to more than 90 ppm U have been found (P. Thompson et al., 1975; Harmon, 1975) though most values fall in the range 0.1 to 2 ppm.

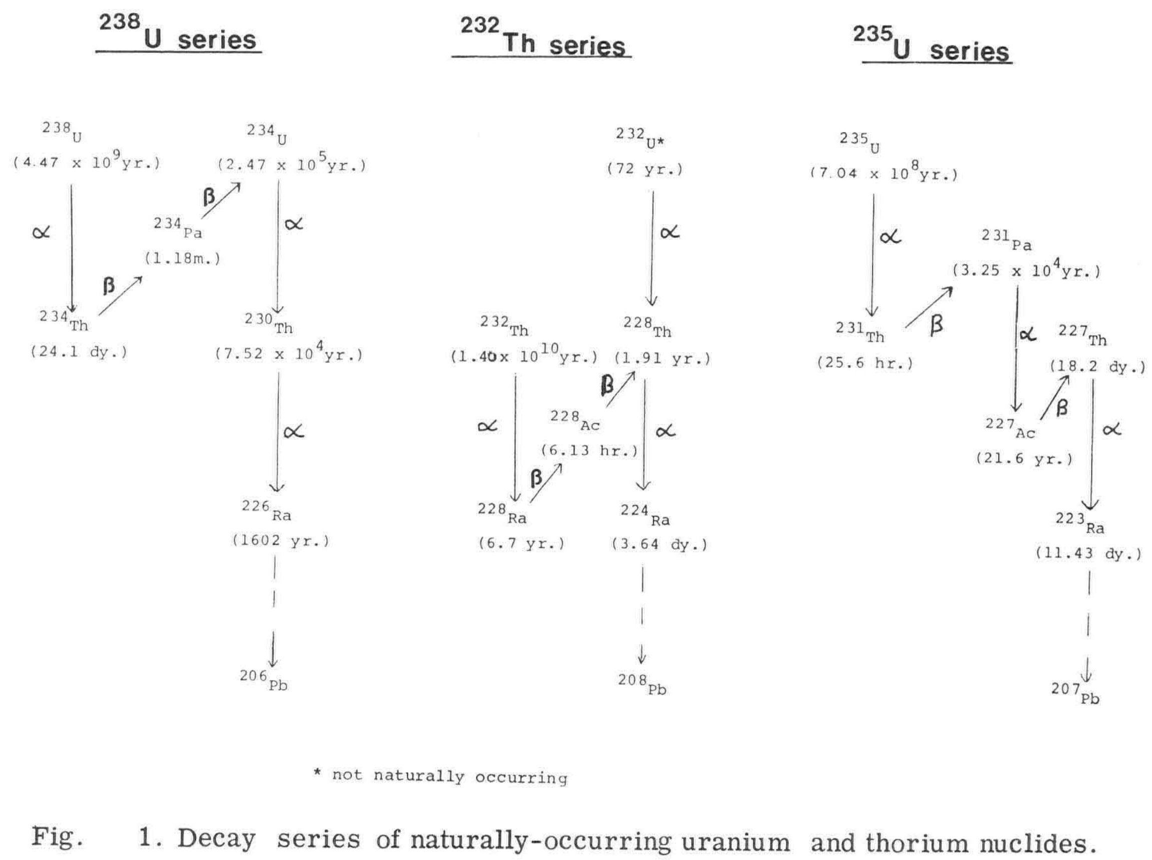

Fig. 1. Decay series of naturally-occurring uranium and thorium nuclides.

URANIUM SERIES DATING METHODS

Since negligible amounts of ^{230}Th are deposited in speleothem calcite, two decay schemes of the ^{238}U series can be used in dating. They are the decay of excess (or growth of deficient) ^{234}U into equilibrium with ^{238}U, which requires about 1.5 million years to attain secular equilibrium, and the growth of ^{230}Th into equilibrium with ^{234}U which takes about 350,000 years depending on the initial excess of ^{234}U. ^{235}U, although of low relative abundance ($^{238}U/^{235}U$ = 137.9) can be used for dating U-rich speleothems by the growth of its daughter ^{231}Pa. This method has a useful time range of about 200,000 years. These are the principal methods applied so far to dating freshwater carbonates, although attempts have been made, using ^{14}C in cases where its initial activity can be reliably estimated (exchange of 'active' carbon in soil CO_2 with 'dead' limestone carbon gives a final activity between 50% and 100% of atmospheric levels). Decay equations and particular characteristics relevant to these methods are summarized below.

i) $^{234}U/^{238}U$

The decay of excess ^{234}U towards equilibrium with ^{238}U is described by the following equation:

$$\left(\frac{^{234}U}{^{238}U}\right) - 1 = \left(\frac{^{234}U}{^{238}U}\right)_o - 1 \;.\; e^{-\lambda_{234}t} \qquad 3)$$

where $(^{234}U/^{238}U)_t$ is the measured (i.e. present-day) activity ratio
$(^{234}U/^{238}U)_o$ is the initial ratio, on deposition
λ_{234} is the decay constant of ^{234}U,
and t is the time since deposition.

Although this method could be used in dating most of the Pleistocene period, its main disadvantage is the requirement that initial $^{234}U/^{238}U$ must be accurately known. As already mentioned, this ratio is highly variable for most freshwater systems and the assumption that the value for modern dripwater can be used in dating a fossil speleothem at/or near the same site is of dubious validity. The ratio is known to be constant in the oceans, and reef terraces and corals have been successfully dated using this assumption. The technique may be applied in one special case to freshwater carbonates that lie partly within the range of an alternative dating method (e.g. $^{230}Th/^{234}U$). If it can be shown that for the datable portion, $(^{234}U/^{238}U)_o$ is constant, then the same value may be assumed for the undatable portion and equation 3) used. A plot of growth rate (age vs. height or weight) may then indicate if this assumption is valid. Note, however, that $(^{234}U/^{238}U)$ ratios commonly change after any interruption in the growth of the speleothem (Harmon et al., 1978) and that the ratio in groundwater may not be that found in the associated speleothem.

ii) $^{230}Th/^{234}U$

The absence of ^{230}Th in fresh calcite deposits is seen as evidence that ^{230}Th in fossil speleothems is derived solely from the in situ decay of ^{234}U and ^{238}U initially co-precipitated with the calcite. The equation to relate ^{230}Th content to the speleothem age is necessarily more complex than equation 3 above, since ^{230}Th derived from the excess ^{234}U must also be taken into account:

$$\left(\frac{^{230}Th}{^{234}U}\right)_t = \frac{1 - e^{-\lambda_{230}t}}{(^{234}U/^{238}U)_t} + \left(\frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\right).\left(1 - \frac{1}{(^{234}U/^{238}U)_t}\right).\left(1-e^{-(\lambda_{230}-\lambda_{234})t}\right) \qquad 4)$$

$(^{230}Th/^{234}U)_t$ and $(^{234}U/^{238}U)_t$ are the measured activity ratios t years after deposition, and λ_{230} is the decay constant of ^{230}Th. A graphical

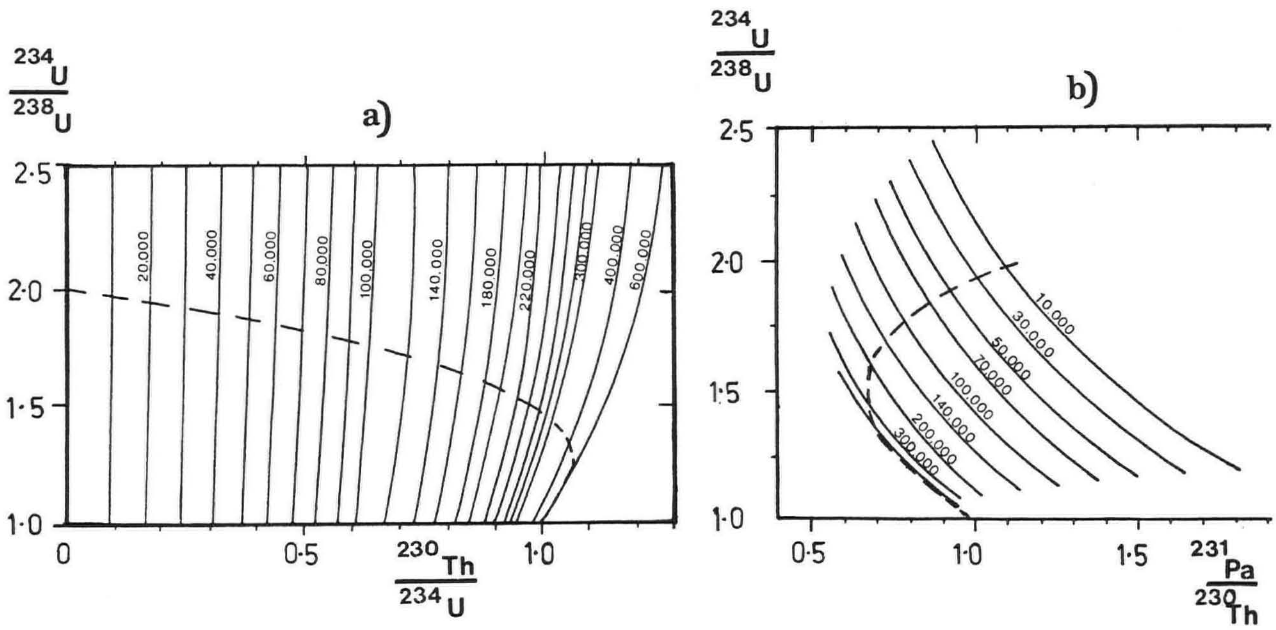

Fig. 2. Isochron plots: solid lines show age in years, dashed line shows typical change in nuclide ratios as age increases, with an initial $^{234}U/^{238}U$ ratio of 2.

solution of this equation is shown in Fig. 2a. If sand or clay are present in the calcite (usually from past flood events) contamination by non-authigenic ^{230}Th can occur, tending to increase the true age, Since this detrital ^{230}Th is usually accompanied by ^{232}Th, its presence is easily recognised in the thorium spectrum (Fig. 3), although allowance for it is not as straightforward because $^{230}Th/^{232}Th$ ratios in sediments vary depending on source, age, sediment type, etc. Furthermore, the possibility of uranium contamination from the sediment must also be acknowledged and no simple correction for this can be made.

iii) $^{231}Pa/^{235}U$

This method is based on the decay of ^{235}U to ^{231}Pa via a short-lived intermediate, ^{231}Th. However, it is easier to detect ^{231}Pa either by β-counting the decay of its daughter ^{227}Ac, or by monitoring the activity of the daughter of ^{227}Ac, ^{227}Th, an alpha emitter. For these two indirect methods, it must be assumed that isotopic equilibrium exists with both daughters and ^{231}Pa. The age of the sample is given by:

$$\left(\frac{^{231}Pa}{^{235}U}\right)_t = (1 - e^{-\lambda_{231}t}) \qquad 5)$$

where $(^{231}Pa/^{235}U)_t$ is the present-day activity rate, t years after deposition and λ_{231} is the decay constant of ^{231}Pa.

Used in this form, the range of the method is about 200,000 years, but if combined with the fact that $^{235}U/^{238}U$ activity ratio in the environment is a constant (1 : 21.7) then equations 4) and 5) may be combined to give:

$$\frac{^{231}Pa}{^{230}Th} = \frac{1-e^{-\lambda_{231}t}}{21.7(1-e^{-\lambda_{230}t})+\{(^{234}U/^{238}U_t)-1.\lambda_{234}/(\lambda_{230}-\lambda_{234})-(1-e^{-(\lambda_{230}-\lambda_{234})t}\}} \qquad 6)$$

This equation is represented graphically in Fig. 2b and it can be seen that the resolution of the method extends to about 300,000 years B.P.

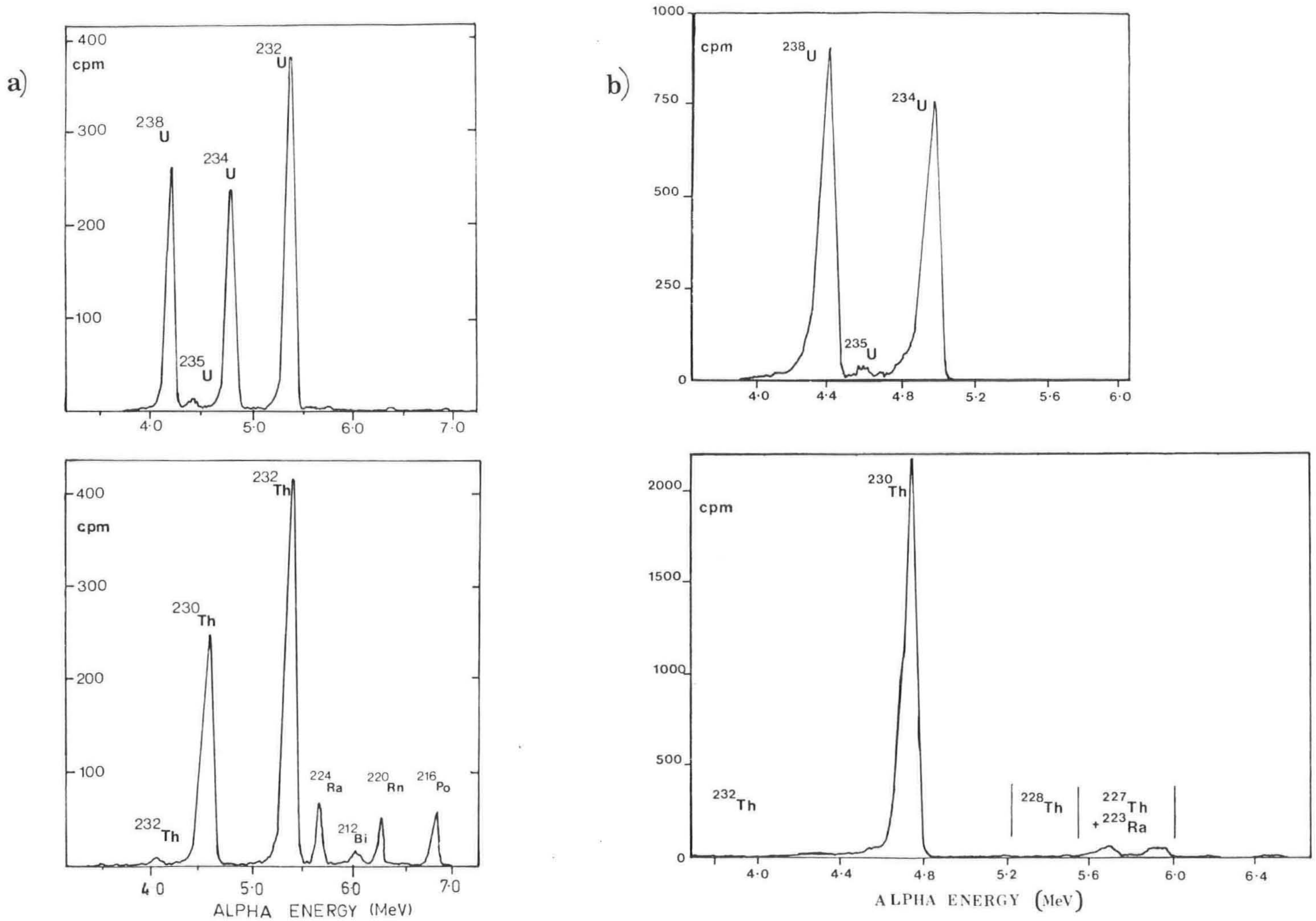

Fig. 3. Typical alpha particle spectra (counts per minute vs. particle energy) of:

a) uranium and thorium nuclides with spike in the $^{230}Th/^{234}U$ dating method.

b) uranium and thorium nuclides in the unspiked $^{231}Pa/^{230}Th$ dating method (^{231}Pa is monitored by the activity of its daughter ^{227}Th).
Daughter nuclides from ^{227}Th and ^{228}Th can be seen in the high energy region.

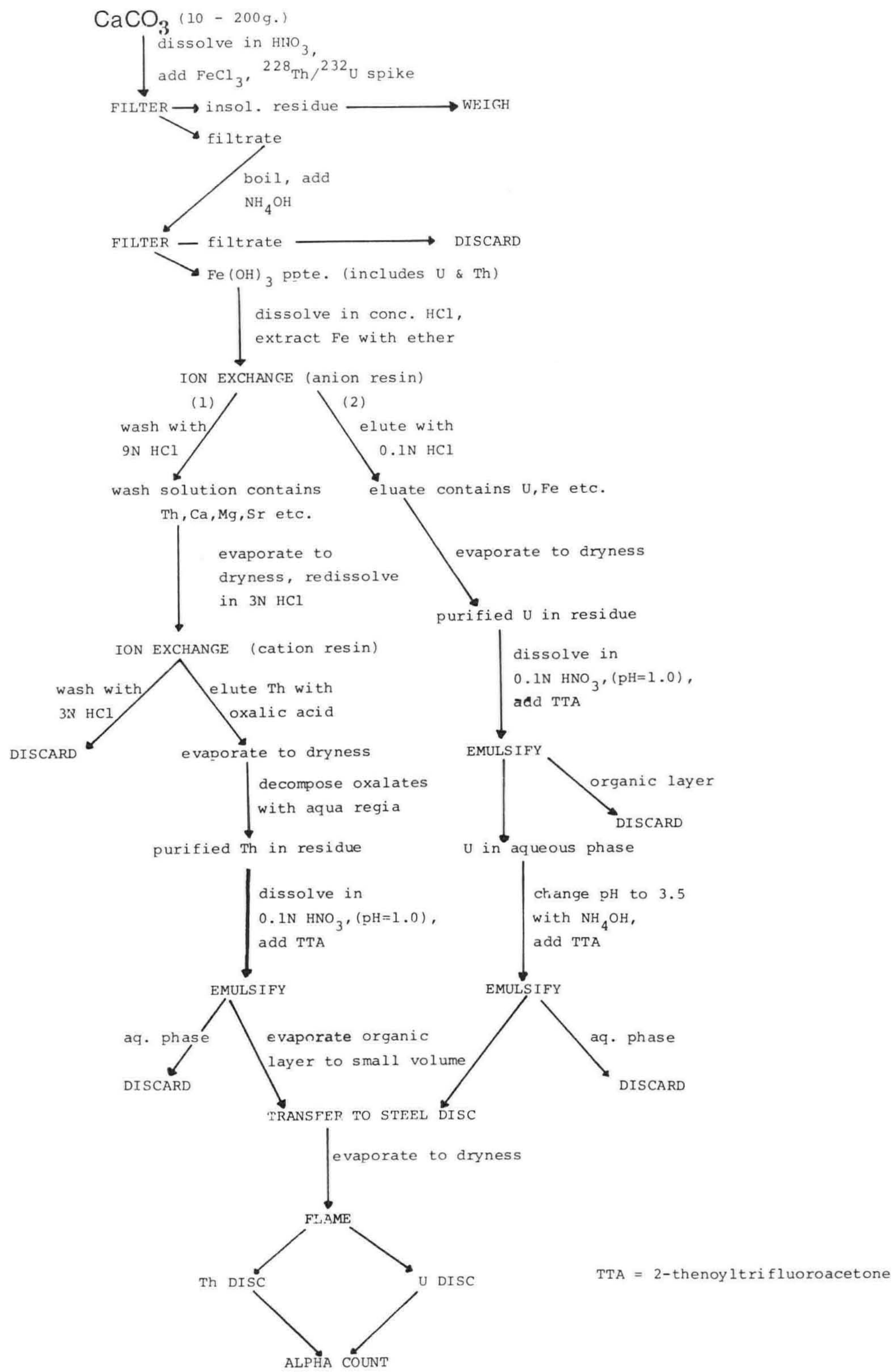

Fig. 4. Flow chart showing extraction and purification technique for speleothem uranium and thorium.

Analytical Technique

In order to date a speleothem by any of the methods previously described it is first necessary to extract and purify each nuclide of interest, correct for chemical yields, measure the relative radioactivities by alpha-particle spectrometry and allow for blank, background and decay corrections.

The chemical procedure used at McMaster was first developed by Peter Thompson (1973) and has been recently revised by Gascoyne (1977). The various stages are shown in Fig. 4. The two steel discs obtained at the end of the extraction are counted separately as shown in Fig. 3. Alpha particles resulting from the decay of each nuclide have a series of charcteristic energies which are absorbed by a silicon barrier detector and converted to corresponding electronic pulses of unique energy. The pulses are then amplified, discriminated and stored in a memory, the contents of which can be printed out after a certain number of pulses (counts) have been obtained. Typical alpha particle spectra are shown in Figs. 3a,b.

At the outset of the extraction, an artificial radioisotope mixture is added as a tracer or 'spike' to monitor the yields of speleothem U and Th. This is necessary because the chemical separation procedures have different efficiencies for U and Th. The spike is a solution of ^{232}U ($t_{\frac{1}{2}}$ = 72 yrs.) usually sold in equilibrium with its daughter ^{228}Th, such that the spike activity ratio ($^{228}Th/^{232}U$) should be 1.027, the value at transient equilibrium. The true $^{230}Th/^{234}U$ ratio is therefore given by:

$$\left(\frac{^{230}Th}{^{234}U}\right)_{true} = \left(\frac{^{230}Th}{^{234}U}\right)_{obs.} \times \left(\frac{^{232}U}{^{228}Th}\right)_{obs.} \times \left(\frac{^{228}Th}{^{232}U}\right)_{sp.} \qquad 7)$$

obs. = observed, sp. = spike

^{228}Th is also the daughter of ^{232}Th (a naturally-occurring nuclide) and if ^{232}Th is seen in the Th spectrum, radioactive equilibrium is assumed and an equal activity is subtracted from the total ^{228}Th count before using equation 7. The presence of additional, unsupported-^{228}Th in the sample can be checked in an unspiked run (as in $^{231}Pa/^{230}Th$ dating). However, it is not as easy to correct for ^{230}Th that accompanies the ^{232}Th and ^{228}Th. Measurements of the $^{230}Th/^{232}Th$ ratio in sediments have shown it to be variable and problems also arise from preferential leaching of ^{230}Th over ^{232}Th from the detrital component during speleothem dissolution.

Dating Criteria

Certain important criteria must be met before precise, reproducible ages can be obtained on cave travertines:

i) the sample must contain uranium above a threshold value of 0.05 ppm. Below this concentration, background activity fluctuations, glassware memory effects and natural levels of U and Th in the reagents used dominate the signal. It is not possible simply to use more sample in the analysis, since correspondingly more reagents must be used, so increasing the reagent contribution to the signal. Specially purified reagents can be used in these cases.

ii) there must be no Th (or Pa) co-precipitated with U in the calcite during deposition. Analysis of recent, pure deposits has shown this to be true.

iii) all ^{230}Th and ^{234}U must be derived solely from the carbonate portion. As previously described, this can easily be recognised for the case of Th, by the absence of ^{232}Th.

iv) the system must remain closed to migration or addition of nuclides after formation. During recrystallisation from aragonite to calcite, U and Th may be removed from the speleothem. Porous, vuggy calcite samples also may have been leached of U or Th or may have suffered additions of these elements after deposition. It has been observed that post-depositional changes affect U more than Th and preferential removal of U results in a characteristically anomalous $^{230}Th/^{234}U$ ratio, significantly greater than 1.0.

v) sequential stratigraphic ordering of ages along the growth axis of a speleothem should be seen. Age inversions, well outside the one standard deviation error overlap may be due to partial nuclide migration or addition, presence of a detrital component or of reagent blank effects, etc. (as in low-U samples).

Research during the last ten years has shown that stalagmites and flowstones are best suited to dating because, when sectioned lengthwise, their growth layers are well-defined and lacking in re-solution holes. Stalactites are unsuitable because their growth layers are usually very thin and difficult to remove, and they often possess a central hole through which water intermittently passes causing resolution. Massive, macro-crystalline speleothems are generally found in cold and temperate climates where growth is fairly slow. Tropical speleothems are sometimes porous and sugary-textured (perhaps due to recrystallization). They often contain detrital horizons and evidence of external resolution, both due to phases of inundation during growth.

Previous Work

Uranium series dating techniques were first applied to carbonates about twenty years ago (Barnes et al., 1956), when the ratio of ^{230}Th to uranium in marine limestone was recognised as being a function of age of the deposit. Subsequently two main fields of study (^{234}U disequilibrium and ^{230}Th/uranium ratios) were investigated for their potential in dating the Pleistocene. The former method met with only limited success since it was found that $^{234}U/^{238}U$ ratios for continental deposits and groundwaters were highly variable, both spatially and temporally, and modern-day ratios could not validly be used as initial ratios in dating fossil samples. Cherdyntsev (1971) summarized the early studies on ^{234}U disequilibrium in the U.S.S.R. and the limitations in dating freshwater carbonates are illustrated by Thurber (1964). Somayajulu and Goldberg (1966) and Thurber et al. (1965) have successfully applied $^{234}U/^{238}U$ ratios in dating marine deposits where a constant initial ratio of seawater (1.14 ± 0.02) can be assumed.

The $^{230}Th/^{234}U$ method has met with more success in dating both marine and freshwater carbonates, the main criteria being low detrital content and maintenance of a closed system since formation. Unrecrystallized aragonitic corals have been found to give reliable ages and some progress has been made with dating contaminated carbonates using an isochron technique (Kaufman, 1971). Mollusc shells, however, have constantly proved problematic because they appear to gain massive amounts of uranium after death (Kaufman et al., 1971), due in part to decay of the organic component of the shell and redox reactions with the surrounding water. The $^{231}Pa/^{235}U$ method has been used extensively to check ages of fossil reef terraces but good agreement is only found if $\lambda(^{231}Pa)$ is decreased slightly from the thermodynamically-determined value, (Ku, 1968).

The first application of U-series dating to speleothems was by Rosholt and Antal (1962). It proved unsuccessful because all of the samples analysed showed evidence of post-depositional U-migration (from excess ^{230}Th and ^{231}Pa contents). Cherdyntsev et al. (1965) was more fortunate in applying the $^{230}Th/^{234}U$ technique to cave deposits although significant amounts of detrital thorium were found in the travertines analysed. Fornaca-Rinaldi (1968) also obtained ages of speleothems collected from Italian caves, but omitted to correct the excess ^{234}U. However, since the deposits were $<$80,000 years old, this error has only a small effect (see Fig. 2a). French workers have successfully used $^{230}Th/^{234}U$ ratios to date low-U speleothems from the Aven d'Orgnac (Duplessey et al., 1970), obtaining five stratigraphically-ordered ages along the length of a 2.44 m columnar stalagmite.

As noted, various attempts have been made to date speleothems by ^{14}C and assumptions have been made as to the initial ^{14}C content. Hendy (1970) has suggested that linear growth rates and 100% initial ^{14}C activity should be first assumed and then an age correction can be added to all dated portions based on the graphical intercept of dates vs. growth rate. An alternative way around this problem is to use ^{13}C content as a monitor of soil carbon contribution and hence derive ^{14}C content, (Wigley, 1975).

Examples of replicate dating by two different methods are rare in the literature but in one instance Spalding and Mathews (1972) found good agreement between ^{14}C age (21,900 ± 600 yrs. B.P.) and $^{230}Th/^{234}U$ age (22,000 ± 350 yrs. B.P.) for a submerged speleothem, although Hendy's assumption of 100% ^{14}C activity was used as an initial value.

Sources of Error

Three general sources of error in $^{230}Th/^{234}U$ ages can be identified:

i) 'chemical' error
ii) error in data processing
iii) 'speleothem' error.

i) The chemical extraction technique embodies relatively few sources of error because a radioactive tracer, in the same chemical form as the speleothem nuclides, is added at the outset. Therefore whatever happens to the calcite nuclides also happens to those of the spike and corrections can be applied. Other than background interferences and contamination of reagents and glassware, precise knowledge of the spike activity ratio is the only major requirement. Variations in the quantity of spike added at the dissolution stage affect only the value determined for uranium concentration in the calcite and apparent chemical yield, - both unnecessary parameters in the age determination (see equations 4 and 7). It is, however, essential to obtain as high a yield as possible of uranium and thorium at the end of the analysis since low-yield samples require long count times, involve larger decay and background corrections and the slight chemical contaminants will have a greater influence, all resulting in larger uncertainty in ages.

ii) Alpha spectra are retrieved by teletype printer and divisions are made between nuclide peaks. This process is somewhat subjective and bias is easily incorporated when reducing nuclide peaks of widely-different intensities. Low energy tail corrections may be necessary in the case of thick sources or poor energy resolution. Count rates can then be determined and corrected for background and blank activities and a computer program is used to solve the age equation. One standard deviation errors (1σ) are also determined for each count rate, based entirely on counting statistics, and the program is again used to translate these into error limits on the final age. Data retrieval and processing errors can therefore range from simple mistakes in hand calculations, to inaccuracies in age equations and values of decay constants.

In addition, precision and reproducibility of an age measurement should be determined to verify that the 1σ error limit is realistic. This is best done by replicate dating of a homogenized calcite powder standard. The precision of ages is best checked by comparison with results from other laboratories for the same sample or by using an alternative dating method. To some extent, the absolute accuracy of an age can be estimated by these latter methods, although errors in decay constants and nuclide abundance measurements will be common to all laboratories.

iii) 'Speleothem errors' have been referred to previously and mainly concern presence of open system conditions after deposition, or contamination by nuclides derived from detritus incorporated in the speleothem. Recrystallization, re-solution and a porous texture can all affect the age. Usually these interferences drastically affect $^{230}Th/^{234}U$ ratios, giving an apparent age of >300,000 years or even $^{230}Th/^{234}U \gg 1$, but partial changes may result in an age shift within the dating limit, and this may be undetectable. Concordancy of ages between two dating methods generally shows that closed-system conditions have existed, because chemical differences between the relevant nuclides will ensure different degrees of migration and therefore differing ages.

A detailed description of potential errors in U-series dating techniques has recently been given by one of the authors (Gascoyne, 1977).

Recent Research

The bulk of the work on speleothem dating since 1970 has been done at McMaster University, using the $^{230}Th/^{234}U$ ratio of relatively pure, massively crystalline speleothems collected from caves throughout North and Central America (Thompson, 1973; Harmon, 1975). The general findings have been:

i) speleothems grow fastest in warmer climates,

ii) uranium concentrations in the calcite vary from <0.01 ppm to >90 ppm; high values are associated with the presence of overlying U-rich deposits, e.g. shales, sandstones, etc.,

iii) $^{234}U/^{238}U$ ratios along the growth axis of a speleothem do not usually decrease progressively with increasing age (i.e., initial $^{234}U/^{238}U$ often changes during the growth period). This fact and the observation that the ratios in modern groundwater vary spatially and temporally (P. Thompson et al., 1975) invalidates most applications of U-disequilibrium dating of speleothems (see, however, G. Thompson et al., 1975). More recent, detailed work by Gascoyne further substantiates the findings of P. Thompson et al.,

iv) in general, for macro-crystalline, low-detritus, impervious speleothems, good agreement has been found between $^{230}Th/^{234}U$ ages and the sample's internal stratigraphy,

v) occasional use of the $^{227}Th/^{230}Th$ ($\equiv$ $^{231}Pa/^{230}Th$) method on samples dated by $^{230}Th/^{234}U$ has shown fair agreement, (Thompson et al., 1976),

vi) speleothem growth during the Late Pleistocene can be generally correlated to warming events between known glaciations both from frequency and clustering of dates and co-incidence of cessation of growth of a number of samples in the same region, presumably indicative of the onset of a cold period, (Harmon et al., 1977; Thompson et al., 1974).

The reproducibility of the dating technique has been checked by regular analysis of a standard. About ten kilograms of a flowstone were collected from Sumidero Tenejapa, Chiapas, Mexico, in January 1976, crushed to $<$100 mesh and homogenized. Eight out of nine analyses have so far given ages lying between 45,700 and 50,200 years B.P. with a mean standard deviation error of $\pm$ 2,400 years (Gascoyne, 1977). One age determination of 62,700 $\pm$ 2,800 years lay well outside even 3σ limits and suggested that the standard was not fully homogenized. Since re-mixing, no more anomalies have so far been found. These results therefore suggest that the only major errors are those inherent in the randomness of radioactive decay.

Current research is focussed on dating speleothems from Vancouver Island, Jamaica and the Craven area of northern England. Results from the latter region will be described in detail, together with their geomorphic and speleogenetic implications in the second part of this paper (to be published in a later Transactions).

STABLE ISOTOPE ANALYSIS OF SPELEOTHEMS AND PALEOTEMPERATURE DETERMINATION

It has been known since the early 1950s, through the work of Epstein et al. (1951), that in principle the temperature of formation of calcite could be determined from the fractionation of isotopes of oxygen (^{18}O and ^{16}O), between calcite and its parent solution, as expressed by the exchange equation:

$$\frac{1}{3}\,CaCO_3^{16} + H_2O^{18} \rightleftharpoons \frac{1}{3}\,CaCO_3^{18} + H_2O^{16} \qquad 8)$$

Isotopes of carbon (^{13}C and ^{12}C) are also fractionated but to a lesser extent, due to the central position of the carbon atom in the CO_3^{2-} ionic groups in the calcite lattice, and the smaller relative mass difference. Measurement of isotope fractionation between two phases in equilibrium was made possible by the development in the 1950s by Nier, of a mass spectrometer with simultaneous detection of two ion beams suitable for direct isotope ratio determination. Using this instrument Epstein et al. (1951) and subsequent workers have calibrated the ^{18}O geothermometer by observation of natural systems or from controlled experiments.

In the late 1960s attention turned to cave travertines (speleothems) because they may have been formed under conditions of isotopic equilibrium and therefore ^{18}O variations in the calcite may be expected to reflect local temperature changes. Coupled with radiometric dating of the travertines this represented yet another way of determining ages and intensities of glaciations and warm periods in the Earth's recent history. Initial work, however, was very discouraging. Fantidis and Ehhalt (1970) and Fornaca-Rinaldi et al. (1968) both found that single growth layers in speleothems varied widely in isotopic composition, as if the water from which they were growing was being isotopically fractionated as it flowed down the side of the speleothem. More optimistic results were reported in a very thorough study by Hendy (1971) who found that deep inside a cave, conditions were such that speleothems apparently formed in isotopic equilibrium with their parent solutions. Variations in ^{18}O of calcite along the growth direction in these cases are a direct indication of change in palaeoclimate, but the exact contribution of temperature to this change cannot be simply determined because the water may have changed in isotopic content, causing the calcite to change also.

For some time no solution to this problem was found since the ^{18}O content of the now-vanished parent water obviously could not be measured. Indirect interpretation was made by comparison with modern deposits and their waters in the same cave (Emiliani, 1971) and by the effects of temperature on the ^{18}O content of rainwater between its source and the site of precipitation, over a glacial to interglacial transition (Hendy and Wilson, 1968). A more direct method of determining ^{18}O content of 'paleowaters' was developed by Schwarcz et al. (1976) by extracting and analysing microscopic inclusions of water trapped in the calcite of the fossil speleothem.

The following pages describe isotope fractionation theory and analytical techniques in more detail and discuss interferences and results found from work done so far.

Isotope Fractionation Theory

Distribution of isotopes of an element in a two or three phase system at equilibrium is a function of the energy of each ionic or molecular species in that system. The total energy of the system is a function of its temperature. Total ionic or molecular energy is composed of a number of individual atomic motions, i.e. vibration, rotation, translation and electronic transitions. Using statistical mechanics theory and assuming ideal behaviour, these energies can be calculated for each species. Good agreement with experimental results has generally been found for isotope distribution in gas mixtures (Urey, 1947; Bigeleisen and Mayer, 1947). A theoretical treatment of condensed systems is more difficult due to non-ideal behaviour and the necessity of summing over all energy modes of the solid or liquid. In some solid phases, the vibrational mode becomes energetically more significant and can be estimated by considering energy modes of the crystal lattice (Bottinga, 1968 & 1973).

The fractionation of an isotope between two systems at equilibrium is inversely related to temperature; that is, the more energy available the less the difference in isotopic composition.

Nomenclature

The partition of an isotope in a two component system at equilibrium is generally described by α_{A-B}, the fractionation factor for phases A and B. For example, oxygen exchange between calcite and water is represented as:

$$\alpha_{c-w} = \frac{(^{18}O/^{16}O)_c}{(^{18}O/^{16}O)_w} \qquad 9)$$

The isotopic ratio of a given phase is more conveniently defined and measured in terms of δ, its deviation from the isotopic ratio of a calibrated, international standard, i.e.:

$$\delta_c = \left(\frac{(^{18}O/^{16}O)_c - (^{18}O/^{16}O)_{std}}{(^{18}O/^{16}O)_{std}}\right) 1000$$

$$\text{or} \quad \delta_c = \left(\frac{(^{18}O/^{16}O)_c}{(^{18}O/^{16}O)_{std}} - 1 \right) 1000 \qquad 10)$$

where δ is expressed in parts per thousand (‰) or 'per mille'. Combining 9) and 10) the fractionation factor becomes:

$$\alpha_{c-w} = \frac{\delta_c + 1000}{\delta_w + 1000} \qquad 11)$$

For values of α near unity, equation 11 may be approximated:

$$1000 \ln \alpha_{c-w} = \delta_c - \delta_w \qquad 12)$$

As noted, the fractionation factor is inversely related to temperature and it has been found from experimental work that:

$$\ln \alpha = \frac{C}{T^2} + D \qquad 13)$$

where T is temperature in ^oK and C and D are constants (O'Neil et al., 1969). For low temperature exchange $\alpha \propto 1/T$ is theoretically more applicable.

Two primary standards are in use for the carbonate-water system. PDB (Pee Dee Belemnite) is the carbonate standard where $\delta^{13}C = \delta^{18}O$ = zero, and SMOW (Standard Mean Ocean Water) is the water standard, for which $\delta^{18}O = \delta^2H$ (commonly written δD) = zero. Published results of analyses of carbonates, organic carbon and natural waters are usually based on one of these two standards. The typical range of $\delta^{18}O$ and $\delta^{13}C$ values in naturally-occurring substances is shown in Fig. 5.

Analytical Techniques

For any given substance $\delta^{13}C$ and $\delta^{18}O$ are best determined by first converting the substance into CO_2 gas. The gas is then passed at very low pressure into a mass spectrometer. Gas molecules are ionised (principally to CO_2^+) by electron bombardment from a tungsten filament source, accelerated by a high potential drop and split by a strong magnetic field into three 'beams': the major beam comprises ions of mass 44 ($^{12}C^{16}O^{16}O$) the most abundant, and minor ion beams of mass 45 (dominantly $^{13}C^{16}O^{16}O$ ions) and mass 46 (dominantly $^{12}C^{18}O^{16}O$ ions). These beams have intensities of about 1% and 0.2% of the mass 44 beam respectively. Other isobars (e.g. $^{12}C^{17}O^{16}O$) of lesser abundance are present in both the mass 45 and 46 beams. Two beams are detected simultaneously using a two-part cup-shaped collector. The signal from a minor beam is approximately balanced against a fixed portion of the mass 44 beam and the remaining signal is then exactly measured using accurate resistances and a strip-chart recorder. Alternatively the ratio of major and minor beams may be directly measured on a digital voltmeter. Each sample is run against a calibrated laboratory (secondary) standard and the result finally expressed in terms of PDB or SMOW.

A number of ways of generating CO_2 (in 100% yield) from materials of interest have been developed. For the carbonate-water system, the most important are:

i) for $\delta^{13}C$ and $\delta^{18}O$ of calcites - dissolution of milligram quantities of calcium carbonate powder in dry, 100% orthophosphoric acid under vacuum conditions at 25°C. CO_2 generated is trapped in a cold-finger and dried by repeated passes through a dry ice/CCl_4 trap. Fractionation of ^{18}O between H_3PO_4, $CaCO_3$ and the CO_2 produced under these conditions has been shown to be constant (McCrea, 1950) and therefore samples and standards prepared the same way may be directly compared.

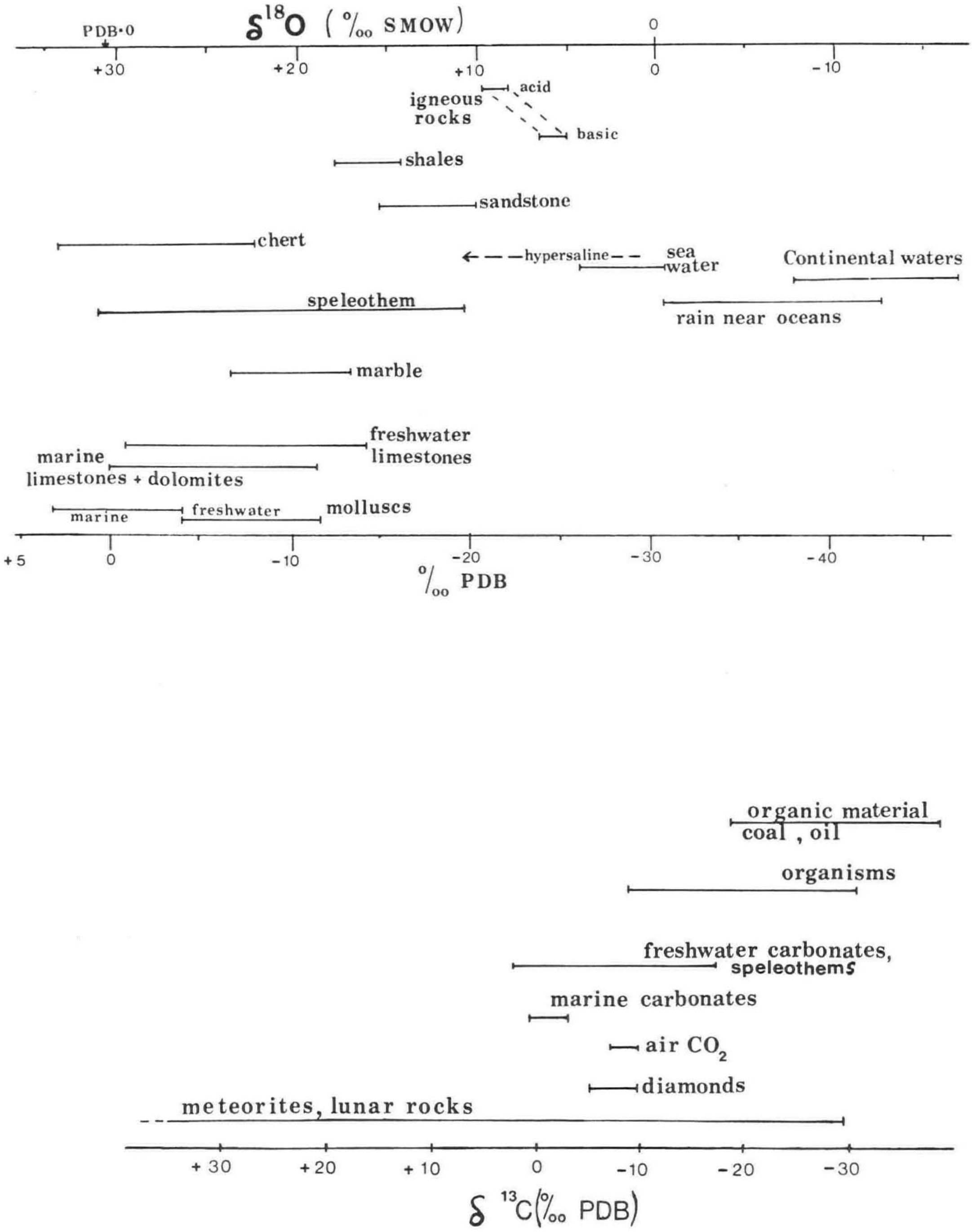

Fig. 5. Diagrams illustrating variation of $\delta^{13}C$ and $\delta^{18}O$ in the natural environment.

ii) for $\delta^{18}O$ of waters - a) by equilibration with CO_2 of known isotopic composition. A flask of the water and cylinder-CO_2 gas is shaken for 2 - 4 days at 25°C and a sample of gas is removed, dried and analysed. A mass-balance equation is used to determine $\delta^{18}O$ of the water (Epstein and Mayeda, 1953).

- b) by the reaction of water with bromine pentafluoride (BrF_5). Oxygen is produced and is then converted to CO_2 using carbon electrodes. This method is best suited to milligram quantities of water (O'Neil and Epstein, 1966).

iii) for δD of waters - water is passed over heated uranium metal at about 800°C, forming hydrogen gas which is collected over mercury or passed directly into the mass spectrometer (Bigeleisen et al., 1952).

$\delta^{18}O$ and $\delta^{13}C$ from CO_2 prepared by the above methods can generally be determined by mass spectrometer to within ±0.1‰ and δD to ±1‰. At best, depositional temperatures may therefore be determined to within ±0.5°C.

Experimental Determination of Alpha

Many attempts have been made to calibrate the α-T relationship for equilibrium two-phase systems precisely, the calcite-water system being the most important of these. Three approaches have been used:

i) high temperature equilibration of the two phases followed by quenching and separation of phases for analysis (Clayton, 1959; O'Neil et al., 1969),

ii) inorganic precipitation from mixtures of reagents at ambient temperatures (McCrea, 1950; O'Neil et al., 1969).

iii) 'in situ' re-growth of calcite by a living shell organism under controlled marine conditions (Epstein et al., 1953).

These calibrations and the theoretical relationship are shown in Fig. 6. It can be seen that the agreement between experimental and theoretical curves is not good. However, the agreement between the various experimental and biogenic syntheses is excellent. The most commonly-used relationships between α and T for calcite-water fractionation of ^{18}O are:

i) from biological studies (Craig, 1965):

$$T = 16.9 - 4.2(^{18}\delta_c - {}^{18}\delta_w) + 0.13(^{18}\delta_c - {}^{18}\delta_w)^2 \qquad 14)$$

ii) from experimental equilibration studies (O'Neil et al., 1969 & 1975):

$$1000 \ln \alpha = \frac{2.78 \times 10^6}{(T + 273.15)^2} - 2.89 \qquad 15)$$

or by expansion:

$$T = 16.9 - 4.38(^{18}\delta_c - {}^{18}\delta_w) + 0.10(^{18}\delta_c - {}^{18}\delta_w)^2 \qquad 16)$$

where T is in °C and $^{18}\delta_c$ and $^{18}\delta_w$ are $\delta^{18}O$ values for calcite (relative to PDB) and water (relative to SMOW) respectively.

From these studies it has been found that $d\alpha/dT$ = -0.22‰/°C at about 20°C and -0.24‰/°C at about 10°C.

Isotope Fractionation in Cave Carbonate Deposits

When $CaCO_3$ is precipitated in equilibrium with water by the reaction

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O \qquad 17)$$

oxygen isotopic fractionation between $CaCO_3$ and water should conform to equations 14 to 16. Analysis of modern calcites and their dripwaters has indicated this to be true (Thompson et al., 1976). In order to use these relationships to determine temperature of formation of a fossil speleothem (i.e. one where the water of deposition is no longer available for analysis) it is first necessary to determine if the speleothem was deposited in isotopic equilibrium with the water and secondly to measure or estimate the isotopic character of the water of deposition.

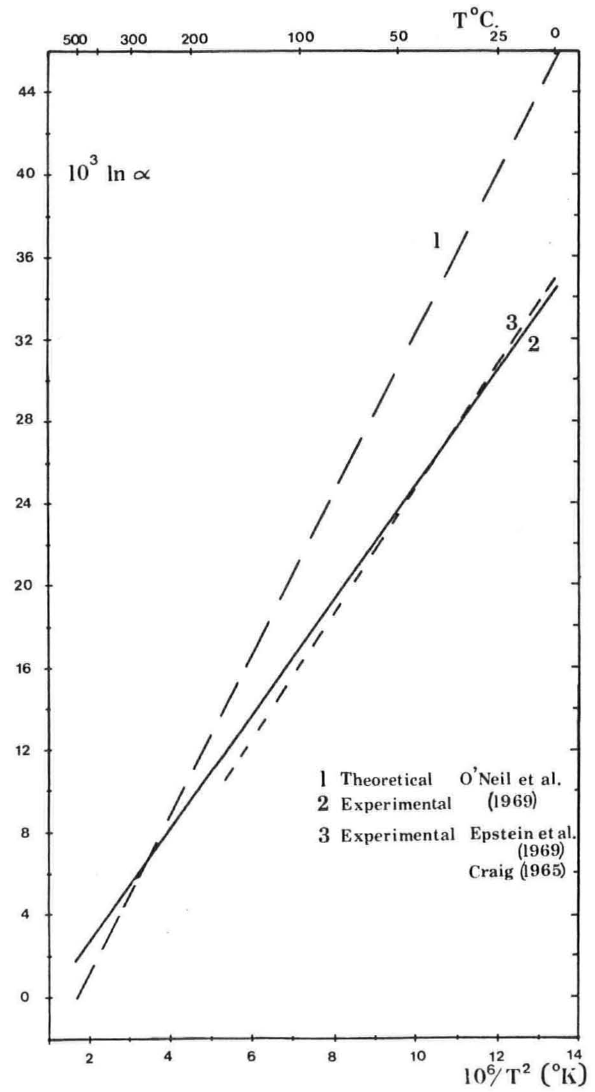

Fig. 6. Theoretical and experimental relationships between the fractionation factor α and temperature for the calcite - water system.

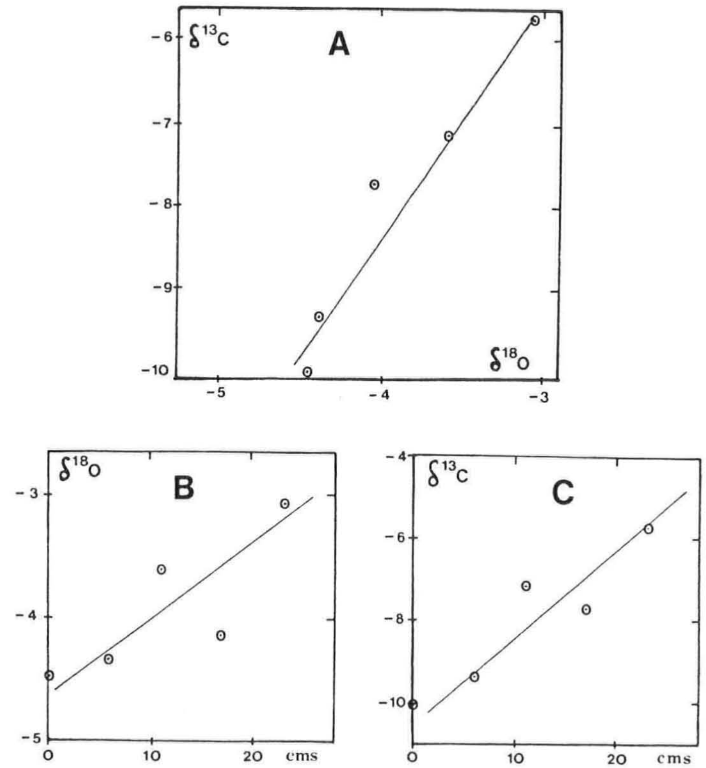

Fig. 7.

Correlation of $\delta^{13}C$ with $\delta^{18}O$ (A) and variation of $\delta^{18}O$ (B) and $\delta^{13}C$ (C) with distance for a growth layer of a kinetically fractionated speleothem. All δ values are in ‰ with respect to the PDB standard.

The first problem has largely been solved because two criteria can be used to recognise equilibrium deposition (Hendy, 1971):

i) constant $\delta^{18}O_c$ along a single growth layer (= same time horizon) in the direction of growth,

ii) lack of correlation of $\delta^{18}O$ and $\delta^{13}C$ of calcite for measurements along a single growth layer.

Variation of $\delta^{18}O$ along a growth layer suggests deposition may have been influenced by evaporation of water, rather than slow loss of CO_2, and a correlation of $\delta^{18}O$ with $\delta^{13}C$ (Fig. 7) shows the presence of an overriding kinetic isotope effect (e.g. rapid loss of CO_2 by aeration) rather than the different, more random processes that affect the $\delta^{13}C$ value alone. Given that a speleothem can be shown to be an equilibrium deposit for a number of growth layers, then variations of $\delta^{18}O_c$ along the growth axis are an indication of climate change, since only $\delta^{18}O_w$ and temperature affect the $\delta^{18}O_c$.

The second problem, measurement of $\delta^{18}O$ of the water of deposition, is more difficult to overcome because modern dripwaters at or near the site of growth of a fossil speleothem may have changed in isotopic character since its deposition. One solution has been to analyse the small quantities of water trapped as fluid inclusions (F.I.) in the calcite lattice during growth (maximum dimensions 50μm). The sample is crushed under vacuum and the water frozen down in a liquid nitrogen trap (Schwarcz et al., 1976). The water is either converted to hydrogen (by passage over heated uranium) or to oxygen (by BrF_5) and then to CO_2, for mass spectrometry. However, it is possible that $\delta^{18}O_{F.I.}$ may be affected by oxygen exchange with the surrounding calcite during the time since deposition, whereas $\delta D_{F.I.}$ would be unaffected. $\delta^{18}O_{F.I.}$ can be estimated instead by using $\delta D_{F.I.}$ and the observed relationship between $\delta^{18}O$ and δD for meteoric waters (Craig, 1961):

$$\delta D = 8\delta^{18}O + 10 \qquad 18)$$

This equation was also valid in glacial times as shown by the Pleistocene glacial ice of Greenland (Dansgaard et al., 1969).

Therefore $\delta^{18}O_C$ and $\delta^{18}O_W$ may be determined for points along the growth axis of a speleothem, and by using equations 12 and 15, the temperature of deposition may be calculated.

Relationship between $\delta^{18}O$ (calcite) and paleoclimate

From stable isotope theory and experiment it has been shown that a decrease in cave temperature will cause an increase in ($\delta^{18}O_C - \delta^{18}O_W$) of about 0.25‰/°C. However, it has also be pointed out that $\delta^{18}O_W$ may vary with time, both seasonally and over glacial-interglacial transitions. This will obviously influence the $\delta^{18}O$ of calcite precipitated from the water. The temperature dependence of $\delta^{18}O_W$* varies between +0.3‰ and +0.7‰/°C (Dansgaard, 1964). Furthermore, since isotopically-light ice accumulates on the continents during an ice age, the ocean becomes steadily heavier (the 'ice volume' effect). Estimates of this change in $\delta^{18}O$ of sea water based on deep-sea core analysis vary from 0.4‰ to 1.65‰ (Emiliani, 1955; Imbrie et al., 1973; Shackleton , 1977)

This differentiation will tend to cause precipitation falling at a site to become lighter during a cooling period, by an amount ranging from 0.05‰ to 0.2‰/°C for an estimated ocean surface temperature drop of 6 to 8°C.

From this, it is difficult to decide exactly how a change in $\delta^{18}O_C$ along a speleothem may be interpreted in terms of climate change. Analysis of rainwaters taken from sites in the continental U.S.A. on a seasonal basis have shown $\delta^{18}O_W/dT$ to vary between 0.17‰ and 0.39‰/°C (Harmon, 1975), substantially less than the Dansgaard values for polar

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* $\delta^{18}O_W$ is not temperature dependent in the sense of varying with temperature in a given sample. Rather δ_W of average rain varies with the temperature at which it is precipitated, which is not quite the same thing.

regions. The effect of this dependence may be further reduced by the fact that most speleothem deposition in cool-to-temperate climates appears to take place during the warmer summer months when groundwater movement is unimpeded and biological-CO_2 generation is high.

The general dependence of $\delta^{18}O_c$ on temperature in speleothems is suggested by the fact that $\delta^{18}O_c$ of speleothems dated at about the time of the last interglacial (100,000 to 120,000 years B.P.) is comparable to modern values, whereas during the Wisconsin (Würm) Glaciation, $\delta^{18}O_c$ values are found to increase.

Recently it has become apparent that change in $\delta^{18}O$ of seawater between glacial and interglacial periods is at least 1‰ and so for oceanic cave sites, $\delta^{18}O_w$ must change by this amount if only because of the ice-volume effect. This has been allowed for in constructing paleoclimate curves from $\delta^{18}O_c$ data for Bermuda by Harmon et al. (1978) but even so, a temperature control on $\delta^{18}O_c$ can still be seen. Analyses of fluid inclusions, in an attempt to estimate $\delta^{18}O_w$ from direct measurements of D/H ratio, has so far only partly solved the problem of variable $\delta^{18}O_w$. Results have shown anomalously low temperatures during glacial periods for Bermudan samples (down to 2°C) and large, seemingly random, temperature fluctuations for this and other regions (Harmon, 1975).

Some general findings from speleothem work done so far are:

i) at most cave sites $\delta^{18}O_c$ decreases with increasing temperature,

ii) the isotopic composition of rainwater in glacial times was lighter (lower in $\delta^{18}O$) than during interglacial times by 3 to 6‰,

iii) temperatures in North American caves were cooler during glacial times than at present by from 3 to 12°C.

One important assumption in all paleoclimatic interpretation of these results is that cave temperature is fairly constant throughout the year and equal to the average annual surface temperature above the cave. This is generally true for caves that are not draughty and do not contain a surface stream, but deeper caves may also be influenced by geothermal heat. If during the Pleistocene, the slow air and dripwater flow were not interrupted (e.g. by ice cover) then cave temperatures should continue to reflect average surface temperature. An exception to this is seen in Castleguard Cave in the Canadian Rockies, where geothermal heat increases the cave temperature to over 3°C whereas the mean annual surface temperature is below zero (Ford et al., 1976).

Speleothem isotopic compositions can give other information about environments of the past. The $^{13}C/^{12}C$ ratio of speleothem calcite is determined by the balance between two inputs:

i) the limestone bedrock of the cave roof and walls, with $\delta^{13}C \cong 0‰$,

ii) dissolved bicarbonate ions in soil water entering the limestone, with ^{13}C ranging from -16 to -24‰ depending on the type of plants in the soil.

During climate shifts associated with continental glacial advances and retreats, the flora above a cave may have changed from grass and sedges (in colder times) to trees and shrubs (in warmer times). These two types of plants fix carbon by photosynthesis with isotopic compositions that differ by up to 8‰. It is therefore possible to detect shifts in $\delta^{13}C_c$ of speleothems that correspond to changes in climate. In some cases these have been found to be correlated with shifts in $\delta^{18}O_c$.

Thus isotopic analyses of speleothems reveal much information about conditions in and above the cave. Although a great deal of information about periglacial climates can be obtained in this way, we cannot unfortunately find out much about conditions close to or under glaciers, for usually there are few or no speleothems being deposited due to lack of liquid water to precipitate calcite, and lack of soil CO_2 to dissolve limestone. In the coldest environments therefore, speleothem deposition should cease altogether. The diminution in frequency of speleothem deposits during certain periods is itself, evidence of cold climate (Harmon et al., 1977).

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M. Gascoyne and H.P. Schwarcz,
Dept. of Geology,
McMaster University,
Hamilton, Ontario,
Canada. L8S 4M1

D.C. Ford,
Dept. of Geography,
McMaster University,
Hamilton, Ontario,
Canada. L8S 4K1

THE CONCENTRATION OF CADMIUM, COPPER, LEAD AND ZINC IN SEDIMENTS FROM SOME CAVES AND ASSOCIATED SURFACE STREAMS ON MENDIP, SOMERSET

by R.D. Stenner

Summary

Streams at Priddy, Somerset, flow through land contaminated by lead smelting from Roman times to the twentieth century, sinking into St. Cuthbert's Swallet and resurging at Wookey Hole. Sediments from both caves were analysed for Cd, Cu, Pb and Zn revealing high levels of contamination by Pb and Zn. The unnatural origin of the contamination was proved by the analysis of stratified deposits in the 4th chamber of Wookey Hole. Archaeological deposits predating the lead industry could be identified by chemical analysis.

The mining and smelting of lead ores on the Mendip Hills has had a long history. At Priddy, Somerset, the blind valley which drains into St. Cuthbert's Swallet was the site of lead industry from pre-Roman times until early in the 20th century (Gough, 1967; Irwin, Stenner & Tilly, 1968). A valley at Charterhouse draining to the Cheddar risings had a mining history of similar duration. Both of these sites remain largely derelict. At Priddy three streams cross disturbed land to enter St. Cuthbert's Swallet, the water from which resurges as part of the River Axe in Wookey Hole Cave (Atkinson, Drew & High, 1967; Stenner, 1968). While the lead industry was in progress, pollution of the risings at Wookey Hole and Cheddar caused contamination which interfered with the production of paper at the Wookey Hole mill and a protracted legal action (including water tracing experiments to prove that the water at St. Cuthbert's leadworks flowed to Wookey Hole) ended with an injunction to stop the leadworks polluting the River Axe.

The present extent of lead contamination in St. Cuthbert's Swallet and Wookey Hole is unknown and a programme of sample collection has been started so that the extent of natural levels of contamination can be assessed, together with the present levels of contamination for which the former lead industry might be responsible.

The collection of samples from surface sites, St. Cuthbert's Swallet, Rod's Pot and Goatchurch Cavern was done with the help of senior pupils of Hartcliffe Comprehensive School, Bristol. The collection of samples from Wookey Hole Cave was made possible by Dr. Tratman, Dr. Stanton and the management of the cave. Members of the Bristol Exploration Club provided more samples from St. Cuthbert's Swallet and Sludge Pit.

The locations of sample sites are shown in Figures 1 - 7, the sample numbers shown refer to those in Tables 1 - 5. Samples were prepared and analysed in laboratories of the Dept. of Inorganic Chemistry, University of Bristol.

Table 1

The concentration of heavy metals in sediments from surface streams on Mendip

Sample No.	Site	Nat. Grid. Ref. (all in square ST)	Cd	Cu	Pb	Zn
			(p.p.m. in dry sample)			
	Plantation Stream, Priddy					
1	Mineries Pool, near exit	5451 5076	1.5	15	14500	820
2	Stream near Pool exit	5448 5076	7.5	35	47000	4000
3	Plantation Swallet	5434 5059	2	35	34000	1700
	Fair Lady Well Stream, Priddy					
4	Spring	5447 5078	2.5	16	7300	1500
5	50m downstream of spring	5444 5074	1.6	25	37500	850
6	Near Plantation Swallet	5433 5060	2.5	30	38500	2000
	St. Cuthbert's Stream, Priddy					
7	St. Cuthbert's Pool	5432 5053	5	85	51000	3100
8	St. Cuthbert's Swallet	5430 5050	4.5	72	55000	3400
	River Axe					
9	Upstream of Wookey Hole Mill	531 478	2.3	25	7500	1300
10	Wookey Hole car park	530 475	6	35	1400	500

Table 1 continued ...

Sample No.	Site	Nat. Grid. Ref. (all in square ST)	Cd	Cu	Pb	Zn
			(p.p.m. in dry sample)			
11	Loxton	379 549	-	22	90	75
12	Swildon's Hole Stream, Priddy	531 513	1.5	21	4100	310
13	G.B. Stream, Charterhouse	477 562	-	25	1000	1500
14	Waldegrave Pool, Priddy S.E. Corner	5473 5050	5.7	30	12500	2200
15	Stream draining N.E. Corner	5472 5156	2.5	5	3500	370
16	Rickford Stream, Plume of Feathers	486 593	-	50	1100	720

Table 2

The concentration of heavy metals in sediments from St. Cuthbert's Swallet, July 1973

Sample No.	Site	Cd	Cu	Pb	Zn
		(p.p.m. in dry sample)			
17	Below Entrance Shaft	7.2	43	64000	1800
18	Below Entrance Pitch, in a side rift	5.7	107	330000	2500
19	Arete Chamber, East Inlet Passage	1.9	20	17500	1200
20	Arete Chamber, N.E. Inlet Passage	2.7	28	32000	1500
21	Arete Chamber, 2nd West Inlet Passage	16	70	132000	4200
22	Mud Hall	3.6	56	24000	1600
23	Lower Mud Hall, old fill	1.6	83	35000	2200
24	Rabbit Warren, passage opposite The Fingers	0.8	8	270	74
25	Stream Passage near Dining Room, at stream level	2.8	45	21000	1800
26	Stream Passage near Dining Room, 3m above stream	0.6	11	890	160
27	Stream Passage, The Sewer, stream level	5	95	33000	3800
28	Stream Passage, Beehive Chamber, stream level	4	56	24000	1600
29	Whitsun Passage, high level oxbow	3.7	11	520	1500

Table 3

The concentration of heavy metals in sediments at Wookey Hole Cave, August 1973.
Water levels refer to low water conditions, entrance dam open.

Sample No.	Site	Cd	Cu	Pb	Zn
		(p.p.m. in dry sample)			
30	1st Chamber, stream bed	4.1	18	6000	1300
31	1st Chamber, water level	3.7	27	10200	1800
32	1st Chamber, top of mud bank	2.9	23	9000	1200
33	3rd Chamber, stream bed	3.5	25	10400	1500
34	3rd Chamber, water level	3.6	17	6300	1100
35	4th Chamber, stream bed	4.1	19	6100	1300
36	4th Chamber, water level	3.4	27	13000	1000
37	4th Chamber, top of mud bank	3.6	18	8100	1050
38	5th Chamber, water level	2.2	22	7100	1600
39	9th Chamber, mud bank beside water	3.3	11	435	400
40	9th Chamber, mud bank at landing	3.0	20	840	230
41	9th Chamber, middle of Upper Rope Pitch	5.3	34	300	280
42	9th Chamber, mud pool at top of Rope Pitches	1.5	43	580	580
43	9th Chamber, mud under stalagmite (site as 42)	4.2	34	580	470
44	9th Chamber, squeeze near entrance	2.2	43	450	270
45	9th Chamber, close to foot of entrance shaft	5.1	45	500	450

Table 4

The concentration of heavy metals in sediments in the archaeological dig in Wookey 4.
The position of the samples in the sections are shown in Figures 1, 2 and 3.

Sample No.	Date	Cd	Cu	Pb	Zn	Sample No.	Date	Cd	Cu	Pb	Zn
		(p.p.m. in dry sample)						(p.p.m. in dry sample)			
46	August 1973	3.6	18	7200	1150	51	August 1974		71	25500	1600
47		4.2	25	11000	1600	52			38	24000	2100
48		5.7	31	26500	2500	53			29	5200	1800
49		4.3	20	9000	1300	54			38	5100	1700
50		3.1	17	6800	890	55			37	4800	780
						56			31	3600	860
						57			34	5100	1500

Table 4 continued ...

Sample No.	Date	Cd	Cu	Pb	Zn
		(p.p.m. in dry sample)			
58	August 1975		54	14500	1600
59			35	11000	590
60			53	4700	680
61			50	3000	820
62			36	480	760
63			75	750	1050
64			28	1100	810

Table 5

The concentration of heavy metals in sediments from Sludge Pit, August 1973.

Sample No.	Site	Cd	Cu	Pb	Zn
		(p.p.m. in dry sample)			
65	Near Entrance (in daylight) 2.0	2.0	23	230	110
66	Near Entrance (inside dark zone)	2.0	25	235	150
67	Main Junction	1.2	12	56	80
68	The Sump	1.5	11	135	85

Table 6

The concentration of heavy metals in sediments from Rod's Pot and Goatchurch Cavern, p.p.m. in dry samples, January 1974.

	Metal	Mean	S.D.	Range
Rod's Pot, 7 samples	Cu	22	8	12 - 35
	Pb	150	90	25 - 280
	Zn	180	100	60 - 400
Goatchurch Cavern, 5 samples	Cu	25	8	12 - 35
	Pb	105	100	25 - 280
	Zn	200	150	60 - 400

Table 7

The concentration of heavy metals in soil samples from an area to the north of North Hill, Priddy, December 1973. A summary of data from 120 samples, including many from mined land, p.p.m. in dry samples.

Metal	Mean	S.D.	Range
Cu	17	6.0	4 - 56
Pb	1250	2900*	90 - 30000
Zn	300	24	20 - 1750

* Not a normal distribution: 61 samples below 500 p.p.m., 6 samples above 5000 p.p.m.

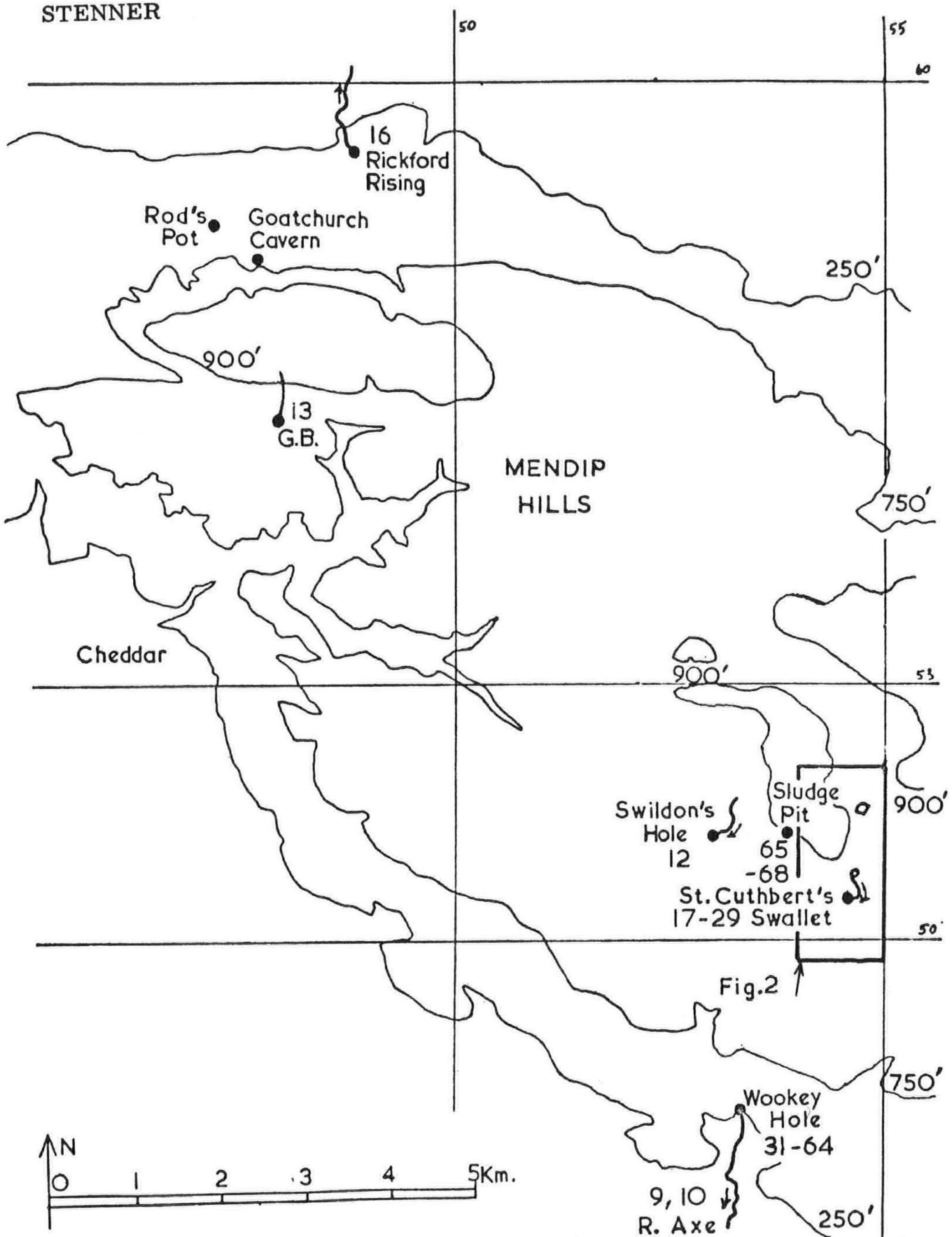


Fig. 1. Sample sites in Mendip. Numbers refer to Tables 1 - 5.

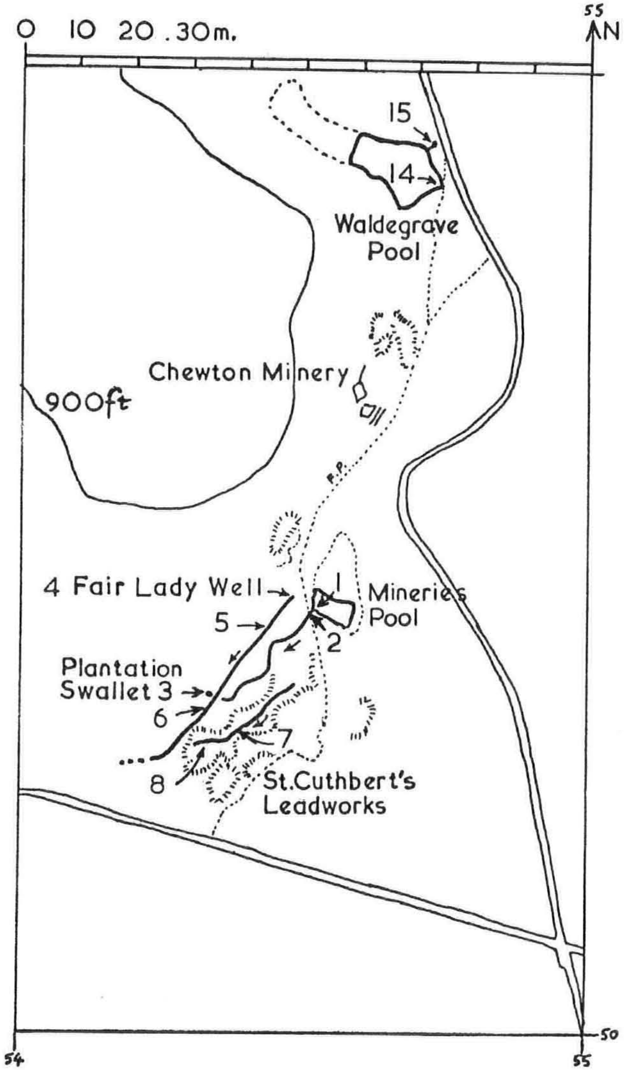
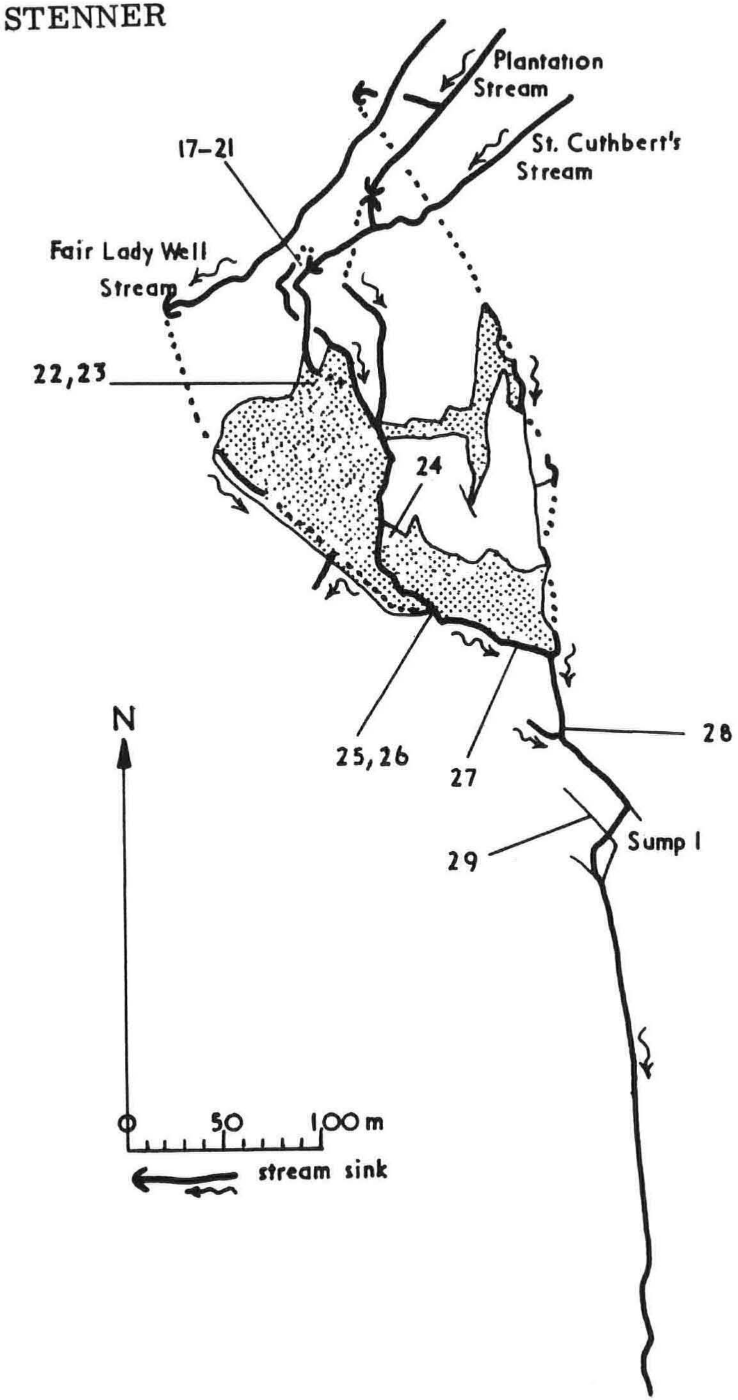


Fig. 2. Sites in and around St Cuthbert's Swallet. Sample numbers refer to Table 1.



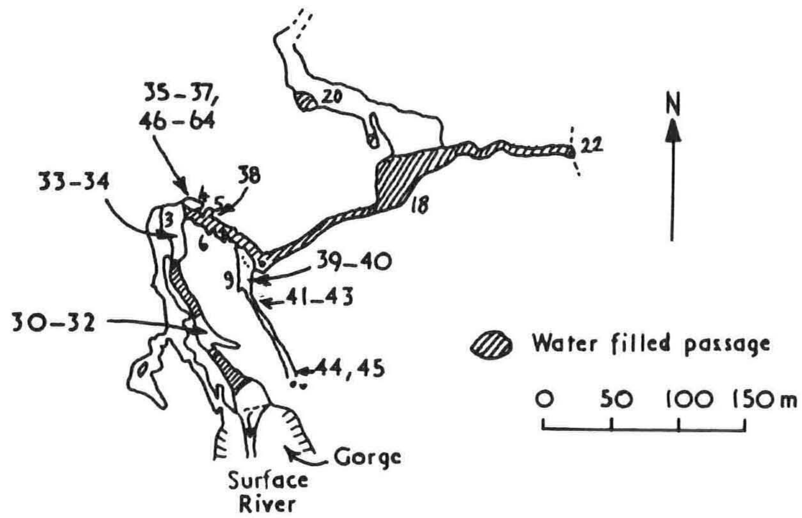
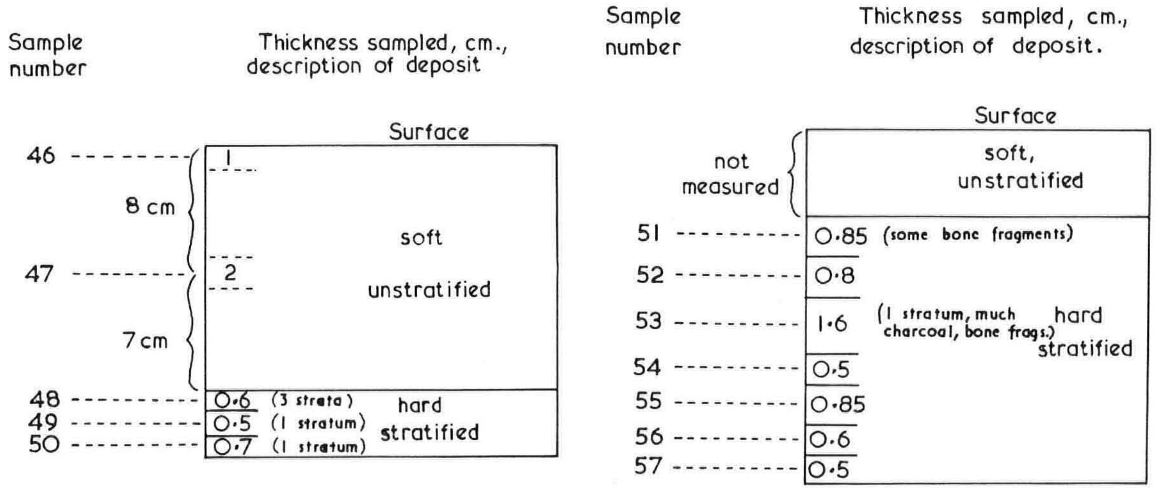
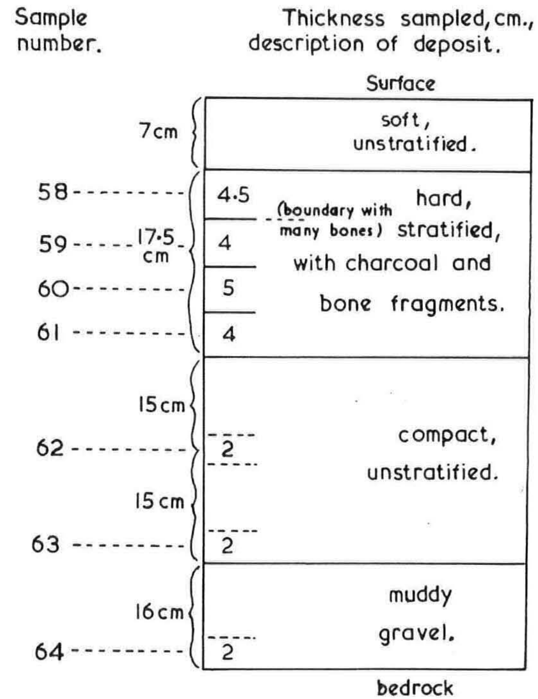


Fig. 4. Simplified plan of Wookey Hole (based on Hanwell 1970). Sample numbers refer to Tables 3 and 4.

Fig. 3. Simplified plan of St Cuthbert's Swallet. Sample numbers refer to Table 2.





Figs. 5, 6 and 7. Cores from archeological dig in Wookey Hole 4th chamber. August 1974 (not to scale). Sample numbers refer to Table 4.

EXPERIMENTAL

Sediment samples were collected in polythene bags, when possible, where contamination by caving activities would be minimal (oxbows, beneath stalagmite flows or rocks). In the laboratory, samples were dried, crushed and screened through a B.S.S. No. 100 mesh sieve. Portions of 0.1 - 0.3 g were weighed to a 1% precision, boiled with 10 cm^3 Analar nitric acid for 2 hrs, and diluted to 50 cm^3 with double-distilled water. Concentrations of Cd, Cu, Pb and Zn were determined by atomic absorption spectrophotometry using a Varian Techtron AA5 instrument. With each batch of samples, 10% of the test tubes were reserved (at random) to check against accidental contamination and to measure reagent blanks. Standard solutions were made in 20% nitric acid. Samples were analysed in duplicate, further samples being analysed on three occasions when the results showed an unusually large disparity.

THE PRECISION AND ACCURACY OF THE RESULTS

Standard errors of Cu, Pb and Zn were 5.5% (90 samples), 5.2% (94 samples) and 5.3% (92 samples) respectively. The precision of Cd (at the 2 S.D. level) was 0.5 p.p.m. (hence a variable percentage error).

Many procedures are currently in use for the analysis of sediments for heavy metals (Willard, Merritt & Dean, 1965; Hesse, 1971). The method used in this study can produce lower results than analysis by X-Ray fluoresence spectrometry, or analyses following digestion by HNO_3HClO_4 or $HClO_4/HF$.

Lead results were not corrected for calcium enhancement, which would be 30-50 p.p.m. in samples low in lead, and negligible in samples which required further dilution prior to analysis.

DISCUSSION

The results in Table 4 show that the high levels of Pb and Zn in Wookey Hole sediments are unnatural, a consequence of the lead industry. The contamination pre-dated artifacts which have been provisionally dated 250-280 A.D. (Tratman, 1976, personal communication). The level of these metals in unpolluted sediments is indicated by the older sediments from the Wookey 4 dig (Table 4), samples 62 and 63, samples 24, 26 and 29 from St. Cuthbert's Swallet (Table 2) and sample 39 from Wookey 9 (Table 3).

The concentration of Pb and Zn in stream deposits shows a steady decrease with distance from the source of contamination, in stream passages in St. Cuthbert's Swallet to Wookey Hole. There are two anomalous results, from samples 18 and 21 (Table 2). Parts of these two samples were analysed independently by Dr. Badham at Southampton University, using X-Ray diffraction analysis. He reported that they contained cerussite (basic lead carbonate), which, from its agglutinated texture, could not have been transported to the sites. The Pb was probably transported in solution from a galena vein undergoing weathering. Sample 18 contained 70% cerussite (Badham, 1974, personal communication). These two samples resembled clay when they were collected, unlike the gravel, sand and silt mixture from other sites.

St. Cuthbert's Swallet has a catchment of 1.2 km^2, while Wookey Hole has a total revised area of 46.2 km^2 (Smith & Drew, 1975, pp. 183 & 200). This swallet therefore contributes only a small fraction of the total flow from the resurgence. The possibility of sediments being carried by percolation water from old mine workings was considered. The poor ability of small streams to carry sediments contrasts with the high transport potential in the swiftly flowing stream from St. Cuthbert's Swallet, with its notably rapid flow - through time to Wookey Hole (Atkinson, Drew & High, 1967). This, taken with the well-documented pollution of the Axe by St. Cuthbert's leadworks, supports the hypothesis that the lead in contaminated Wookey Hole sediments were transported via St. Cuthbert's Swallet.

The first two sets of results from the Wookey dig show a narrow band of sediment with a very high lead content. This was masked to some extent in the third set of results because sample 58 was taken from a wide thickness, 4.5 cm, compared with 0.6 cm, 0.85 cm and 0.8 cm at samples 48, 51 and 52. The three sets of results are compatible with one another, and a summary has been published (Stenner, 1977). The possibility that deposits at the top of the hard strata were enriched with lead and zinc in the time since their deposition cannot be ignored, particularly since the zone coincided with a discontinuity in the physical nature of the deposits.

A similar situation exists at Charterhouse. It can be predicted that deposits at Cheddar will show a similar pattern; high lead levels post-dating the start of the lead smelting at Charterhouse, while older deposits and deposits not associated with contaminated streams will contain considerably lower levels of lead and zinc.

The results for cadmium and copper are much less informative. Natural variability seems to be greater. In retrospect, analyses for iron and manganese are more likely to have produced results of value to cavers.

The analysis of traces of sediments would make it relatively straightforward to confirm whether an object from Wookey Hole pre-dates the lead industry, and it can be predicted that this will also apply at Cheddar. The analysis of small sediment samples may also have great potential value in following the Axe upstream towards St. Cuthbert's Swallet, with particular importance in sudden changes in lead levels acting as markers of major stream junctions which may escape notice in deep sumps.

Biological consequences of long-term exposure of cave-dwelling invertebrates to lead-rich sediments need to be investigated. In the Axe at Wookey Hole and in the surface streams near St. Cuthbert's Swallet, lead concentrations in plants, invertebrates and fish are considerably higher than normal.

While the results presented here may have biological, archaeological and speleological interest, they have no commercial interest. Apart from the relatively small quantities it is clearly impossible to consider utilising the lead-rich deposits without causing unacceptable environmental havoc.

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R.D. Stenner,
18 Stafford Place,
Weston-super-Mare,
Avon. BS23 3QZ

A MODEL FOR THE DEVELOPMENT OF BROAD SCALE NETWORKS OF GROUNDWATER FLOW IN STEEPLY DIPPING CARBONATE AQUIFERS

by Ralph O. Ewers

ABSTRACT

Laboratory analogue experiments, computer simulations and field evidence from the midwestern United States, Western Canada and Central Europe support a comprehensive model for the development of the network of solution tubes which are responsible for high volume flow in carbonate aquifers. The model proposes that broad scale networks (networks draining more than 100 km^2) are established by the integration of smaller networks which propagate from discrete input sources as distributary systems. Within the framework of regional hydraulic gradient established by geologic structure, topography and lithology the integration process proceeds headward in a stepwise fashion from the resurgence point. The direction and rate of growth of the smaller elements is determined by lithologic anisotropies and the geometry of the input and resurgence array. These factors together with regional boundary conditions determine the pattern of the larger networks.

SPELEOGENESIS - A FIELD PROBLEM

To consider speleogenesis as a field problem is not a new concept. Davis (1930), Swinnerton (1932), M. King Hubbert (1940), Rhoades & Sinacori (1941) and others have used flow field arguments in support of speleogenetic hypotheses. All of these workers have confined their representations of these fields to the vertical plane.

In this research the evolution of secondary porosity in carbonates is considered as primarily a function of flow fields in the horizontal plane or in a plane parallel to the bedding. This perspective permits an assessment of the factors controlling the development of the conduit networks of large areal extent which most karst drainage systems represent. In laboratory experiments two types of boundary conditions are considered: point resurgence and linear resurgence (Fig. 1).

ELECTRICAL ANALOGUE EXPERIMENTS

Liquid medium electrical analogue experiments were used to determine the relative flow rates (Q) through each of several inputs to a simulated bedding plane. Two general types of effects were seen: density effects and distance effects.

As the distance between the input and resurgences is increased, the Q through that input decreases. The expected plot of Q vs. distance should yield a rectangular hyperbola with Q very high at small distances and very small at great distances.

As the density of inputs increases the Q through each input also decreases. The combination of these effects are illustrated in Fig. 2 for a linear resurgence case. These plots are in good agreement with the expected values.

In the point resurgence case each input in a linear array lies at a different distance from the resurgence and therefore each displays a different value for Q depending upon that distance and the density of inputs. When such inputs are asymmetrically arrayed relative to the resurgence (Fig. 3) and the input-resurgence distances are increased the input Qs become more nearly equal.

The asymmetrical point resurgence case with a linear input array is analogous to the situation where groundwater flow is accomplished through a steeply dipping planar discontinuity such as a fault or steeply dipping bedding planes. In such cases groundwater flow begins where the bedding plane intersects the surface and frequently must be discharged along the strike to a point resurgence.

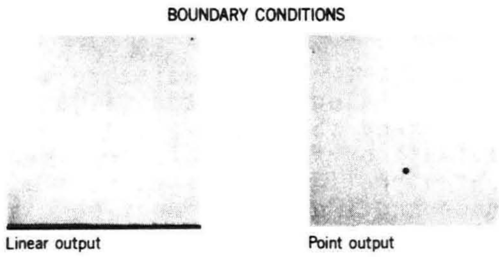
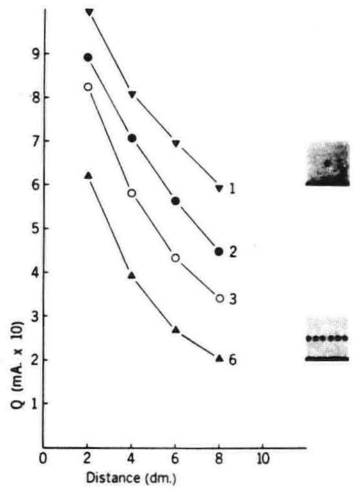


Figure 1.



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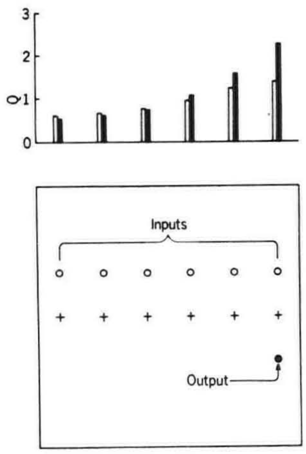

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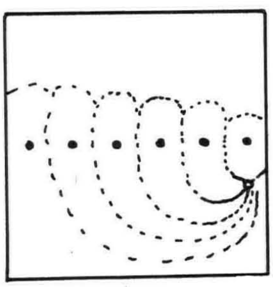

Figure 3A.

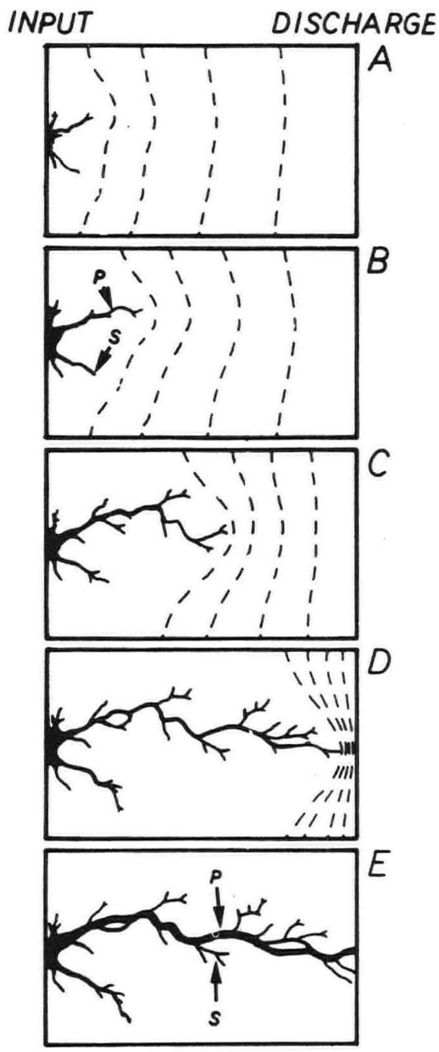

Figure 4.

FLOW ENVELOPE EXPERIMENTS

The previously described experiments provide information concerning the relative Q for each of several inputs to a dipping bedding plane. This value governs the rate at which solution porosity will develop from each input. Before considering this rate further, it is necessary to determine the vector along which such development takes place.

By injecting dyed water into a thin (5mm) saturated sand layer beneath a transparent confining layer the size, shape and rate of movement of the flow envelopes of a multiple input array can be determined.

The flow envelopes for an input array similar to Fig. 3, were mapped by this method and are presented in Fig. 3A. This clearly shows the separate nature of the discharge from each input and the path of its discharge. Initially then, each input should give rise to separate solution openings parallel to one another and along paths nearly at right angles to the shortest path to the discharge point.

THE SOLUTION EXPERIMENTS

The nature of the solution openings has been deduced through solution experiments in plaster of paris and salt media (Ewers, 1972 & 1976). These experiments indicate that early solution openings in bedding planes grow from input points in the form of distributary networks of tubes. These networks discharge effectively saturated water into the surrounding unaltered bedding plane. The discharge rate from any particular region of the network is controlled by the pressure field in the bedding plane. The rate of discharge governs the rate of growth for each region. The largest of "principal" tubes in the network develops in the direction of greatest hydraulic gradient and lengthens at an increasing nonlinear rate. The growth of this tube distorts the pressure field in such a way as to cause deteriorating discharge potential and therefore deteriorating growth rates for distributary tubes which diverge from the principal tube. This effect confines the network to a narrow band with its long dimension directed toward the resurgence along the central axis of the flow envelope (Fig. 4).

When a network breaches the bedding plane in which it formed, a low resistance path is established between the input and resurgence producing a fundamental change in the flow characteristics within the network. The principal tube will then be capable of conducting much larger quantities of water, and the head at its input is likely to be much reduced. However, the most important change with regard to this discussion is the reorganization of the surrounding flow field.

THE DIPPING BED MODEL

In steeply dipping carbonate sequences a bedding plane is likely to have many ground water inputs where the plane intersects the surface. These inputs will be linearly arranged. Groundwater resurgence occurs where surface erosion or joints expose the bedding plane at a lower level than the inputs. The flow envelope experiments have shown that within the complex flow field of such a multiple input array, the flow contributed by each input remains separate. These experiments have further shown that the growth of the proto-cave passages from each input is directly proportional to the discharge space it commands at the flow field output boundary. Thus, each input generates a separate distributary network of tubes and those closer to the discharge boundary grow most rapidly (Fig. 5). The first input to establish a low resistance link with the boundary will reorder the pressure field producing what is best described as a piezometric draw down cone in its vicinity. The nearby networks will respond to this pressure field change by increasing their growth rate and redirecting their growth toward the low resistance tube (Fig. 6). The first of these to link with the initial low resistance tube will become the discharge target for the next adjacent network and so forth (Fig. 7).

If surface erosion processes establish lower resurgence points the same process can be repeated (Fig. 8).

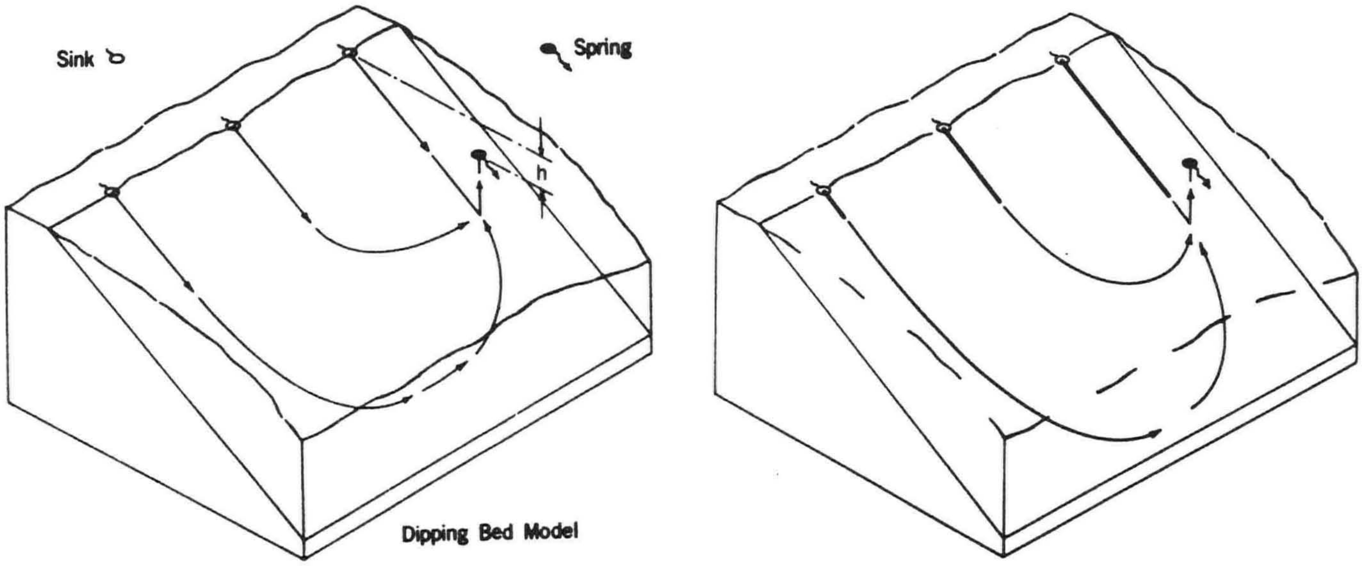

Figure 5 . Heavy lines indicate developing tubes

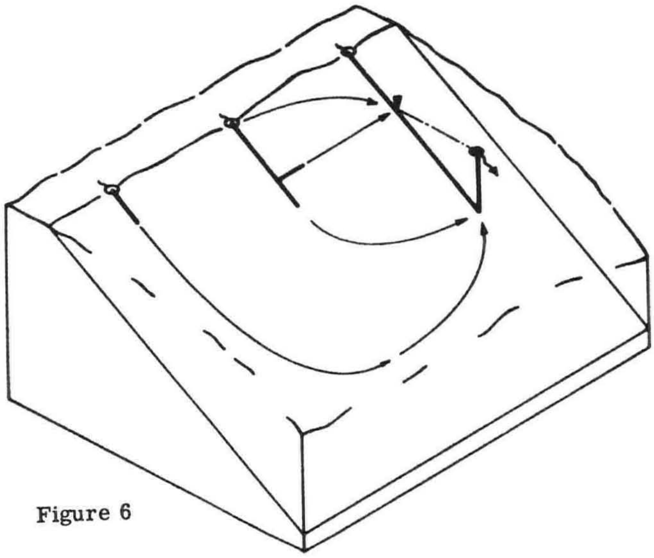

Figure 6

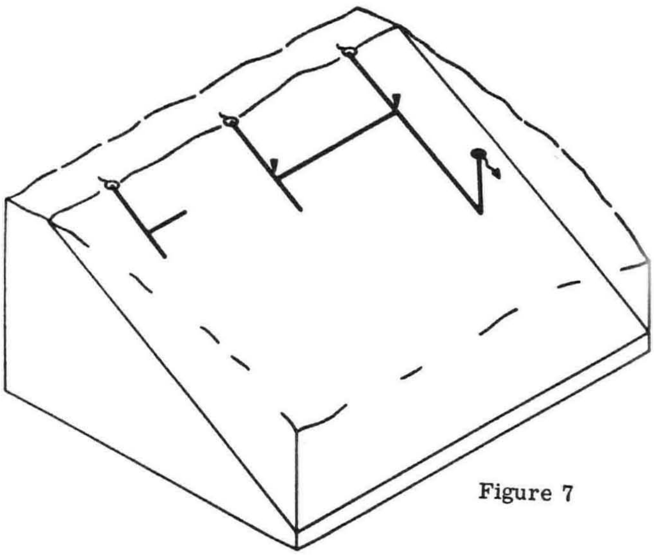

Figure 7

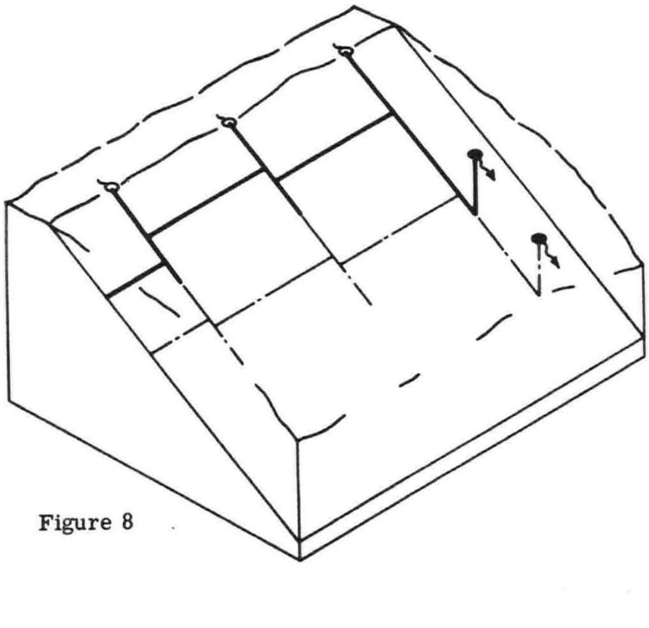

Figure 8

CONCLUSION

The kinetics of limestone solution require the early framework of solution openings in the karst subsurface to run from the source toward the discharge boundary. Initially individual parallel distributary networks should form from each input. As these networks breach the bedding plane, links should develop between the originally separate flow systems. These should produce in a dipping bed situation an interconnected set of strike and dip tubes which characterize most explorable caves in these settings. The patterns of many caves in steeply dipping carbonate strongly suggests that they have evolved by this process. The plan of the well-known Holloch in Switzerland is a typical example. The passages are developed near the same bedding plane and show little or no evidence of joint control. The inputs occur at joints or suspected joints near the region where the bedding plane intersects the surface.

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R.O. Ewers,
Science Museum,
West Palm Beach,
Florida, U.S.A.

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